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Enhancing Hull Performance Analytics with Vision AI
− A New Hybrid Biofouling Analytics Approach

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Abstract

The past decade has seen significant advances in computer learning and robotics delivering tools to tackle biofouling with data. AI-based image recognition can now bridge the gap between biofouling in-water inspection and data analytics. This paper introduces a new vision-centric method for biofouling imagery evaluation that can be used in performance monitoring reporting. The paper outlines how the image processing outputs are intended to integrate with operational performance reporting by linking quantified fouling state to longitudinal hull-condition tracking and decision support for maintenance and efficiency management.

1. Introduction

Marine biofouling remains to be one of the most persistent (hidden) drivers of ship energy demand. Even moderate biological growth increases hull roughness and frictional resistance, which can translate into substantial additional fuel burn and emissions, often dwarfing the direct costs of coating or cleaning interventions, *Schultz et al. (2011), Farkas et al. (2021).* In parallel to its efficiency penalty, biofouling is also recognized as a vector for invasive aquatic species transfer, motivating international guidance on systematic biofouling management and documentation, *IMO (2023).*

Recent advances in compact robotics and computer vision have shifted hull-performance management from periodic, experience-based decisions toward condition-based strategies that allow combining operational data streams with objective evidence of the hull's physical state. Micro-ROVs can acquire hull imagery more frequently and with better repeatability than traditional drydock-only assessment − potentially enabling "longitudinal hull condition" datasets rather than isolated inspection snapshots. The potential of this rising technology for the maritime sector has been highlighted by *Stein (2023)*.

Yet, translating real-world underwater inspection footage into reliable quantitative indicators remains difficult. Underwater imaging suffers from scattering, backscatter, wavelength-dependent attenuation and severe contrast loss, to name only a few of 27 influencing factors, which distort texture cues and suppress boundaries that segmentation models rely on, *Akkaynak and Treibitz (2018)*. In addition, operational hull imagery is highly variable across ports, seasons, coatings, lighting setups, camera optics, and cleaning histories − conditions that routinely produce domain shifts between curated training data and deployment reality. These constraints have driven a growing body of work on ML-supported hull inspection, including semantic segmentation benchmarks for underwater ship inspections and transfer-learning approaches for hull-surface condition recognition, *Waszak et al. (2022), Kim et al. (2022).*

For hull performance analytics, the technical challenge is not only "detect fouling," but "detect fouling in a way that is operationally interpretable." This is where vision-centric inspection can bridge into performance monitoring standards and decision support. ISO 19030 formalizes principles and indicators for tracking changes in hull and propeller performance over time, enabling consistent, within-ship comparisons for maintenance planning, *ISO (2016)*. However, operational performance deltas alone rarely identify why performance changes (e.g., fouling vs. weather routing effects vs. sensor drift). A quantified, class-resolved fouling state derived from ROV imagery can act as an evidence layer to interpret performance trends − linking the "what we observe on the hull" to "what we observe in propulsion and fuel-time series," thereby strengthening both reporting credibility and maintenance decision quality.

This paper contributes to this integration by presenting a vision-centric method for robust biofouling imagery evaluation under real inspection conditions, with an explicit focus on scalability and downstream utility for performance-oriented reporting. It frames the core bottleneck as data scarcity and generalization: high-quality pixel labels are often disclosed, while real-world hull imagery varies dramatically between aerial (in-air) and underwater domains (turbidity, illumination, reflections, and coating appearance). To address this, the paper evaluates mask-conditioned synthetic data generation − leveraging high-resolution conditional GAN families (e.g., Pix2PixHD and SPADE) and exploring diffusion-based control − to generate realistic, label-aligned fouling imagery at scale.

2. Problem statement

High-quality, well-labelled underwater ship-hull imagery is a critical bottleneck for advancing hull performance analytics. Vision-AI models that quantify biofouling state, coating degradation, corrosion, and structural anomalies depend on pixel-accurate ground truth to learn robust representations and to produce outputs that can be trusted in operational decision support. Without reliable labels, models may appear accurate on narrow test sets yet fail when confronted with the real diversity of vessel types, coatings, lighting conditions, water properties, and inspection practices encountered across the global fleet.

Conventional underwater data acquisition relies heavily on diver-led class or in-water surveys. While divers remain essential for many tasks, diver-based inspection introduces structural constraints for building scalable labelled datasets. Even when conditions allow, diver time-on-task is limited and the work environment can be hazardous; inspections must be performed efficiently, often under schedule pressure, and imagery collection is typically optimized for immediate survey findings rather than for consistent, ML-ready coverage and annotation. More fundamentally, diver inspections do not naturally produce standardized, repeatable scans at the scale required for data-driven hull-condition tracking.

Drydock inspections provide higher-quality access and can support meticulous documentation, but they are episodic. Relying on drydock-only imagery therefore produces an "ex ante" condition snapshot: it explains the hull state at docking, but it does not capture how condition evolves during the years between dockings, when decisions about cleaning, coating performance, routing, speed management, and efficiency interventions are most valuable. For hull performance analytics, the central requirement is longitudinal evidence: frequent, comparable observations that can be linked to time-series performance indicators, as emphasized by in-service monitoring standards, *ISO (2016)*.

Hull-scanning ROV systems offer a practical path through these constraints. ROV-based inspection can be scheduled more frequently than drydock events, can reduce human exposure to hazardous conditions, and can be engineered for systematic coverage (e.g., consistent stand-off distance, lighting, overlap, and georeferenced scan paths). This improves not only inspection repeatability but also the feasibility of building large labelled corpora - especially when paired with semi-automated annotation tools, active learning workflows, and synthetic augmentation pipelines validated against real deployment conditions. In short, ROV scanning shifts underwater imagery from "ad hoc evidence" to "measurement infrastructure."

Despite progress, publicly available datasets are still insufficient to train models that generalize across the global shipping industry. A useful example is the LIACi contribution, *Waszak et al. (2022)*, used in recent work on synthetic marine-growth segmentation: while valuable for benchmarking, it remains limited in scale and scope in the variety of hull geometries, coatings, biofouling regimes, and imaging environments required for cross-sector, cross-region robustness. Surveys of underwater image synthesis and datasets similarly emphasize that data scarcity and domain shift are persistent barriers to transferable performance as for example seen in *O'Byrne et al. (2018), Mai et al. (2024)* and *Barbosa and Apolinario (2025).* The core problem, therefore, is not simply to "collect more images," but to build well-labelled, operationally representative datasets - at scale, over time, and across conditions - so that hull analytics can support five-year-cycle decision making rather than just post-drydock assessments.

3. Implications to Maritime Economics

Biofouling remains a persistent, operationally "hidden" driver of energy demand for seagoing ships. Even moderate growth elevates hull roughness and frictional resistance, *Schultz et al. (2011)*, with measurable consequences for fuel consumption, emissions, and total voyage cost. Beyond efficiency, biofouling constitutes a biosecurity concern through invasive species transfer, which has increased the regulatory emphasis on systematic biofouling management and documentation, *IMO (2023)*. Within this context, the present work positions vision-based inspection not as an isolated detection task, but as an evidence layer that can be linked to longitudinal performance monitoring and maintenance decision support. A key implication for shipping is the role of micro-ROV systems in shifting hull assessment from episodic snapshots toward continuous, repeatable measurement. Compared with diver-based surveys or drydock-only documentation, micro-ROVs can be deployed more frequently, potentially generating a vast amount of crucial hull condition knowledge. This supports the creation of high-definition, temporally comparable "longitudinal hull condition" datasets, which are essential if hull-state evidence is to be integrated with operational efficiency indicators. In practical terms, frequent imagery closes the evidentiary gap between observed performance deltas and their physical cause, strengthening the credibility of performance reporting and the timing of cleaning or coating interventions.

However, the industry-wide adoption of data-driven biofouling analytics is constrained by underwater data scarcity and domain variability. Real-world hull imagery is difficult to label at scale and is affected by scattering, backscatter, attenuation, and highly heterogeneous operational conditions, which collectively induce domain shift and degrade model generalization. The paper's synthetic, mask-conditioned image generation pipeline has direct implications for overcoming this bottleneck: by producing label-aligned synthetic hull imagery, it can expand training coverage, mitigate class imbalance (including rare fouling states), and reduce dependence on costly manual annotation. Crucially, the reported results emphasize that synthetic realism alone is insufficient; generator choice and hybrid (real + synthetic) training must be validated against underwater imaging physics to yield robust gains in downstream segmentation performance.

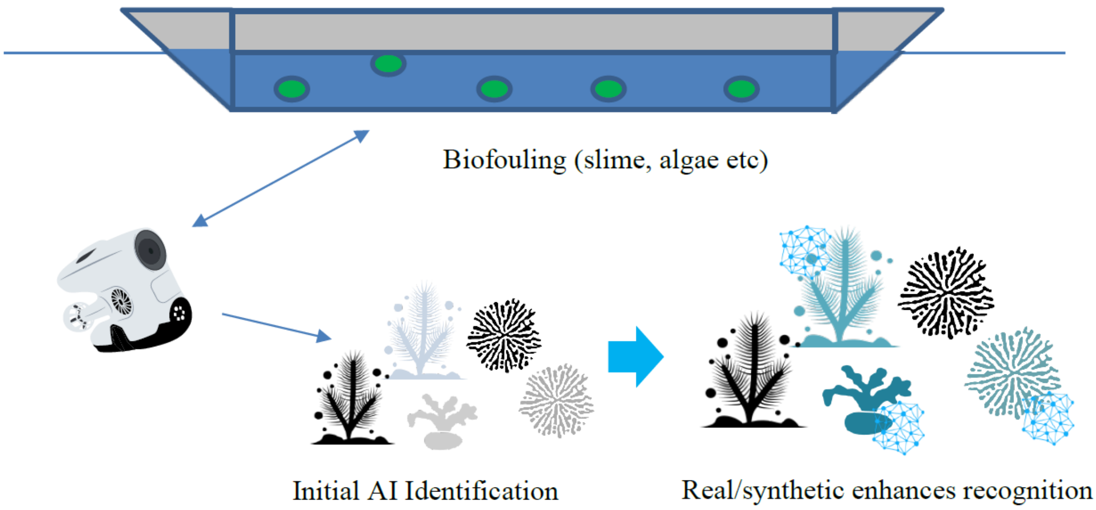

Fig.1: Schematic of this paper's contribution to maritime economics

4. Methodology

This study develops and evaluates a vision-centric pipeline for quantifying hull biofouling from inspection imagery and translating the resulting fouling state into inputs suitable for longitudinal hull-condition tracking and performance reporting. The core methodological idea is data-centric robustness: rather than relying solely on larger real-world labels, the approach systematically expands and diversifies training data with label-preserving synthetic imagery, reducing the sim-to-real gap through controlled variability, *Tobin et al. (2017)*.

To further close bespoke gap, this study combines aerial test plate data as well as real-world ROV inspection data in its research. To the best of our knowledge, this mixed-data source approach has not been conducted before and reflects a novelty in biofouling research. Two complementary, manually annotated datasets were constructed to reflect distinct operational inspection domains:

1. Aerial test plate dataset: 216 labelled images spanning 11 fouling categories
2. Underwater ship hull dataset: 225 labelled images spanning 6 fouling categories.

The test plate data was extracted from photographs of anti-fouling coating test sites in Scandinavia and the Mediterranean provided by an anonymous stakeholder in coating research. The underwater ship hull dataset has been provided by a service operating company specializing in global ROV ship hull inspections. The sample of images varies across multiple inspections and ships in order to account for small sample biases and provide a variation of lighting, visibility, fouling distribution and other image defining factors.

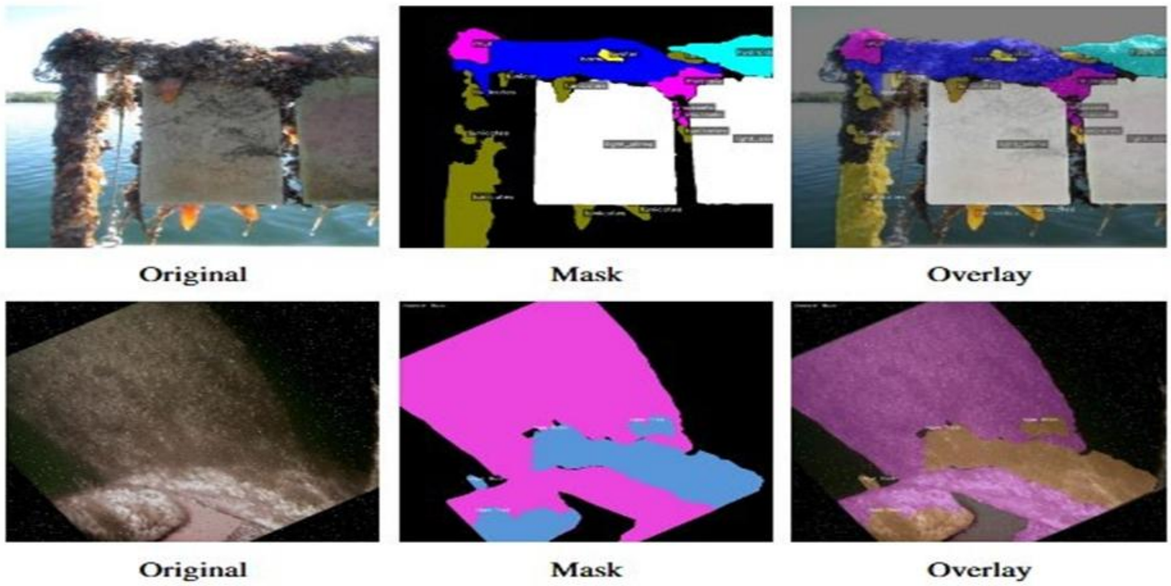

Fig.2: Examples of image–mask alignment used during quality verification

In the first stage, all images and annotations were standardized into a unified training representation. Raw images were automatically oriented and resized to a fixed resolution to support downstream segmentation. The corresponding labels were exported in COCO JSON format, *Lin et al. (2014)*. Because the export provides polygon vertices rather than raster masks, we developed custom scripts to (i) rasterize polygons into RGB/ID mask images, (ii) generate mask–image overlay previews for visual quality control, and (iii) compute per-class statistics to audit label distributions and identify potential imbalance. In parallel, routine pre-processing and validation steps were applied to ensure dataset integrity, including mask–image alignment checks, removal of corrupted samples, and any model-specific normalization required by the respective training pipelines.

In the second stage, synthetic image generation was performed using paired mask-to-image translation. This follows established conditional synthesis paradigms in which semantic layouts guide high-resolution image generation (e.g., Pix2PixHD and SPADE-style conditioning) as already introduced by *Wang et al. (2018)* and *Park et al. (2019)*. Both high-resolution conditional GAN generators were trained separately for the aerial and underwater domains using paired (m, x) samples, where m denotes the segmentation mask and x denotes the corresponding RGB image. Both generators were optimized using Adam for 200 epochs per dataset. Training used a conditional adversarial objective augmented with stabilization and perceptual components (adversarial loss, feature-matching loss, and a VGG-based perceptual loss), while SPADE additionally injected the mask through spatially-adaptive normalization layers to strengthen semantic alignment and boundary preservation, *Wang et al. (2018), Park et al. (2019).* For GAN training, images were resized to 512×512 and normalized to [-1,1], while downstream segmentation training was conducted at 640×640.

In the third stage, synthetic datasets were constructed via automatic label propagation, in which each synthetic image inherits its exact conditioning mask as its segmentation label. This eliminates manual annotation for generated data and ensures strict image–label correspondence. To test whether synthetic data improves real-world performance, the study trains YOLO-family segmentation models under three regimes:

1. Real-only: trained solely on the curated labelled images
2. Synthetic-only: trained solely on generated images with propagated labels
3. Hybrid (real + synthetic): trained on the union of real and synthetic data

This approach enables the isolation of domain-gap effects and measurement of practical gains from synthetic augmentation following *Tobin et al. (2017).* Deterministic file naming and label duplication were used to preserve alignment between generated images and YOLO-format label files.

The final evaluation stage focussed on multi-level performance assessment of the models. Because visually plausible images do not always improve downstream learning, generator evaluation was conducted on both perceptual/structural similarity and task utility. For perceptual/structural similarity, realism was assessed using widely adopted metrics, including:

- FID for distributional similarity in deep feature space, *Heusel et al. (2017)*
- LPIPS for perceptual similarity aligned with human judgment, *Zhang et al. (2018)*
- SSIM for structural fidelity, *Wang et al. (2004)*

These metrics provide complementary signals: FID emphasizes feature-distribution alignment, LPIPS captures perceptual differences, and SSIM focuses on structural consistency. Importantly, the study treats these as necessary but insufficient, prioritizing downstream segmentation outcomes as the decisive criterion.

For task-level utility, segmentation models from the YOLOv8 and YOLOv11 families were trained with consistent hyperparameters (fixed input resolution, fixed epoch budget, and unified augmentation policies) and evaluated on held-out real test images. Performance was reported using precision, recall, F1-score, mIoU, and per-class IoU, with additional attention to robustness in visually challenging cases such as low visibility, occlusion, and texture variability, *Redmon et al. (2016).*

Performance is evaluated on held-out real test data, using mean Intersection-over-Union (mIoU) as the primary segmentation metric (consistent with common semantic segmentation practice). The hybrid regime consistently provides the strongest robustness, with reported absolute mIoU gains up to ~0.2 on real test imagery. Improvements are especially evident for minority/rare fouling classes, consistent with the hypothesis that synthetic augmentation can expand coverage of underrepresented visual states and reduce class-imbalance effects. A final methodological element lies in the explicit comparison between aerial and underwater domains. The study reports that generator and training effectiveness can differ by environment, underscoring a practical lesson for ROV-based analytics: synthetic data is not a single universal lever. Generator selection, conditioning strategy, and augmentation scope must be validated against the target deployment domain's imaging physics and operational variability.

5. Results

Synthetic outputs were first evaluated qualitatively, since visual plausibility alone does not ensure effective segmentation training expressed by improved downstream segmentation performance.

Beyond realism, generated imagery must preserve conditioning mask boundaries and structural integrity, *Wang et al. (2004),* while also avoiding perceptual artifacts that can mislead learning, *Zhang et al. (2018)*. Representative samples were selected to capture diverse mask complexities and environmental conditions, ensuring balanced coverage of both aerial and underwater domains. Each qualitative comparison is presented as a triplet: (A) input mask, (B) real image, and (C) corresponding synthetic image. This protocol enables consistent evaluation of each generator's ability to produce realistic, mask-aligned outputs across contrasting inspection scenarios, *Heusel et al. (2017).*

1) Aerial Domain: In aerial imagery, both Pix2PixHD and SPADE accurately reproduce the global structure of the conditioning mask, but they differ in texture fidelity and lighting adaptation. Pix2PixHD often over-smooths fine-scale regions, such as thin slime trails or surface micro-irregularities, which can reduce perceived detail. SPADE generates visually sharper outputs with stronger local contrast and more realistic micro-texture variation. Boundaries remain well aligned with the conditioning masks for both models. SPADE shows greater robustness to uneven illumination and reflective hull surfaces. to its spatially adaptive normalization that better preserves local semantic and lighting context. Overall, SPADE produces more convincing aerial results, due to its spatially adaptive normalization that better preserves local semantic and lighting context, Fig.3.

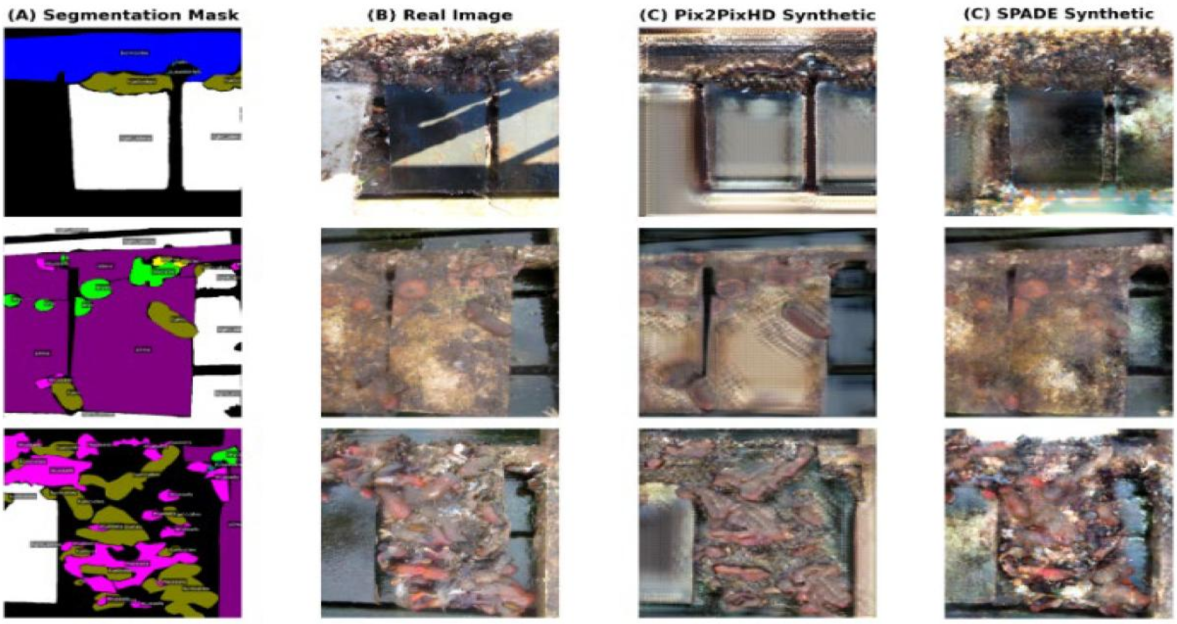

Fig.3: Aerial Training Data Example Results, Pix2PixHD vs. SPADE synthesis

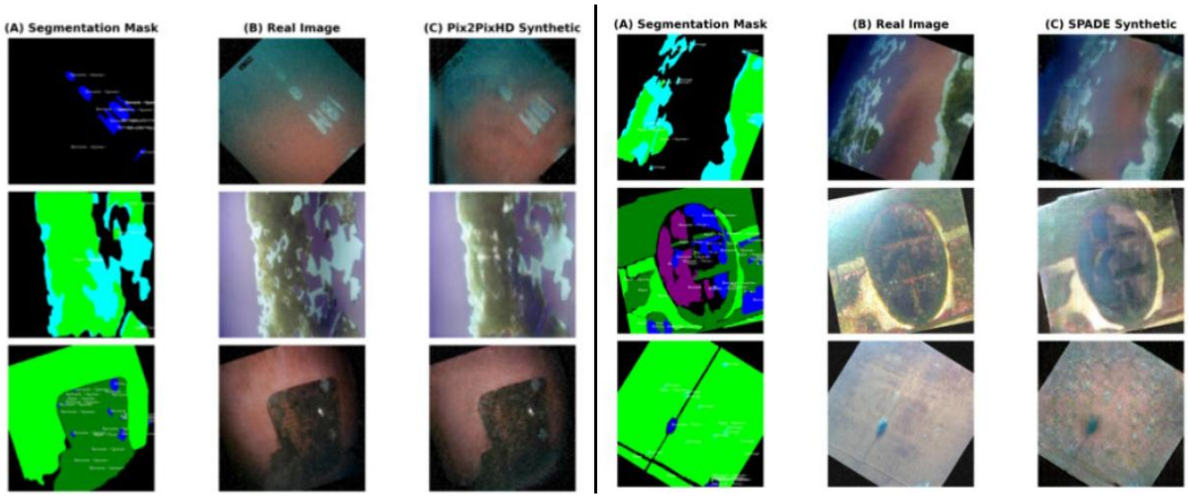

Fig.4: Underwater Training Data Example Results, left Pix2PixHD, right SPADE synthesis

1) Underwater Domain: Underwater synthesis is more challenging due to turbidity, backscatter, and pronounced colour distortion to only name a few underwater image influencing factors, *Akkaynak and Treibitz (2018)*. In this context, Pix2PixHD demonstrates greater stability, reproducing global structure and consistent illumination patterns that closely resemble real underwater lighting conditions. SPADE maintains accurate mask adherence and produces clear object boundaries, but some outputs show excessive contrast or colour exaggeration in highly scattered scenes. As a result, Fig.4, Pix2PixHD generates more natural underwater representations, while SPADE remains superior in aerial imagery. These domain-specific behaviours show that spatially adaptive normalization benefits above-water performance, while Pix2PixHD's simpler architecture generalizes more effectively under the low-frequency illumination and reduced texture typical of underwater environments.

Beyond visual confirmation, the generated images were rigorously assessed using five widely recognized metrics: FID, IS, CAS, LPIPS, and SSIM. While qualitative analysis focuses on how realistic and accurate the images appear, these metrics provide a statistical lens on how closely synthetic images mirror real ones in both structure and perception. In this context, lower FID and LPIPS scores, alongside higher IS, CAS, and SSIM values, signal superior generative performance. Separate evaluations for the aerial test plate and underwater marine fouling datasets were conducted.

In each case, synthetic images from Pix2PixHD and SPADE were compared under identical preprocessing steps, ensuring a fair match. FID and IS relied on InceptionV3 features, CAS drew from CLIP ViT-L/14, and LPIPS and SSIM were calculated on paired samples with matching masks, Table I. By fixing random seeds, reproduction of every experiment is guaranteed.

Table I: Statistical comparison of data synthesis

Sample	Model	FID ↓	IS ↑	CAS ↑	LPIPS ↓	SSIM ↑
Aerial Test Plates	Pix2PixHD	244.52	3.40	0.6600	0.7073	0.1354
	SPADE	**142.52**	3.40	**0.7700**	**0.6967**	**0.1428**
Underwater ROV Inspection	Pix2PixHD	**140.94**	3.65	**0.8500**	**0.4563**	**0.4432**
	SPADE	176.19	3.65	0.7900	0.5887	0.3891

The statistics echo the visual impressions described above. On the aerial dataset, SPADE stands out with lower FID and LPIPS and higher CAS and SSIM, pointing to images that look more realistic, with sharper textures and stronger structural integrity. Its spatially adaptive normalization helps capture subtle lighting and intricate textures, making the aerial scenes especially convincing. In contrast, Pix2PixHD took the lead underwater, delivering lower FID and LPIPS and higher CAS and SSIM. This suggests Pix2PixHD is more attuned to the gentle lighting and smooth textures found beneath the surface, whereas SPADE tends to boost contrast and color in murkier waters.

In summary, SPADE excels when aerial images demand intricate textures and shifting light, while Pix2PixHD proves more reliable underwater, where preserving overall structure and color is key. These results underscore the importance of matching generative models to their environment and show how domain-aware synthetic data can elevate maritime inspection.

The synthetic data utility was evaluated towards its downstream improvement by training YOLOv8 and YOLO11 under three regimes: real-only, synthetic-only, and hybrid (real + synthetic). All results are reported on held-out real test data. In addition to global metrics, per-class IoU is reported to analyze whether synthetic augmentation benefits rare or visually subtle fouling categories.

Thus, hybrid training achieves the most consistent improvement in mIoU across both datasets and generators, indicating that synthetic data is most effective when combined with real supervision.

Table II: Downstream training results of aerial test plates dataset

Pix2PixHD					
Model	Regime	Prec.	Rec.	F1	mIoU
YOLOv8	Real	0.8022	0.7398	0.7697	0.3568
	Synthetic	0.4653	**0.9307**	0.6205	0.4031
	Hybrid	**0.8876**	0.7822	**0.8316**	**0.5756**
YOLO11	Real	0.7861	0.7335	0.7589	0.4073
	Synthetic	0.7089	0.5545	0.6222	0.3221
	Hybrid	**0.8478**	**0.7723**	**0.8083**	**0.5318**

SPADE					
Model	Regime	Prec.	Rec.	F1	mIoU
YOLOv8	Real	0.8022	0.7398	0.7697	0.3568
	Synthetic	0.6000	0.7426	0.6637	0.3999
	Hybrid	**0.8125**	**0.7723**	**0.7919**	**0.5412**
YOLO11	Real	0.7861	0.7335	0.7589	0.4073
	Synthetic	0.6190	**0.7723**	0.6872	0.4163
	Hybrid	**0.8298**	**0.7723**	**0.8000**	**0.5334**

Table III: Downstream training results of underwater ROV inspection dataset

Pix2PixHD					
Model	Regime	Prec.	Rec.	F1	mIoU
YOLOv8	Real	0.7241	0.7778	0.7500	0.4859
	Synthetic	0.7059	**0.8889**	0.7869	0.4923
	Hybrid	**0.7500**	0.8400	**0.7925**	**0.5062**
YOLO11	Real	0.6296	0.6800	0.6538	0.4171
	Synthetic	0.7059	0.8889	0.7869	0.5577
	Hybrid	**0.7667**	**0.9200**	**0.8364**	**0.5833**

SPADE					
Model	Regime	Prec.	Rec.	F1	mIoU
YOLOv8	Real	0.7241	0.7778	0.7500	0.4859
	Synthetic	0.7692	0.3704	0.5000	0.2589
	Hybrid	**0.7931**	**0.8519**	**0.8214**	**0.5153**
YOLO11	Real	0.6296	0.6800	0.6538	0.4171
	Synthetic	0.8333	0.4000	0.5405	0.3125
	Hybrid	**0.8750**	**0.8400**	**0.8571**	**0.6019**

Table IV:

Pix2PixHD					SPADE				
	Class	Real	Synthetic	Hybrid		Class	Real	Synthetic	Hybrid
YOLOv8	barnacles	0.3302	0.4545	**0.5833**	YOLOv8	barnacles	0.3302	0.4615	**0.5000**
	bryozoa	0.1298	0.2273	**0.5714**		bryozoa	0.1298	0.2857	**0.8333**
	heavy slime	0.4444	0.2500	**0.5714**		heavy slime	**0.4444**	0.1667	**0.4444**
	hydroids	0.1318	0.2000	**0.4000**		hydroids	0.1318	0.2000	**0.3750**
	light slime	0.7437	0.7727	**0.9412**		light slime	0.7437	0.7143	**0.8333**
	mussels	0.7333	0.5909	**0.9231**		mussels	0.7333	0.6000	**0.9231**
	oyster	0.0000	0.0000	0.0000		oyster	0.0000	0.0000	0.0000
	slime	0.4731	**0.5455**	0.4667		slime	**0.4731**	0.4615	0.4375
	tubeworms	0.0000	0.1429	**0.5000**		tubeworms	0.0000	0.1250	**0.3333**
	tunicates	0.7711	**1.0000**	**1.0000**		tunicates	0.7711	**1.0000**	**1.0000**
	white tunicates	0.1668	0.2500	**0.3750**		white tunicates	0.1668	**0.3846**	0.2727

Pix2PixHD					SPADE				
	Class	Real	Synthetic	Hybrid		Class	Real	Synthetic	Hybrid
YOLO11	barnacles	0.3777	0.3333	**0.5385**	YOLO11	barnacles	0.3777	0.3846	**0.6923**
	bryozoa	0.3540	0.5000	**0.5714**		bryozoa	0.3540	0.3077	**0.8333**
	heavy slime	0.2862	0.1667	**0.5714**		heavy slime	0.2862	0.1429	**0.4444**
	hydroids	0.2218	**0.2727**	0.0000		hydroids	0.2218	0.2500	**0.2857**
	light slime	0.7425	0.7500	**0.8824**		light slime	0.7425	0.8421	**0.8824**
	mussels	0.7511	0.2667	**0.9231**		mussels	0.7511	0.6190	**0.8571**
	oyster	**0.4041**	0.0000	0.0000		oyster	**0.4041**	0.0000	0.0000
	slime	0.4620	0.1429	**0.5294**		slime	0.4620	**0.5333**	0.4000
	tubeworms	0.0000	0.0000	**0.5000**		tubeworms	0.0000	0.2143	**0.2500**
	tunicates	0.7502	**1.0000**	**1.0000**		tunicates	0.7502	**1.0000**	**1.0000**
	white tunicates	0.1309	0.1111	**0.3333**		white tunicates	0.1309	**0.2857**	0.2222

- Aerial Dataset (Pix2PixHD): Hybrid training substantially improves segmentation quality on real test images for both YOLO variants, with strong gains in mIoU compared to real-only training. Synthetic-only training tends to increase recall but reduces precision, suggesting over-segmentation and weaker boundary alignment under domain shift.
- Aerial Dataset (SPADE): SPADE-based synthetic data improves mIoU under hybrid training for both models, while synthetic-only training achieves moderate performance. The largest improvements are observed for rare categories such as bryozoa and tubeworms, suggesting that label-aligned synthetic examples can strengthen minority-class learning.
- Underwater Dataset (Pix2PixHD): On underwater imagery, Pix2PixHD synthetic data improves performance particularly under hybrid training, with the strongest gains observed for YOLO11. Per-class results indicate notable improvements for algae and barnacle variants, while highly sparse classes such as Damage with Rust and mixed growth remain challenging.
- Underwater Dataset (SPADE): For SPADE, synthetic-only training degrades performance, indicating that the generator alone may not reproduce underwater texture statistics sufficiently for robust generalization. However, hybrid training recovers and improves performance for both YOLO variants, showing that real samples provide essential anchoring for learning stable underwater representations.

Table V:

Pix2PixHD	Class	Real	Synthetic	Hybrid
YOLOv8	Algae_sparse	0.6250	0.7000	**0.7500**
	Algae_thick	0.6667	0.6667	**0.7143**
	Barnacle_sparse	0.6667	0.5714	**0.8000**
	Barnacle_thick	0.5000	**1.0000**	**1.0000**
	Damage	0.4286	**0.5000**	0.2857
	Mussels_thick	**1.0000**	0.5000	0.5000
YOLO11	Algae_sparse	0.5714	**0.7000**	0.6250
	Algae_thick	0.5556	0.5000	**0.8750**
	Barnacle_sparse	0.6667	**0.8333**	**0.8333**
	Barnacle_thick	0.4000	**1.0000**	**1.0000**
	Damage	0.1429	**0.4286**	0.3333
	Mussels_thick	**1.0000**	**1.0000**	**1.0000**

SPADE	Class	Real	Synthetic	Hybrid
YOLOv8	Algae_sparse	**0.6250**	0.5714	0.5556
	Algae_thick	0.6667	0.5000	**1.0000**
	Barnacle_sparse	**0.6667**	0.0000	**0.6667**
	Barnacle_thick	0.5000	0.0000	**1.0000**
	Damage	**0.4286**	0.0000	0.4000
	Mussels_thick	**1.0000**	**1.0000**	0.5000
YOLO11	Algae_sparse	0.5714	**0.8333**	0.6250
	Algae_thick	0.5556	0.3333	**0.8571**
	Barnacle_sparse	**0.6667**	0.0000	**0.6667**
	Barnacle_thick	0.4000	0.3333	**1.0000**
	Damage	0.1429	0.0000	**0.6667**
	Mussels_thick	**1.0000**	**1.0000**	**1.0000**

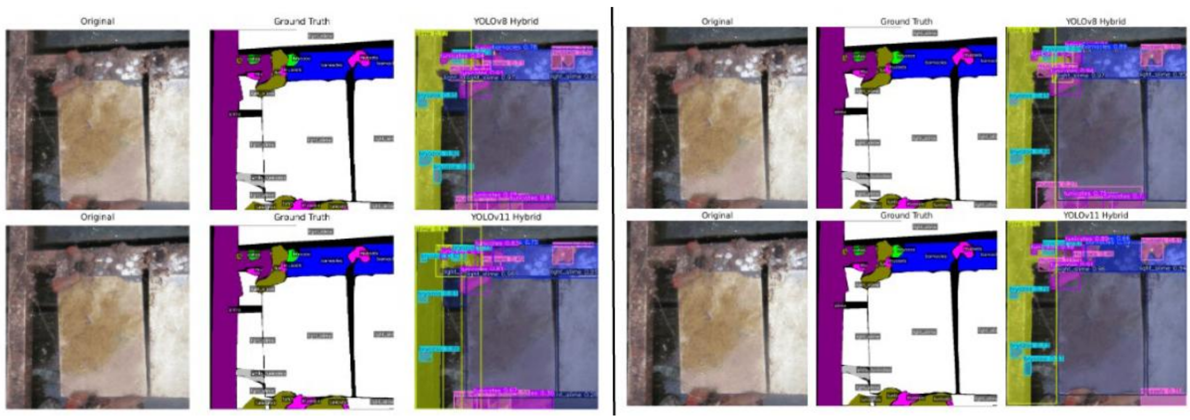

Fig.5: Downstream segmentation aerial data, left Pix2PixHD, right SPADE hybrid training

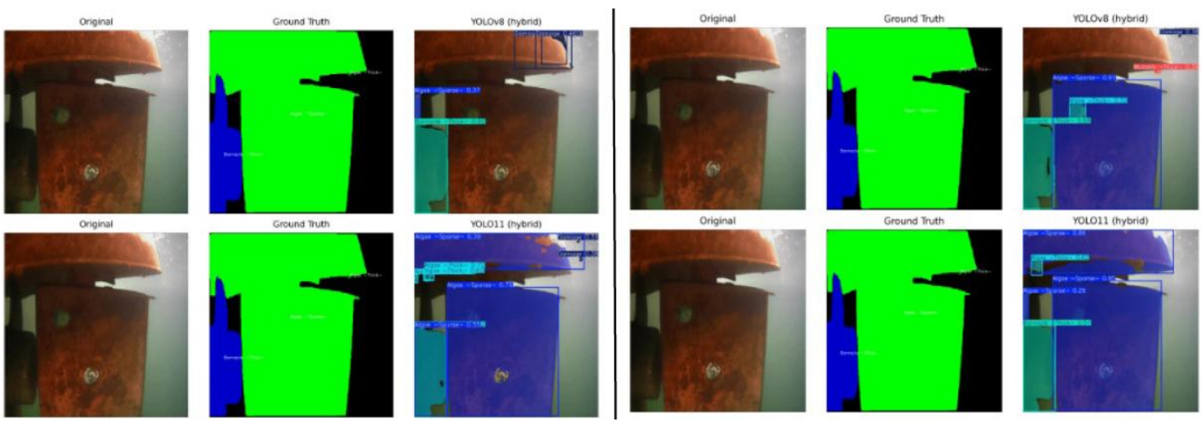

Fig.6: Downstream segmentation underwater data, left Pix2PixHD, right SPADE hybrid training

6. Conclusion

This paper demonstrates that Vision-AI can serve as a practical bridge between biofouling in-water inspection and performance-oriented shipping analytics. By combining aerial test plate imagery with real underwater ROV inspection data, the study shows that biofouling recognition is inherently domain-dependent: generator behaviour and training utility differ between above-water and underwater environments, reflecting the distinct imaging physics and operational variability that characterise each domain.

To address the central bottleneck of underwater label scarcity, the paper evaluates a mask-conditioned synthetic pipeline that preserves exact image-label correspondence through automatic label propagation, enabling scalable data augmentation without additional manual annotation. Critically, the results confirm that perceptual realism metrics alone are insufficient; synthetic outputs must be assessed against downstream task utility. Across experiments, hybrid training (real + synthetic) provides the most consistent robustness on held-out real data, yielding absolute mIoU improvements and notable benefits for minority and rare fouling classes, indicating that synthetic augmentation can expand coverage of underrepresented states when anchored by real supervision.

For current research, the implication is a methodological shift toward domain-aware synthesis selection and evaluation protocols centred on operational generalisation. For future work, priorities include scaling longitudinal micro-ROV datasets, integrating uncertainty and domain-shift monitoring in deployment, and extending controllable generation (including diffusion-based control) to better reproduce underwater texture statistics while remaining aligned with performance-reporting requirements. Overall, these findings are highly relevant for future marine biofouling research, and their implications for AI-based fouling detection are of significant importance.

Acknowledgement

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ISO 6319 – From Standard to Practice

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Abstract

ISO 6319—Conducting and documenting in-water cleaning of biofouling on ships—was published in March 2026. Now is the time for the transition from international standard to operational implementation in port governance of in-water cleaning. This article reflects on the emerging role of ISO 6319 as a practical tool for regulatory design and considers how its principles may be interpreted in real-world port contexts—assisting early regulatory choices and harmonising port practices across jurisdictions.

1. Introduction

As awareness of biosecurity risks has grown among ports and regulators, in-water cleaning is receiving greater attention as both a mitigation measure and a potential risk pathway. Many ports are now in the process of developing or revising local regulatory frameworks for in-water cleaning operations. In several jurisdictions, however, experience with in-water cleaning remains limited, partly because regulatory approaches are currently being developed in parallel with the technology itself. This can make it challenging for ports and regulators to define consistent criteria for evaluating applications, particularly when distinguishing between operations that are environmentally acceptable and those that may pose unacceptable risks. A key difficulty lies in defining what information should be required from service providers and how that information should be assessed in a consistent manner. Without a structured framework, there is a risk that approvals become either overly restrictive or insufficiently precautionary. ISO 6319, *ISO (2026)*, supports ports and regulators by providing such a framework.

2. Why ISO 6319 was developed

The development of ISO 6319 began with the Clean Hull Initiative intending to produce a standard specifically for proactive in-water cleaning. At the time, emerging industry guidance largely focused on reactive cleaning with capture, and there was a perceived need for a complementary standard addressing proactive cleaning. However, as the work progressed, it became evident that the term proactive in-water cleaning was interpreted in different ways across the maritime industry. For some stakeholders, it referred to scheduled or routine cleaning; for others, it meant frequent cleaning, cleaning limited to microfouling, or cleaning conducted without capture. Since then, the IMO has defined proactive in-water cleaning as the periodic removal of microfouling on ships' hulls to prevent or minimize attachment of macrofouling.

However, these discussions led the working group to reconsider the scope of the project. Rather than focusing on a specific cleaning philosophy or frequency, it concluded that greater value would be achieved by standardising the planning, approval, execution and documentation of the in-water cleaning event itself—including all forms of in-water cleaning. The working group recognized that, regardless of the level of biofouling or the cleaning technology employed, the processes for planning, conducting and reporting a cleaning operation are largely the same. By focusing on the isolated cleaning event rather than a particular cleaning regime, the standard provides a common operational framework that can be applied consistently across a wide range of cleaning scenarios. ISO 6319 is aligned with the IMO 2023 Biofouling Guidelines, *IMO (2023)*, and its recommendations for cleaning with and without capture technology. ISO 6319 supports consistent decision-making before, during and after in-water cleaning events, and specifies common documentation requirements, reporting formats and operational workflows that can be applied across ports and jurisdictions. The standard includes requirements related to documentation of coating compatibility and testing results, e.g. ISO 20679, *ISO (2025)*.

3. From IMO guidance to operational implementation

The IMO Guidance on In-water Cleaning of Ships' Biofouling (MEPC.1/Circ.918), henceforth referred to as IMO 2025 Guidance for in-water cleaning, *IMO (2025)*, establishes the key principles for IWC operations on micro and macrofouling, and addresses performance criteria for in-water cleaning systems with capture. As an IMO guidance document, it is necessarily broad in scope. ISO 6319 was developed to complement, rather than replace, this guidance. The standard is fully aligned with the principles of the IMO 2025 Guidance for in-water cleaning, but focuses on practical implementation.

One of the principal contributions of ISO 6319 to the mentioned IMO document is its process-oriented structure. The standard follows the chronological workflow of an in-water cleaning operation, from long-term or short-term approvals, through event-specific preparation and hull condition assessment, to operational coordination, execution, reporting and record keeping. This makes the document particularly suited for operational use by ports, regulators, ship operators and service providers, who can follow the sequence of activities and documentation required throughout the cleaning process. This chronological structure is particularly valuable for ports and regulators that are new to in-water cleaning, as it provides a practical entry point into a technically complex subject.

Compared to the IMO Guidance, the ISO standard goes further by defining how information should be evaluated. The standard helps users understand not only what information is needed, but also when and how it should be used. Rather than simply requesting documentation, it establishes a structured approval process that includes verification of documentation quality, evaluation of coating compatibility, assessment of hull condition, consideration of the vessel's operational history and, where necessary, process for determining whether additional inspection should be undertaken. However, ISO 6319 does not determine the conclusions reached by ports and regulator. Rather, these elements create a practical implementation framework that supports traceability, as well as transparent and repeatable decision-making.

4. From standard to implementation

ISO 6319 is a qualitative standard, and does not form the basis for third-party certification. However, ports and regulatory authorities may require applicants to document their in-water cleaning procedures in accordance with ISO 6319. This allows shipowners and service providers to prepare a standardized set of documentation that can be submitted to multiple ports and jurisdictions, reducing duplication and promoting greater consistency across regulatory processes. At the same time, ISO 6319 does not prescribe environmental performance thresholds or approval criteria. Regulators must still establish their own requirements and acceptance criteria for issues such as the release of biofouling, microplastics, biocides and other materials, taking local environmental conditions and regulatory objectives into account.

Early indications suggest that some ports participating in the development of ISO 6319 are already exploring how their local regulatory frameworks can be aligned with the structure and terminology of the standard. In this context, an interesting question is whether future regulatory practice may allow reference to ISO 6319 as a procedural basis for approvals, for example through formulations such as "in-water cleaning applications and operations shall be conducted in accordance with ISO 6319".

5. Conclusion

Today, ports and regulators request different types of information from shipowners and service providers as part of their in-water cleaning approval processes. The information requested, as well as the formats and documentation requirements, vary considerably between jurisdictions. This lack of consistency creates additional complexity for operators and may lead to fragmented regulatory approaches.

At the same time, two parallel environmental concerns are driving the increasing need for regulatory frameworks for in-water cleaning. On one hand, ports and regulators must address concerns related to the potential release of biofouling and chemicals during cleaning operations and ensure that cleaning activities are conducted in an environmentally responsible manner. On the other hand, there is growing recognition that in-water cleaning is an important tool for reducing the accumulation of biofouling and supporting efforts to limit the spread of invasive aquatic species. This creates a need not only to manage potential risks locally, but also to enable and encourage preventive and proactive in-water cleaning practices that contribute to cleaner hulls worldwide.

In this evolving regulatory landscape, ISO 6319 provides an opportunity to reduce fragmentation by establishing a common operational framework and terminology. By referencing ISO 6319 in local and national regulatory approaches, authorities can support greater consistency, transparency and predictability while still allowing decisions to reflect local environmental conditions and risk considerations.

With the publication of the standard, the focus now shifts from development to implementation. Its value will ultimately be demonstrated through its use in practice, as ports and regulators apply it to structure their decision-making processes and harmonise their regulatory approaches.

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A Practical Approach to Large-scale Hull Roughness and Fuel Impact Estimation during Regular Biofouling Inspections

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Abstract

This paper presents a methodology for estimating hull roughness from ROV inspection footage. Semantic segmentation classifies biofouling types, while stereo vision provides distance measurements for converting pixel dimensions to physical units. For barnacles, basal diameter is measured and height inferred using empirical relationships. Frame-level equivalent sand roughness (k_s) values computed using established correlations are spatially averaged across hull sections. The resulting k_s estimates serve as input to hydrodynamic resistance models for fuel consumption prediction. While validation remains necessary, the approach provides a framework for quantitative roughness estimation from standard inspection workflows.

1. Introduction

Hull biofouling represents one of the most significant operational challenges in maritime operations, causing substantial increases in fuel consumption, greenhouse gas emissions, and operational costs, *Glofouling (2022)*. The accumulation of marine organisms on underwater hull surfaces increases frictional resistance, which translates directly into elevated propulsion power requirements and fuel consumption.

While the adverse effects of biofouling on vessel performance are well-established, quantifying excess fuel consumption attributable to biofouling during routine operations remains a significant challenge. Two primary approaches exist for assessing hull condition and its impact on vessel performance, tackling the problem from different angles: fuel consumption monitoring and hull roughness measurement.

Fuel consumption monitoring provides direct operational feedback by tracking changes in specific fuel oil consumption (SFOC) or analyzing noon report data over time. This approach offers high precision in detecting performance degradation but faces challenges in isolating hull condition effects from other operational variables such as weather conditions, cargo loading, and engine efficiency variations.

Hull roughness measurement, in contrast, offers a direct physical assessment of surface condition, *Schultz (2007)*. The critical parameter for hydrodynamic modeling is equivalent sand roughness k_s, which directly determines frictional resistance increases through established similarity laws and roughness functions. Surface profilometry using hull roughness analyzers (e.g., NACE SP0616-2022 standard) provides accurate measurements but requires dry-docking and complete biofouling removal, thereby precluding the assessment of hull roughness in its fouled operational state. While 3D laser profilometry systems offer high-resolution surface characterization, their application remains predominantly limited to controlled laboratory environments and small-scale measurements, rendering them impractical for comprehensive hull assessments. Underwater visual inspections are standard practice and can be performed during regular maintenance intervals, but conventional approaches rely on subjective fouling rating scales that cannot be directly integrated into physics-based fuel impact calculations. This creates a critical gap: while visual assessments can identify the presence and extent of biofouling, they cannot provide the quantitative roughness data required for accurate hydrodynamic modeling and fuel consumption prediction.

Recent advances such as the AQUAMARS system demonstrate the feasibility of underwater hull roughness measurement with high precision, *Kogios et al. (2025)*. However, these approaches require specialized hardware, diver operation, and measure limited surface areas (approximately 10 × 10 cm per scan), constraining their applicability for comprehensive hull-wide assessments during routine inspections.

The fundamental challenge lies in balancing measurement precision, spatial coverage, and integration capability within existing inspection workflows.

This work presents a practical, scalable methodology for quantifying hull roughness from standard underwater inspection footage. The approach combines stereo video analysis with computer vision algorithms to extract frames, segment biofouling regions, estimate camera-to-hull distances, and quantify covered areas. Barnacle heights are estimated through empirically derived diameter-to-height relationships, while slime layer thickness is assigned based on typical values reported in the literature. The resulting biofouling dimensions are converted to equivalent sand roughness k_s values, which are subsequently integrated into established hydrodynamic resistance models to predict fuel consumption impact.

2. Methodology

2.1. Data Acquisition

Comprehensive hull surface characterization requires systematic underwater imaging capable of covering large surface areas (typical wetted surface area of up to 10.000 m² per vessel, and more) while maintaining sufficient spatial resolution for biofouling quantification. This necessitates the use of remotely operated vehicles (ROVs) or autonomous underwater vehicles (AUVs) equipped with calibrated stereo vision systems.

Camera orientation has to be maintained perpendicular to the hull surface throughout data acquisition to ensure geometric consistency for size measurements. We used the Sentinus 2 ROV from Blue Atlas Robotics with a synchronized stereo camera system mounted on the front of the ROV. The camera has a basis of 60 mm with known camera intrinsics and distortion coefficients. At a camera-to-hull distance of 0.7 m the resolution is roughly 0.5 mm per pixel for HD video (1920×1080).

Hull inspection follows a predefined mission plan dividing the underwater hull into discrete sections. For each section, typically 30 – 60 s of video footage are recorded.

2.2. Image Extraction

While the camera captures video at a fixed frame rate of 30 fps, resulting in substantial frame overlap during ROV traversal, the analysis objective is to cover the inspected surface exactly once without redundancy. To achieve this, an optical flow-based motion detection algorithm (based on OpenCV implementation) tracks the apparent motion of surface features between consecutive frames. New images are extracted from both stereo video streams whenever the ROV has moved one frame width relative to the hull surface, as determined by the integrated optical flow displacement. This adaptive extraction ensures complete surface coverage with minimal overlap. Motion-based extraction is advantageous over fixed-interval sampling especially when ROV motion is non-uniform. Image extraction is performed using the HullVAR platform (Atlantic Tech & Candy). Only the center squares are extracted to limit distortion, and variance in lighting.

Representative examples of extracted imagery from two sample videos are shown in Fig.1, illustrating the spatial distribution of frames along the ROV trajectory. The perpendicular camera orientation requirement becomes evident from the consistent geometric representation of surface features across the extracted frames.

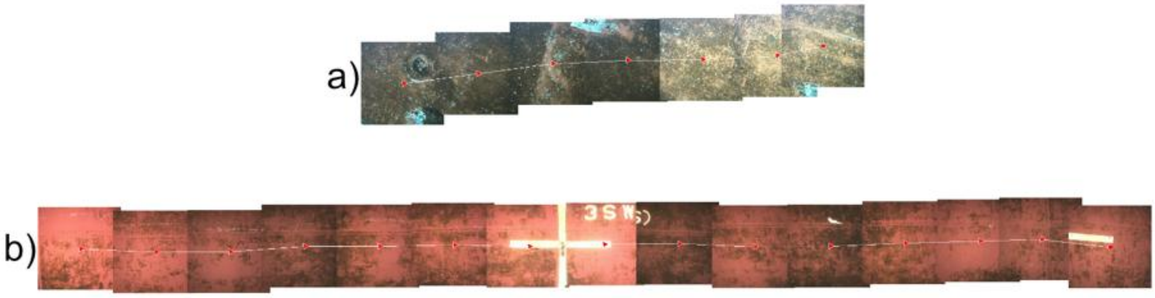

Fig.1: Extracted images with small overlap for two sample videos. The arrows indicating ROV movement. Sample a) 7 out of 900 frames (30 seconds), sample b) with 15 out of 1618 frames (53 s). Each image has an original size of 1080×1080 px.

2.3. Semantic Segmentation

Each extracted image is analyzed for biofouling presence and classification using semantic segmentation. The deep learning model employed by the HullVAR platform generates pixel-wise segmentation masks that classify surface regions into distinct biofouling categories: clean areas, light slime, heavy slime, soft fouling, and hard fouling (barnacles). The model architecture has been pre-trained on a large-scale dataset of synthetic underwater imagery to learn robust feature representations, *May et al. (2024)*, followed by fine-tuning on real underwater hull imagery to adapt to operational conditions including varying lighting, turbidity, and surface textures.

The segmentation output provides both spatial masks and quantitative coverage metrics, reporting the percentage of surface area occupied by each fouling category. An example segmentation result is shown in Fig.2, demonstrating the model's ability to distinguish between different biofouling types and clean hull surfaces.

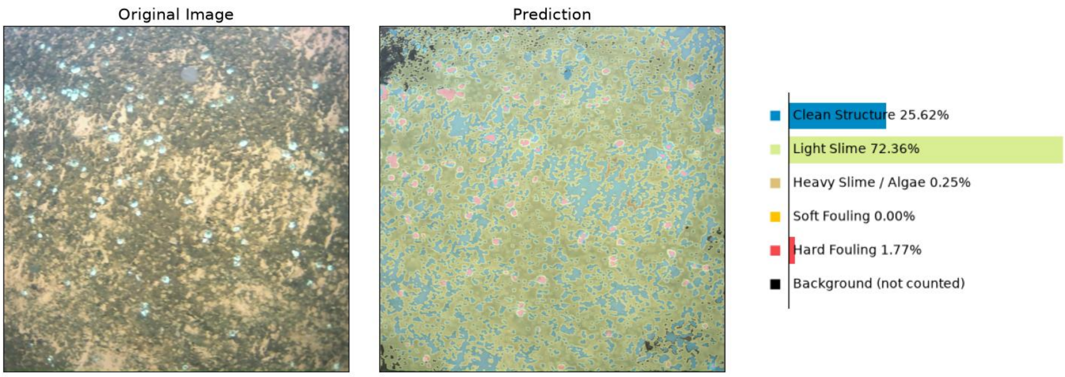

Fig.2: Sample semantic segmentation for an image from sample a) as provided by HullVAR

2.4. Distance Estimate

Accurate distance measurements are essential for converting pixel-based measurements to physical dimensions. The extracted stereo image pairs undergo geometric correction through barrel distortion removal and stereo rectification.

Distance estimation employs stereo matching using the Semi-Global Block Matching (SGBM) algorithm (OpenCV implementation). SGBM performs dense correspondence matching by identifying corresponding pixels between the top and bottom camera views (Sentinus' stereo camera orientation is vertical). For each pixel, the algorithm computes the horizontal displacement (disparity d) between its position in the rectified stereo pair. The disparity is inversely proportional to depth: larger disparities correspond to closer objects, while smaller disparities indicate greater distances.

The depth Z for each pixel is calculated using the standard stereo vision triangulation formula:

$$Z = (f \times B) / d$$

where f is the focal length in pixels (derived from camera calibration), B is the physical baseline distance (60 mm), and d is the disparity in pixels. The baseline is converted to pixel units using the sensor pixel size (3 µm) for dimensional consistency. The resulting depth values are converted to centimeters for reporting.

For each frame, statistical metrics (mean, median, minimum, maximum, and standard deviation) are computed from the valid depth measurements, providing robust distance estimates even in the presence of outliers or regions with poor stereo correspondence. Fig.3 shows the mean distance profile for sample video a), demonstrating stable ROV positioning at approximately 70 cm from the hull surface. The elevated variance in the initial frames results from partial hull coverage in the field of view during approach.

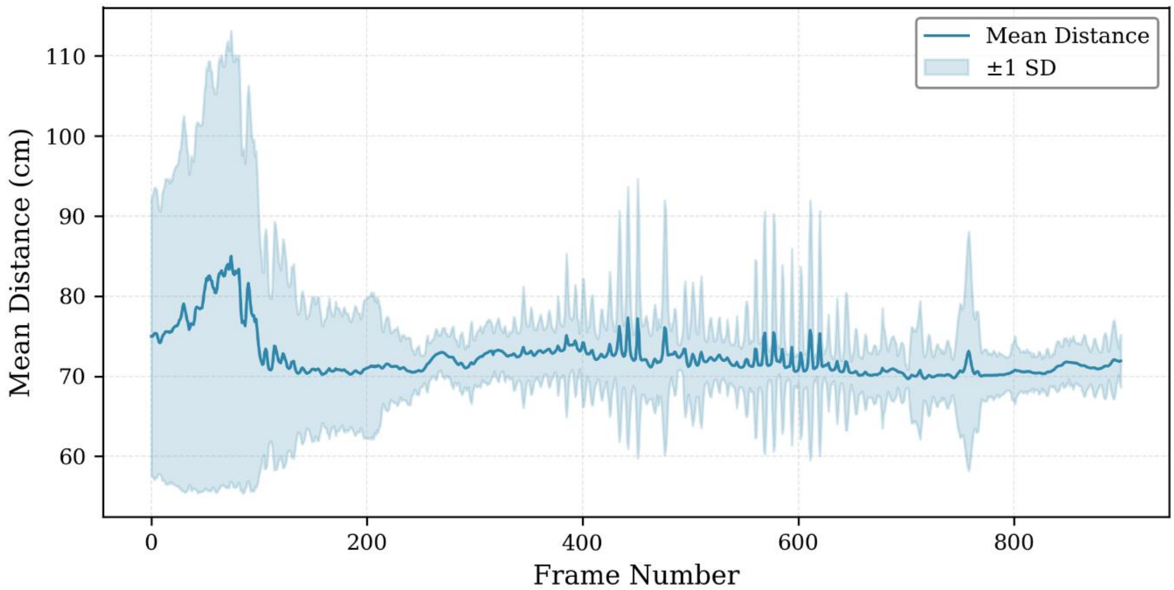

Fig.3: Mean distance from camera to hull for sample video a). The ROV maintains a stable standoff distance around 70 cm throughout the inspection. The higher variance at the start is due to the hull not covering the full image during the approach phase.

2.5. Biofouling Height Assumptions for Hull Roughness Estimation

While semantic segmentation provides spatial coverage for each fouling category, the hydrodynamic impact depends critically on both coverage area and fouling height. The equivalent sand roughness k_s is calculated using empirical correlations developed by *Schultz (2004,2015)*:

For slime and soft fouling: $k_s = 0.055 \times h \times \sqrt{A}$

For barnacle fouling: $k_s = 0.059 \times h \times \sqrt{A}$

h is the fouling height and A the percentage area coverage. For barnacle fouling the height represents the maximum of all barnacles in the sample.

2.5.1. Limitations of Stereo-based Height Measurement

The stereo camera configuration employed in this study lacks sufficient resolution to directly measure biofouling height, particularly for thin biofilms and small calcareous organisms. Direct height measurement would require specialized systems such as AQUAMARS (*Kogios et al., 2025*), which employs eight high-resolution cameras to achieve sub-millimeter profilometry over limited surface areas (~10 × 10 cm). Such approaches are impractical for comprehensive hull-wide assessments due to time and operational constraints.

2.5.2. Height Assignment Strategy

Given these constraints, we adopt a hybrid approach combining literature-based values for biofilms and geometry-derived estimates for hard fouling:

Biofilm and soft fouling:

light slime: 300 µm
heavy slime: 600 µm
soft fouling: 1 mm

These values represent typical thickness ranges reported in the literature. Soft fouling (e.g., hydroids, algae) is assigned a height similar to heavy slime based on the assumption that these organisms remain compressed against the hull during vessel motion, minimizing their effective roughness height.

Hard Fouling / Barnacles:

In this work, we focus on barnacles as the primary hard fouling organism to demonstrate the methodology. Barnacle height is estimated from measured basal diameter using an empirically derived linear relationship validated by *Anani et al. (2022)*, who demonstrated strong correlation between barnacle diameter and height through combined 2D imaging and 3D profilometry.

Extension to Other Hard Fouling Types:

The approach presented here for barnacles requires adaptation for other hard fouling organisms such as tubeworms and mussels, which exhibit different morphological characteristics and growth patterns. While barnacles have been extensively studied, comparable diameter-to-height relationships for tubeworms and mussels remain less well-characterized. Future work should establish similar empirical relationships for these organisms through targeted morphological studies, enabling comprehensive hard fouling assessment across all common calcareous species encountered in operational hull inspections.

2.6. Hard Fouling Size Estimation

Quantifying individual barnacle dimensions is essential for applying the diameter-to-height relationship described in Section 2.5. The approach combines semantic segmentation masks with stereo-derived distance measurements to compute physical dimensions (area, width, height) for each detected barnacle. The methodology addresses two key challenges: (1) converting pixel measurements to physical units using calibrated field-of-view parameters, and (2) handling barnacle clusters where individual organisms cannot be visually separated.

2.6.1. Connected Component Analysis

Binary masks isolating barnacles (white pixels) from background (black pixels) are generated from the hard fouling class in the semantic segmentation output. Connected component analysis (OpenCV's connectedComponentsWithStats) identifies spatially contiguous white regions, labeling each as a distinct blob. For each blob, the algorithm computes geometric statistics including pixel area, bounding box dimensions (width and height), and centroid coordinates.

2.6.2. Pixel-to-Physical Dimension Conversion

Physical pixel dimensions are derived from the stereo-estimated distance and camera field-of-view (FOV) parameters. For each frame, the horizontal and vertical FOV at the measured distance are calculated using the camera's calibrated angular FOV. Physical pixel size is then computed as:

Horizontal pixel size (mm) = (horizontal FOV_cm × 10) / image_width_pixels

Vertical pixel size (mm) = (vertical FOV_cm × 10) / image_height_pixels

Blob measurements are converted to physical dimensions:

- Area (mm^2) = blob_area_pixels × pixel_size_horizontal × pixel_size_vertical
- Width (mm) = blob_width_pixels × pixel_size_horizontal
- Height (mm) = blob_height_pixels × pixel_size_vertical

The basal diameter is approximated as the geometric mean of width and height, providing a rotationally-invariant size metric.

2.6.3. Cluster Detection and Decomposition

Barnacles frequently colonize surfaces in dense aggregations where individual organisms merge into continuous patches without visible boundaries. To distinguish isolated individuals from clusters, we employ a statistical threshold based on the median blob area within each frame:

1. Compute median blob area (robust to outliers)
2. Define cluster threshold as 3× median area
3. Blobs exceeding this threshold are classified as clusters
4. Estimate individual count: ⌊cluster_area / median_area⌋ (rounded)
5. Report both detected blob count and estimated individual barnacle count

This median-based approach assumes that the majority of detected blobs represent isolated individuals, making the median a reliable reference for typical barnacle size. The 3× threshold provides a conservative criterion that minimizes false cluster identification while capturing genuine multi-organism aggregations. Clusters are decomposed arithmetically based on the median reference size, enabling population density estimation even when individual boundaries are not resolvable. Fig.4 provides an example with the original image, the segmentation mask, and the annotated binary mask with estimated barnacle sizes.

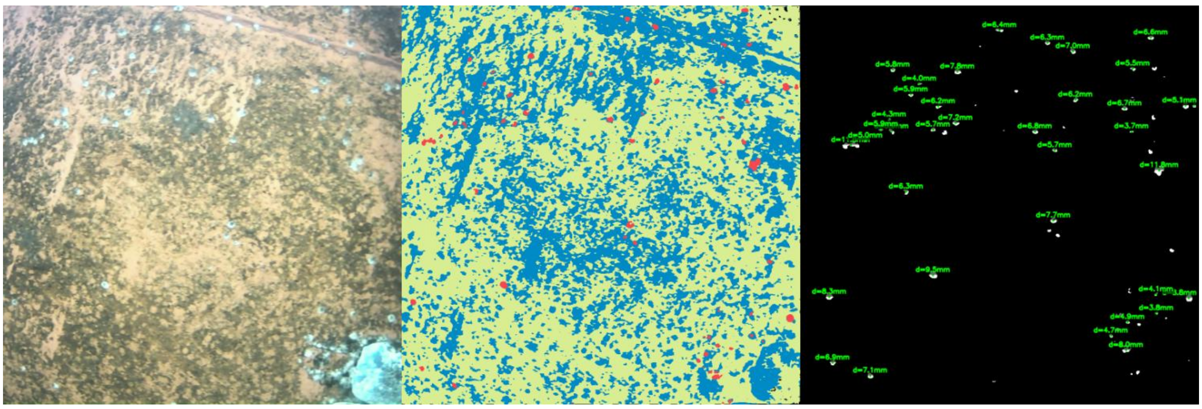

Fig.4: Left to right: original image from sample a), segmentation with clean (blue), light slime (light green), and barnacles (pink), isolated barnacles with size estimate. Only the binary mask has been rectified with regard to barrel distortion.

2.7. Spatial Averaging of Hull Roughness

The equivalent sand roughness k_s is computed for each extracted frame by combining the segmentation-derived coverage percentages with the height assumptions (Section 2.5) using the Schultz correlations. This frame-level calculation produces a spatially-resolved roughness map across the inspected hull surface.

2.7.1. Section-Level Aggregation

For each predefined hull section (as defined in the inspection mission plan), the k_s values from all constituent frames are averaged arithmetically to produce a representative section roughness. This simple averaging approach assumes uniform weighting of all frames within a section, which is justified by the motion-based frame extraction strategy (Section 2.2) that ensures approximately uniform spatial sampling density.

2.7.2. Hull-Wide Aggregation and Spatial Heterogeneity

The appropriate method for aggregating section-level roughness values into a single hull-representative k_s remains an active research question. Recent work by *Hutchins et al. (2023)* has highlighted that spatial heterogeneity in fouling distribution may influence overall hydrodynamic resistance in complex ways not captured by simple averaging. Different averaging schemes (arithmetic mean, area-weighted mean, or maximum value approaches) can yield substantially different results, particularly when fouling is highly localized.

Given the absence of consensus on the optimal aggregation methodology, we adopt arithmetic averaging across all hull sections as a baseline approach. However, we emphasize that the primary value of this methodology lies in capturing high-fidelity spatial distribution data rather than producing a single summary statistic. The resulting spatially-resolved k_s dataset, Fig.5, provides valuable input for advanced hydrodynamic models that can account for spatial heterogeneity, and enables validation of fuel consumption predictions against operational measurements by preserving the full spatial information.

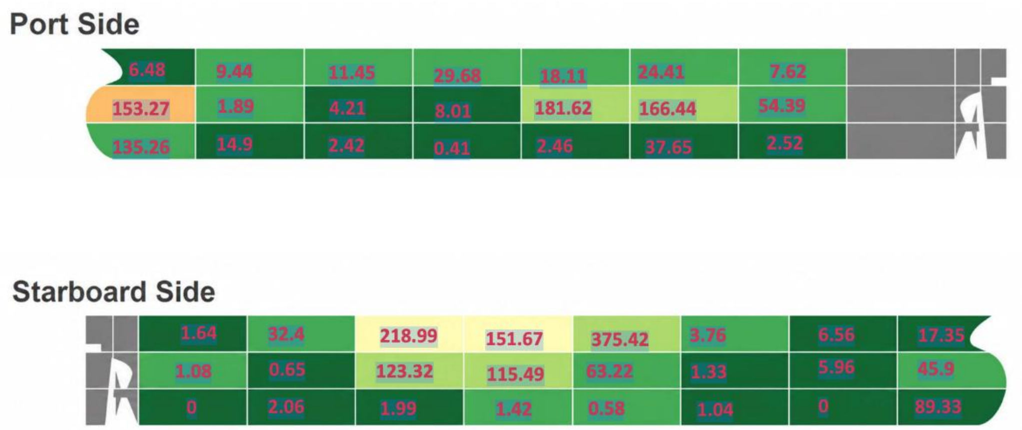

Fig.5: k_s values for each hull section taken from a large hull inspection. The section color represents the fouling rating according to the AMPP scale, and not the roughness value.

2.8. Fuel Impact Modeling

The spatially-averaged k_s values derived from the biofouling analysis serve as direct input to hydrodynamic resistance models that predict the fuel consumption penalty associated with hull roughness. This section outlines the modeling framework that translates roughness measurements into operational fuel impact estimates following *Schultz (2007)* or *Demirel et al. (2019)* .

2.8.1. Hydrodynamic Resistance Modeling

The increase in frictional resistance due to hull roughness is quantified through the roughness function ΔU^+, which relates the equivalent sand roughness to the increase in skin friction coefficient. We employ the correlation developed by *Schultz (2007)*, which has been extensively validated for marine biofouling:

$$\Delta C_F = [\Delta U^+(k_s^+) / \kappa] \times [2 / (\ln Re)^2]$$

C_F is the skin friction coefficient, k_s^+ the non-dimensional roughness height ($k_s^+ = k_s \times u\_\tau / \nu$), κ the von Kármán constant, and Re the Reynolds number based on ship length. The total resistance increase accounts for both the direct frictional component and form drag effects through vessel-specific form factors.

2.8.2. Power and Fuel Consumption Prediction

The resistance increase translates to required propulsive power through:

$$\Delta P = \Delta R \times V / \eta_D$$

ΔR is the resistance increase, V the vessel speed, and η_D the propulsive efficiency. Fuel consumption increase follows from the power-fuel relationship, accounting for engine-specific fuel consumption characteristics.

2.8.3. Operational Fuel Impact Assessment

Fig.6 presents example fuel consumption curves based on the vessel from Fig.5, showing both base-line (clean hull) and fouled hull consumption as functions of vessel speed. The excess fuel consumption attributable to biofouling is shown as the difference between these curves.

2.9. Validation Requirements

While the methodology presented here provides a systematic framework for translating visual inspection data into quantitative roughness estimates, several key assumptions require empirical validation to establish confidence in the predicted fuel impacts. This section outlines the critical validation pathways necessary for operational deployment.

2.9.1. Morphological Relationships

The diameter-to-height relationship for barnacles, adopted from *Anani et al. (2022)*, requires validation across diverse barnacle species, growth stages, and environmental conditions. Field validation should include:

- Direct comparison of stereo-estimated diameters with high-resolution profilometry measurements (e.g., AQUAMARS system) on the same hull sections
- Statistical analysis of diameter-height correlations across different barnacle populations
- Assessment of variability introduced by barnacle orientation, substrate curvature, and clustering effects
- Extension to other hard fouling organisms (tubeworms, mussels) necessitates establishing analogous morphological relationships through targeted measurement campaigns combining 2D imaging with 3D profilometry.

Vessel Length (m):	205.00	**Propulsive Efficiency:**	0.70
Beam (m):	30.00	**Engine Efficiency:**	0.45
Draft (m):	10.00	**C_R/C_F Ratio (estimated):**	1.6 - 2.5
Block Coefficient:	0.620	**Fuel Type:**	HFO
Estimated k_s (μm):	46		

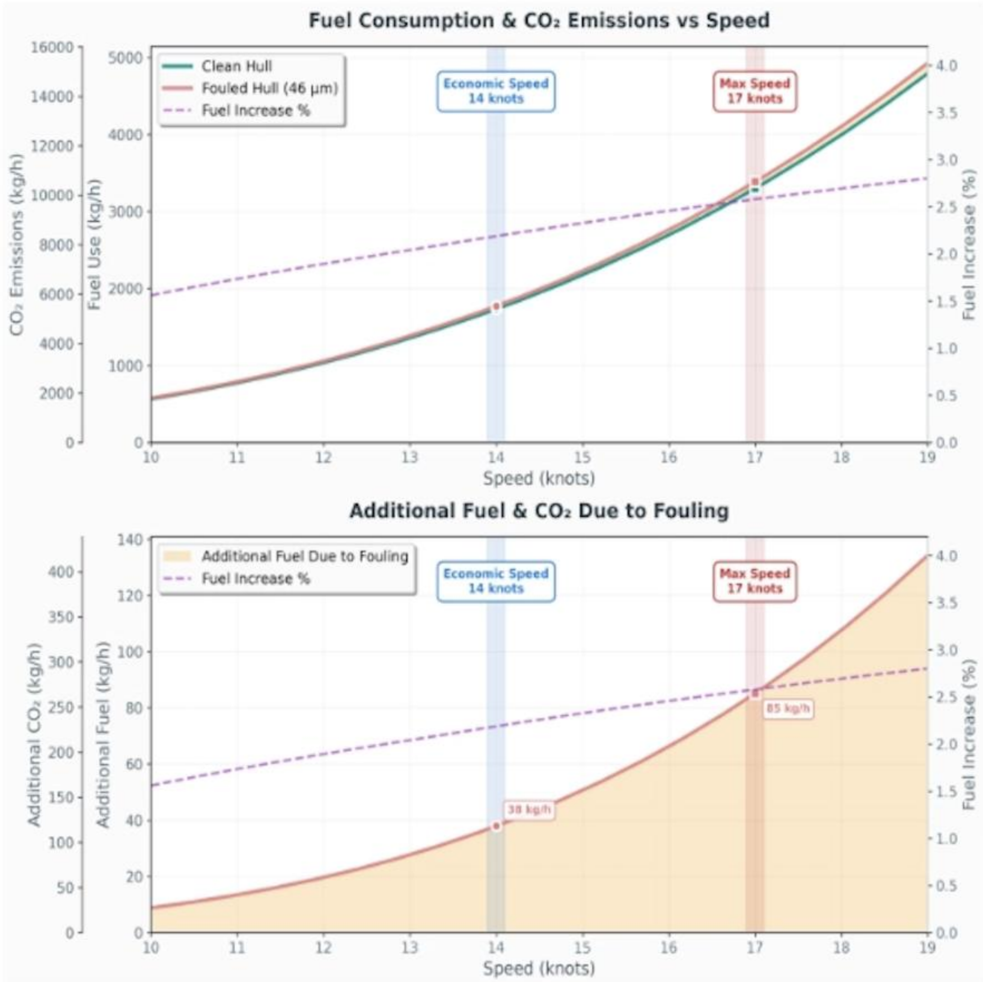

Fig.6: Example graphs of fuel and excess fuel consumption based on calculated k_s value, and vessel dependent form factors

2.9.2. Roughness Superposition

The current approach calculates k_s independently for each fouling category and combines them to produce a composite roughness value for each frame. This additive superposition assumption requires validation, as the hydrodynamic interaction between different fouling types (e.g., barnacles on a slime layer) may not follow simple linear combination rules. Validation approaches include:

- Controlled towing tank experiments with multi-layer fouling configurations
- Comparison with direct profilometry-based k_s measurements on surfaces with mixed fouling
- Sensitivity analysis to determine the impact of different combination methodologies

on predicted resistance

2.9.3. Fuel Consumption Prediction Accuracy

The ultimate validation criterion is the accuracy of fuel consumption predictions compared to operational measurements. This requires:

- Longitudinal studies tracking vessel fuel consumption before and after hull inspections
- Statistical decomposition of measured fuel consumption to isolate the biofouling contribution from other operational variables (weather, loading, speed variations)
- Comparison of predicted fuel penalties with empirically derived estimates from performance monitoring systems
- Validation across multiple vessel types, operational profiles, and fouling conditions

Establishing these validation datasets will enable refinement of morphological assumptions, roughness combination rules, and hydrodynamic models, ultimately improving prediction accuracy and building confidence in the methodology for operational decision-making.

3. Conclusion

This work presents a practical methodology for quantifying hull roughness during routine underwater inspections, bridging the gap between qualitative visual assessments and quantitative hydrodynamic modeling. By combining stereo vision, semantic segmentation, and empirical morphological relationships, the approach converts standard ROV inspection footage into spatially-resolved equivalent sand roughness k_s values suitable for fuel consumption prediction.

The methodology's key strength lies in its integration within existing inspection workflows, requiring no specialized hardware beyond calibrated stereo cameras. It provides comprehensive hull-wide coverage while maintaining sufficient spatial resolution to capture biofouling heterogeneity—a capability not achievable with high-precision profilometry systems limited to small surface areas.

Critical validation work remains necessary, particularly regarding barnacle diameter-to-height relationships, roughness superposition rules for mixed fouling, and end-to-end fuel consumption prediction accuracy. However, the framework establishes a foundation for data-driven hull maintenance decisions, replacing subjective fouling ratings with physics-based fuel impact estimates. As validation datasets accumulate and morphological relationships are refined, this approach offers a scalable pathway toward quantitative biofouling management across operational vessel fleets.

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The BRADD Project:
Building the Evidence Base for a Legally Binding Biofouling Instrument

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Abstract

This paper provides an update on *BEMA's Biofouling Research and Data Development (BRADD) project, which will provide the scientific and technical foundation needed to inform the IMO biofouling convention process as confirmed at MEPC 84. Updates on the seven core questions - prevention technologies, microfouling risk, cleaning-without-capture, capture performance, coating compatibility, global service capacity, and compliance frameworks – are provided with status on key deliverables for submission to PPR 14 and 15 between now and 2027. Further project participation is welcome and encouraged to help ensure the convention is grounded in demonstrated technology, environmental evidence, and commercial feasibility.*

1. Introduction

The Biofouling Research and Data Development (BRADD) project is a BEMA-coordinated, multi-stakeholder data development project, championed by Bellona, drawing on BEMA's membership across the industry, including cleaning and inspection service providers, robotic and equipment manufacturers, coating suppliers, antifouling additive manufacturers, equipment-based AFS suppliers and independent test laboratories. BEMA supplies data and project management while funding for the research work is being sought through public/private partnership.

Each of the seven questions is assigned a project lead responsible for scoping the question, recruiting data contributors, managing the analysis and delivering the intended output. Leads were selected on the basis of demonstrated technical depth in the subject matter of their question, which in practice means each lead comes from an organisation that works commercially in that area. This was a deliberate decision as the questions are operational rather than academic, and the people who can answer them are the people who do the work. The composition of the teams provides a safeguard as the workstreams draw on competing equipment suppliers, service providers, coating manufacturers, etc., so that no single commercial position can carry a workstream on its own. Findings and recommended outputs are reviewed across the project before release under BEMA's name. When implemented, BRADD was only focused o the first 6 questions, however after PPR13 and the initiation of a Correspondence Group to aid in drafting the Convention, the need to add a 7th question regarding compliance was deemed necessary.

2. The Seven Questions

2.1. What technologies, products and practices exist to prevent biofouling accumulation?

Significant discussions through PPR13 and into the Correspondence Group have shown there is strong interest in regulating the cleaning of biofouling, while prevention has received less attention. An instrument that only regulates cleaning will drive cost while leaving the biofouling risk incompletely managed. This workstream catalogues and characterizes a wide toolbox, to include novel antifouling and foul-release coatings, coating additives and application/curing processes; non-coating AFS including ultrasonic, air-bubble and sheathing systems; and marine growth prevention systems (both internal and external).

An initial summary paper has been drafted that serves as a sort of structured technology register with the claimed mechanism, the evidence class supporting it (manufacturer data, third-party test, in-service data), and the operating envelope. It is anticipated that this will be turned into an information paper that supports and highlights the need for prevention-focused provisions in the convention and could serve as source material for any necessary supporting guidelines.

2.2. What is the risk of invasion from microfouling?

Whether microfouling on ships hulls constitutes a meaningful invasion vector remains a topic of debate, and this single question drives a large share of the regulatory burden on frequent hull cleaning. The answer, as well as the answer to the related sub-questions about the behaviors of undisturbed microfouling, will play a critical role in both how, and when, ships' hulls will need to be cleaned. While significant academic research is occurring globally on the behaviors of biofilms (and other fouling organisms), further focused study is likely needed to better understand the risks, and ultimately establish appropriate risk management strategies. This question starts to overlap with Q3, as comparisons of undisturbed organisms with organisms disturbed by cleaning activities will be needed.

To date, BRADD has collected a small, and growing, library of papers documenting many of the studies completed to date on microfilming behaviors. Providing a consolidated list of, and access to, these papers can help regulators make better informed decisions. Further, BRADD has started development of a test protocol for assessing the behaviors of microfouling within harbors and the risk of shipborne organisms colonizing harbor surfaces. However, funding and a test partner (or partners) for this study are needed before these critical tests can move forward. BEMA has pursued a couple of grant opportunities to date and will continue to seek support opportunities. Upon completion of the study, BEMA intends to make a technical submission with an accompanying literature review, ideally co-sponsored by one or more Member States to the IMO.

2.3. What is the risk of cleaning microfouling without capture?

Proactive cleaning (grooming) of lightly fouled hulls is generally considered operationally desirable and is permitted without capture under the current voluntary guidelines, although many local authorities prohibit it. As hull biofouling is an open loop system and any fouled hull has some risk profile, this workstream serves as a natural follow on to the question above. It addresses both the potential risk posed by the detached microfouling as well as the potential risks posed by cleaning such as the release of coating material and/or biocides. These releases must be benchmarked marked against passive release from a vessel, whether moored/at anchor, idle or in transit, and appropriate regulations established accordingly. There is a second-order regulatory risk this workstream is intended to highlight, in that restrictive local rules do not eliminate cleaning demand, they relocate it, potentially shifting the biosecurity burden toward jurisdictions with the least capacity to manage it.

Multiple studies have been identified that assess the amount of material released during a cleaning and its impact on local water quality, often in the form of Total Suspended Solids, dissolved metals or similar, but rarely focus on the follow-on risks associated with the removed biofouling, i.e. can it settle and reproduce on harbor surfaces. BEMA members have commenced studies on this issue and results will be available at a future date.

Similar to subchapter 2.2, a technical submission providing a defensible risk profile for cleaning without capture, expressed as thresholds, is anticipated. It will be intended to inform the operative cleaning provisions of the Convention itself rather than any supporting guidelines.

2.4. What is the best reasonably achievable capture rate?

To date, discussions around acceptable capture rate or capture efficiency use a singular number like 80% or 95%, which is implied as the ratio of material collected compared to the material removed from the hull. The issue with this is that the amount of material removed from the hull is not easily measured, particularly through any sort of in-situ testing. It is also important to note that a simple capture rate does not necessarily address overall treatment of the collected material and the makeup of any effluent.

For in-situ ISO 20679 which addresses in-situ testing of cleaning equipment opted to assess impact to the water quality, which could be restated as the "release rate". And the amount of material released is ultimately the concern. To build on the ISO standard, ex-situ testing in a standard large scale test setup will be necessary to effectively validate system capture performance and determine an acceptable performance standard for cleaning systems.

BRADD is developing an ex-situ test protocol that assesses release rate of a cleaning system and can be applicable to both capture and non-capture systems. This test would support laboratory testing for a range of factors to include TSS, suspended biocides, microplastics, viable vs non-viable organisms etc. This testing can then allow for comparison of a system performance against established scientific standards for what poses a risk to a given waterbody. BRADD anticipates conducting tests with this protocol prior to project completion.

The intended output from this workstream is a proposed standardised release-rate test protocol suitable for adoption as a supporting guideline, and an evidenced statement of best achievable performance by system class. A threshold performance criteria can then be established from the body of evidence from continued testing under the protocol.

2.5. How is compatibility with coatings demonstrated?

Fear of coating damage from cleaning is rightfully a significant concern to both shipowners and coating manufacturers, as well as the service providers themselves. If more frequent cleaning is mandated by the Convention, assurances that coating damage will be avoided will be necessary through some means. The current volume of coating products in service makes product-by-product validation of every cleaning tool commercially impossible. This workstream addresses a standardised definition of coating damage which distinguishes cosmetic from functional damage and physical abrasion from chemical or antifouling-function loss; and a data-driven approach to compatibility that groups coatings by type and mechanism (SPC, CDP/ablative, foul-release, hard, etc) rather than by brand name. Further this effort looks at what exactly compatibility means, including actual cleaning performance of the cleaning system and the impacts to the coating as noted above. A cleaning system that doesn't damage the coating but fails to actually remove the biofouling is pointless.

BRADD is developing a compatibility testing standard and a compatibility assessment framework that allows for cleaning system validation against a representative coating within a type to be presumed compatible across that type. This is intended as a supporting guideline as in its absence, a compatibility requirement in the instrument is unenforceable in practice.

2.6. What is the global capacity for cleaning with capture?

If/when the Convention requires capture, the global service base must be able to meet the demand or the requirement becomes a de facto trading restriction. Despite the high profile advancement of a few capture system on the market, the hull cleaning industry remains almost exclusively non-capture. And even without the capture requirement, the argument can be made that there is an inadequate supply and distribution of hull cleaning to meet the current demand. The workstream is compiling an inventory of current capture-capable and non-capture service providers, as well as inspection providers, by region, with supplementary information about how cleaning permits are issued. This will also highlight the regions where hull cleaning is prohibited or severely restricted. A second effort is to produce scaling models for both a full-capture and a microfouling/grooming-without-capture regime to demonstrate the capacity growth needed to properly support the shipping industry.

A global capacity database by cleaning type and region is being built, and a summary overview will be provided as an informational paper, highlighting where capacity gaps currently exist. A follow-on informational paper will present the scaling models demonstrating indicative implementation needs and timelines.

2.7. What does compliance look like?

Questions 1 through 6 establish what is technically achievable. Question 7 asks what the instrument will actually require a ship/service provider/supplier etc, to do, how that requirement will be verified, and what follows if not met. It was added as a distinct workstream because the PPR 13 terms of reference direct the correspondence group toward structure, objectives and supporting guidelines, a compliance architecture, and because the technical findings from Q1–Q6 have no regulatory effect until they are expressed as a verifiable obligation on an affected party.

The workstream divides into two halves, the performance standard and its verification which further break down into four sub-questions:

1. What is a measurable performance standard for biofouling? A standard that cannot be measured consistently by two different assessors, in different water conditions, cannot be enforced. Candidates include fouling-condition ratings, cleaning interval, coating condition, and hull performance indices — each with different measurement reliability and different susceptibility to dispute.
2. What performance standard would actually prevent transfer of invasive species, and is that standard technologically achievable? If 100% prevention is not achievable, what is the best technologically achievable standard, and what residual risk does the gap between the two represent? This framing is intended to keep the trade-off visible in the drafting rather than buried in a negotiated number.
3. How will a ship demonstrate compliance? Inspection, continuous performance monitoring, cleaning and BFMP records, third-party certification, or some combination thereof are the options. Each imposes a different burden on the ship and a different verification capability requirement on the port State.
4. What are the consequences of failing to demonstrate compliance? Options range from a documented management plan requirement, through mandated cleaning before onward movement, to detention. The consequence chosen determines how much evidentiary weight the measurement method in sub-question 1 must carry.

A parallel inventory of the compliance monitoring tools and equipment currently available to assess hull fouling condition, together with emerging technologies for inspection, performance monitoring and compliance assessment would be required to implement the instrument as drafted. This includes diver and ROV inspection, hull-crawling and free-swimming autonomous inspection systems, in-service performance monitoring against ISO 19030-type methods, image-based fouling classification and any automated analysis applied to it, and the data formats through which any of it would be reported to a port State.

The intended output consists of two deliverables. First, a comparative assessment of candidate performance standards against measurability, repeatability, achievability and enforceability, with a recommended standard and an explicit statement of the gap between the protective and achievable positions. Second, an inspection and monitoring technology inventory identifying the capability gaps that must be closed before any given compliance mechanism becomes workable. This will leverage the work done in Q6 above. Together these are intended as a submission to the correspondence group on the compliance architecture of the instrument, and as source material for a supporting guideline on survey, inspection and reporting.

3. Cross Cutting Observations

In completing the work to date, a few issues have been noted that cross multiple workstreams. These include the shortage of independent, non-manufacturer performance data; the absence of any agreed measurement protocol as the common blocker across Q3 (Microfouling cleaning), Q4 (Capture Rate) and Q5 (Compatibility); the interaction between Q4 (Capture Rate) and Q6 (Capacity), where a stringent threshold set without capacity data creates a compliance gap; and the dependency of Q7

(Compliance) on Q1–Q6, in that no compliance regime can be specified until the underlying performance standard has a measurable basis. Th interdependency of these factors highlights the criticality of this project and the urgency to submit the technical and informational papers for consideration by both the correspondence group and the subcommittee as appropriate.

4. Future Work

The BRADD Project welcomes additional input from across the industry. Membership in BEMA is not required. Each workstream is operating on its own schedule, with its own set of participants. Support is particularly needed to advance the testing on the risks posed from microfouling. For further information about participating in, please contact the Technical Director, Mark Riggio at techdirector@bwema.org.

5. Conclusion

The regulatory question is no longer whether a mandatory biofouling instrument will exist, but what it will require and whether those requirements will be achievable. The technical annexes and supporting guidelines drafted between now and 2029 will determine whether the instrument is enforceable or aspirational. BRADD exists to ensure the numbers written into that text, capture rates, fouling thresholds, compatibility criteria, implementation timelines, are drawn from measured performance rather than negotiated in the absence of data. The window for contributing that data is open now and will not stay open for the life of the drafting process.

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Challenges and Victories in Testing of In-Water Cleaning Systems

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Abstract

The growing regulatory pressure to manage hull biofouling has accelerated demand for proven in-water cleaning and capture (IWCC) systems, yet rigorous, real-world testing of these systems remains limited and technically demanding. Drawing on lessons learned by Subsea Global Solutions through work with Transport Canada, Belgium and the Netherlands, this paper examines the practical challenges and operational successes encountered when testing IWCC systems under commercial operating conditions. These findings carry implications well beyond a single contractor or test program — they underscore the need for industry-wide standardized testing protocols, pre-qualified laboratory networks capable of the required analysis, vessel selection criteria appropriate for demonstration programs, and sampling designs that produce practically and scientifically meaningful results.

1. Introduction

The paper presented to this conference last year described how Subsea Global Solutions, a company built on divers, absorbed robotic cleaning, capture and filtration into its service portfolio. It closed by noting that a demonstration event with Transport Canada was still in progress. That demonstration is now complete with the publishing of the final report from Transport Canada imminent, and in the interval Subsea Global Solutions has also participated in test programs in Belgium.

The technology questions that dominated this discussion a few years ago are largely answered. Tools clean, shrouds capture, filters filter. What is not answered is how any of that gets proven to the satisfaction of an authority, at a cost and on a schedule a commercial service provider can absorb. Testing has become the bottleneck in the adoption of in-water cleaning with capture and can be one of the most expensive line items in bringing a system to a new market. A convention will require thresholds; thresholds require test data; and test data require testing capacity that, on the evidence of the last two years, does not exist at the scale or price the industry will need.

The regulatory clock explains the urgency. The progression from MEPC 83 through PPR 13 to MEPC 84 has resulted in an agreement that a standalone legally binding instrument (Convention) should be developed and approved terms of reference. Industry analysis of the MEPC 83 decision anticipated two two-year work periods, placing a draft text around 2029. On the standards side, ISO 20679 was published in January 2025, ISO 6319 in March 2026 and the IMO issued MEPC.1/Circ.918 in April 2025 as guidance on in-water cleaning.

2. Testing to a Contract Is Not Testing to a Standard

One potentially expensive lesson of the last two years is a distinction that is easy to miss until you are standing on deck with a sample cooler. At least three activities get called “testing” and they are not interchangeable: independent performance testing to a published protocol such as ISO 20679; a regulator-funded demonstration, where deliverables and sampling regime are set by contract with the funding authority; and a local permit trial, which asks only whether a given discharge in a given harbor meets that jurisdiction’s numbers.

The Transport Canada program was the second type. Subsea Global Solutions tested to a set of contractual requirements, not to an industry standard. That is not criticism of the authority (it is what a demonstration contract is for) but the consequence is that the data does not automatically travel, because it was not generated under a protocol another administration has agreed in advance to recognize. Nor would a full ISO 20679 campaign close that gap by itself: the standard explicitly places performance requirements, criteria and thresholds outside its own scope, leaving those to individual administrations.

A completed ISO 20679 test tells an authority what a system does. Critically, it does not tell them whether it passes.

MEPC.1/Circ.918 adds a harder constraint. It recommends in-situ testing on the surfaces of at least three different ships, each a separate test, with the set presenting distinct coating types including the softest coating the technology is intended for, and with both capture and non-capture modes tested where a system offers both. For an operator that is the single largest cost driver in the regulatory package. Subsea Global Solutions works from 13 offices in 8 countries and routinely operates in ports beyond them, so absent mutual recognition, qualification cost scales with the number of jurisdictions rather than the number of systems. Better tools do not solve that.

3. The Test Programs, 2024–2026

The Transport Canada demonstration [Contract T8080-230283] was conducted in Halifax Harbor between November 2024 and September 2025. It evaluated five cleaning tools used with filtration and treatment systems across two vessels, covering flat bottom, vertical side and niche surfaces. The cleaning tools were the Remora diver-driven cart, the internally developed Cleaning ROV (C-ROV), the Beluga diver-operated niche and propeller polishing unit, and two diver hand tools. Each cleaning unit is configurable for capture, with shrouding and a suction uptake feeding a surface treatment train. The treatment system, described in last year's paper and unchanged, was the WhaleShark, consisting of prefiltration, dosing, settling, staged filtration to 1 µm and organoclay polishing, intended to address dissolved copper and zinc from the coating as well as removed solids.

Testing in Belgium was conducted in Zeebrugge over a similar timeline on two vessels under the oversight of the Port Authority of Antwerp-Zeebrugge as part of the local permitting process. Operations were conducted with the C-ROV and a purely mechanical unit handling solids only, with ultraviolet treatment of the effluent.

4. Where the Difficulties Actually Lie

4.1. Vessel selection is the binding constraint

With in-situ testing required in a test program, the hardest element to control is the ship. A test vessel must satisfy a long list of conditions simultaneously, and commercial vessels are not built to satisfy them.

The schedule must accommodate the test rather than the cleaning, because a sampled, timed and documented pass can take substantially longer than the same pass done commercially, and a port stay is set by operational considerations. The shell plating must suit the tool: a shrouded capture unit depends on staying in contact with the plate to keep the shroud sealed, and where service has left the plate deformed the seal opens and captured material escapes. Measured capture efficiency then reflects the condition of that hull as much as the capability of the tool; hard to defend, harder to compare. (Note: cleaning tools need to be designed to accommodate real world hull conditions, but there will always be outlying conditions, and those may be difficult to identify prior to a test event). Coating type matters, and the guidance pushes toward the difficult end by asking for the softest coating a system is intended to clean. Niche areas of interest must be present and accessible. Fouling must support the intended test, and fouling cannot be ordered: arrive to test heavy macrofouling on a hull that was recently groomed and there is nothing to remove. Concurrent port operations — bunkering, cargo, other contractors alongside, restrictions on diving during those operations — can compress or cancel a window that took months to arrange.

Set that against the recommendation for at least three ships with distinct coating types and the scale of the problem is clear. The constraint on qualifying an in-water cleaning system is not engineering. It is finding suitable ships whose owners are willing to host the work. The Port Authority of Antwerp-

Zeebrugge's testing procedures to create flexibility by allowing the test to be conducted when completing a commercial cleaning activity under a provisional permit.

4.2. Tool maneuverability on real hulls

Heavy macrofouling changes the geometry of the surface being cleaned. Hard growth — barnacles, tubeworms, mussels — produces an irregular, load-bearing layer that holds a wheeled or tracked unit off the plate, degrades adhesion and raises the load on brushes and drive. Deformed plating does the same from the opposite direction. The tool that performs best on a fair, lightly fouled hull is therefore not necessarily the tool to send to a heavily fouled one, and a result obtained on one hull condition says very little about the other. This is also where diver-operated tools continue to earn their place. In a market that increasingly assumes robotic superiority by default, on deformed plating and against well-established hard fouling, hand tools and a competent diver remained both the effective option and the one able to adapt in real time when the plan met the hull.

4.3. Sampling the debris stream

Sampling was the most underestimated technical problem in the program, for an almost comically simple reason: removed macrofouling can be physically larger than the sample ports. Barnacle plates, mussel shells and weed fronds do not pass through a small port, so the sample reaching the laboratory is systematically biased toward the fine fraction, and any estimate of captured biomass built from those samples understates what the system actually removed.

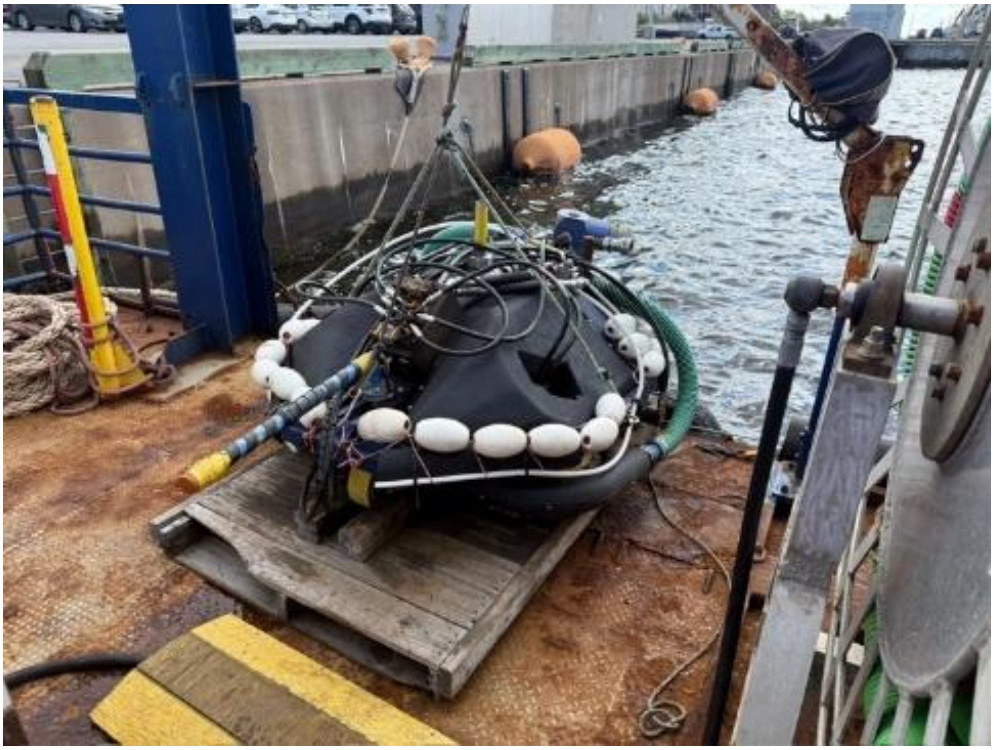

Fig.1: Remora Hull Cleaning Vehicle awaiting deployment, Credit: Subsea Global Solutions

Where in the flow path a sample is drawn also determines the answer — at the tool, at pump discharge, at filter inlet, or at final effluent. Each location measures something different, and a protocol that does not specify the point produces numbers that cannot be compared between systems. Add volumes, preservation, hold times and chain of custody, executed on a working vessel by a dive team, and sampling becomes a discipline in its own right. The Transport Canada program generated 72 samples requiring laboratory analysis. The test procedure for Antwerp-Zeebrugge currently requires 20 samples, which is more easily managed. This is not to say that either one is better than the other, rather it is intended to demonstrate the variation that can exist.

4.4. Laboratory capability and cost

Analysis of those 72 samples for sediment, metals and particulate size distribution ran at roughly USD 333 per sample. Microplastic and nanoplastic analysis of coating debris, which would be genuinely valuable information for the coatings and cleaning industries alike, was quoted at approximately USD 1800 per sample. At that price, on that sample count, the analysis did not survive contact with the budget.

Price was not the only obstacle. The available analytical standards fit this matrix poorly. ISO 24187, published in 2023 as the principles document for microplastics analysis, is written around waters of low organic and suspended solids content and lists mineral particles, pigments, biofilm and weathering alteration among its key interferences. Hull cleaning effluent contains all of them by definition; it is close to a worst-case matrix. ASTM D8332-20 covers collection from high-solids water, but identification and quantification remain the hard part. The outcome, reported last year and unchanged since, is that no laboratory was identified that could perform the analysis in an economically viable manner which was viewed as a capability gap in the supporting infrastructure, not a procurement failure by the contractor.

4.5. The burden on the vessel and the dive team

Testing on an operational vessel imposes real costs on people not paid to do research. In-water time increases substantially once every pass has to be bounded, timed, sampled and logged. Dive teams run longer, with more personnel, under procedures different from commercial work; holding a measured pass rather than getting the job done, labelling and logging rather than moving to the next panel. A commercial dive team asked to function as a research team will do it, but it needs briefing, practice and supervision, and should be planned and priced as a distinct scope. In a regulator-funded demonstration part of that cost is carried by the authority while in a local permit trial the provider carries all of it and the vessel owner carries the schedule risk.

Fig.2: WhaleShark Filtration Barge, Credit: Subsea Global Solutions

5. What Went Right

The program was completed. Five cleaning tools and the treatment system were exercised on working commercial hulls, across flat bottom, vertical side and niche surfaces, under the observation of a national authority, and reported. Subsea Global is certainly not the first to do such work, but the breadth of the requirements makes this an uncommon achievement in this industry. Transport Canada is expected to have published their report on the study in between submittal of this paper and presentation at the PortPIC conference in September 2026.

The hybrid operating model was validated under scrutiny. Using the C-ROV on flat bottom and vertical sides while divers address niche areas proved cost-effective and operationally sound. Subsea Global Solutions also came out of the program with trained personnel, written sampling procedures, working relationships with laboratories and authorities, and a realistic cost model for future campaigns. The capability to run a test program is itself a commercial asset, and it did not exist in this form two years ago.

6. What the Industry Needs Next

Four things are needed, in rough order of leverage. First, standardized protocols with recognized results. ISO 20679 is the obvious vehicle and its publication is real progress, but it has yet to become the universal reference, several practical aspects would benefit from further guidance, and testing under a recognized protocol is only useful if administrations accept results generated elsewhere. Without mutual recognition, a published standard reduces ambiguity but not cost. While the findings presented here are all focused on the issues around in-situ testing, there also exists a need for a robust protocol for ex-situ testing. Ex-situ testing can be tailored and controlled to highlight specific performance areas that can effectively match cleaning efficacy with capture efficacy.

Fig.3: The Standardization Quagmire,Credit: Always Sunny in Philadelphia

Second, a pre-qualified laboratory network: authorities requiring an analysis should identify laboratories demonstrably capable of performing it on high-solids marine effluent, at published rates. Requiring an analysis for which no accessible capability exists is, in practice, a prohibition. Third, published vessel selection criteria for demonstration programs — plating condition, coating type and age, fouling range, niche inventory, schedule availability — so providers and authorities can pre-screen candidates rather than discover unsuitability mid-test. Fourth, sampling designs that are physically possible: ports sized to pass the largest expected debris, defined sampling points in the flow path, and defined units of measurement, so that results from different systems can be compared at all.

There is a market structure point underneath all of this. Substantial alignment exists between technology providers and the shipping industry on what is needed. The harder task is common ground with flag States. Meanwhile the inspection and cleaning market is not sized to meet the demand the proposed rules will create, and qualification cost acts as a barrier to entry. Testing cost is not a neutral technical detail; it helps determine how many companies are left to do the work.

7. A Problem the Current Regime Does Not Address – Departure Control

In the words of the famed British comedy troop Monty Python, and now for something completely different. The frameworks and protocols discussed throughout the regulatory development process all appear oriented toward the arriving vessel; how do we keep the bad stuff from impacting our port?

Earlier in 2026, Subsea Global Solutions was asked to consider the issue of the Golden Mussel (Limnoperna fortunei) in California. It was first detected in Stockton California in 2024, and likely arrived via ballast water, rather than hull fouling. However, it has subsequently been proven to attach to vessel hulls and can be transported as such. The Western States (California, Oregon and Washington) are now concerned with preventing its further spread, considering the amount of vessel traffic that moves between the Stockton area and the Columbia River.

Fig.4: Golden Mussels on a Small Vessel, Credit: Fred Greaves, CalMatters

For a departure-port vector, cleaning on arrival is too late. It reduces risk far less than preventing the organism from leaving in the first place would. Reframed as a pre-departure problem, the question changes: thorough removal from a lightly fouled hull, against organisms that are small, numerous and viable (not to mention already locally established), rather than bulk removal of established macrofouling in an at-risk location. Cleaning well-attached mussels can leave the attachment base behind and accelerate recolonization, while cleaning aggressively enough to remove it risks the coating; uncaptured mussels can resettle. An added factor specific to the Golden Mussel is there is no established route for what a provider does with captured mussels; in fact, possession of the golden mussel is prohibited under law. No test program to date was designed with freshwater invasive bivalves in mind, and the next one should be.

Advocates of proactive cleaning, specifically the high frequency hull grooming concept, often to preach to "groom before you go." California's golden mussel situation presents a very specific example of how the concept can be beneficial. If a vessel is cleaned immediately prior to departure, it will not be transporting the high-risk species out of the port. The vessel will not pick up any golden mussels in transit. It logically follows that it won't be bringing any golden mussels into its next port. The vessel can then be cleaned again before its next departure, without risk of removing any species of local risk. This system is founded on having cleaning services available at every port, which will likely only be possible, practically and economically, if cleaning or microfouling without capture is permitted. This specific issue also services as a strong argument for the use of marine growth prevention systems, which can reduce the settlement of organism in the first place.

8. Summary

Two years ago, the open question for in-water cleaning with capture was whether the technology could do the job. That question is largely settled. The open question now is whether the industry can prove it, repeatedly, in every jurisdiction that asks, at a cost that leaves a viable business behind. On present evidence, the answer depends less on tools than on four pieces of missing infrastructure: recognized protocols, capable laboratories, workable vessel selection criteria, and sampling designs that survive contact with a barnacle. With a binding IMO instrument now formally under development and a draft not expected before the end of the decade, there is a window in which those could be built deliberately rather than improvised port by port.

Acknowledgement

Thanks to the regulatory bodies around the world that have engaged constructively with these emerging technologies and are actively looking for ways to allow hull cleaning to be performed in an environmentally sound manner. These organizations include, but are not limited to, Transport Canada, the California State Lands Commission, the California Water Boards, the Rijkswaterstaat and the Flemish ports. Thanks also to the vessel owners and operators who made their hulls, their schedules and their crews available to testing that offered them no direct commercial benefit.

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Scaling Commercial Robotic Hull Cleaning Operations: A Redundant Hybrid Workboat Support System for Port-wide Biofouling Management

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Abstract

In-water robotic hull cleaning has emerged as a cornerstone of proactive ship biofouling management, promising reduced fuel consumption and greenhouse gas emissions while mitigating the transfer of invasive aquatic species. However, transitioning this technology from localized trials to continuous, port-wide commercial service introduces distinct challenges in power stability, operational uptime, and regulatory compliance. This paper establishes an operational framework for scaling robotic biofouling management utilizing a purpose-built, highly redundant support workboat platform (GTH001). We discuss the system architecture, specifically the role of its hybrid 450 kW operational grid, 100% active standby redundancy, and B100 biodiesel compatibility in achieving continuous, low-emission operations. The paper demonstrates how integrating dedicated support vessels and localized operating partners provides a scalable solution that meets the emerging standard of environmentally safe and commercially viable harbour cleaning.

1. Introduction

1.1. The Commercial Impetus for Proactive Cleaning

The maritime industry is facing intensifying pressure to manage hull performance, driven by International Maritime Organization (IMO) Carbon Intensity Indicator (CII) ratings and evolving biosecurity guidelines. Unmanaged biofouling can result in fuel consumption penalties exceeding 10%. While reactive cleaning, typically triggered by performance degradation, is common, proactive "grooming" of early-stage slime holds significant potential for maintaining peak efficiency.

1.2. Constraints on Port-wide Scale

Despite the clear benefits, widespread adoption of robotic systems faces two primary constraints:

- Power Stability: Cleaning robots, water filtration systems, and tether management systems require significant, stable electrical power.
- Operational Redundancy: Commercial port environments have strict operational windows; technical failures during a cleaning operation can impose significant delay costs on ship operators. Current operating models, often reliant on portable generators on a static barge, fail to address these needs effectively. A dedicated support vessel is required to bridge this gap.

2. Methodology and System Architecture

2.1. Purpose-Built Workboat Platform (GTH001)

Our solution leverages a specialized 28m aluminium lines plan for a hybrid workboat, optimized for harbour manoeuvring and robotic operations support. This dedicated vessel integrates the launch-and-recovery system (LARS), filtration units, and a localized power plant, removing the logistical strain of mobile power setup from the client vessel or a static barge.

2.2. Power Generation and Operational Grid

The cornerstone of our scalability strategy is the workboat's highly redundant and high-capacity hybrid power grid, Table I. Traditional set-ups rely on a single primary generator. Our framework utilizes three separate, full-time marine generators.

Table I: Technical specifications of the GTH001 Dedicated Support Workboat (Oceanis Robotics)

System Component	Specifications & Role
Operational Grid	2x 225 kW hybrid diesel-electric generators, running in parallel
Total Operational Capacity	450 kW (serving robot, pumps, filtration, winch)
Backup Redundancy	1x 225 kW identical generator, 100% active standby
Zero-Emission Mooring	< 320 kWh Lithium Iron Phosphate battery system
Biodiesel Compatibility	Hybrid generators compatible with B100 fuel

2.3. Active Standby Redundancy for Commercial Reliability

Technical failure must not result in operational downtime. Our power architecture addresses this: during active ROV grooming, the operational load is distributed across two 225 kW generators. The third 225 kW unit remains in active standby, synchronization with the main grid. This means if a primary operational unit encounters a fault, the standby generator seamlessly and instantly absorbs the required load without interruption to the ROV thrusters or vacuum systems. This N+1 redundancy guarantees continuity, critical for commercial acceptance in high-traffic hubs.

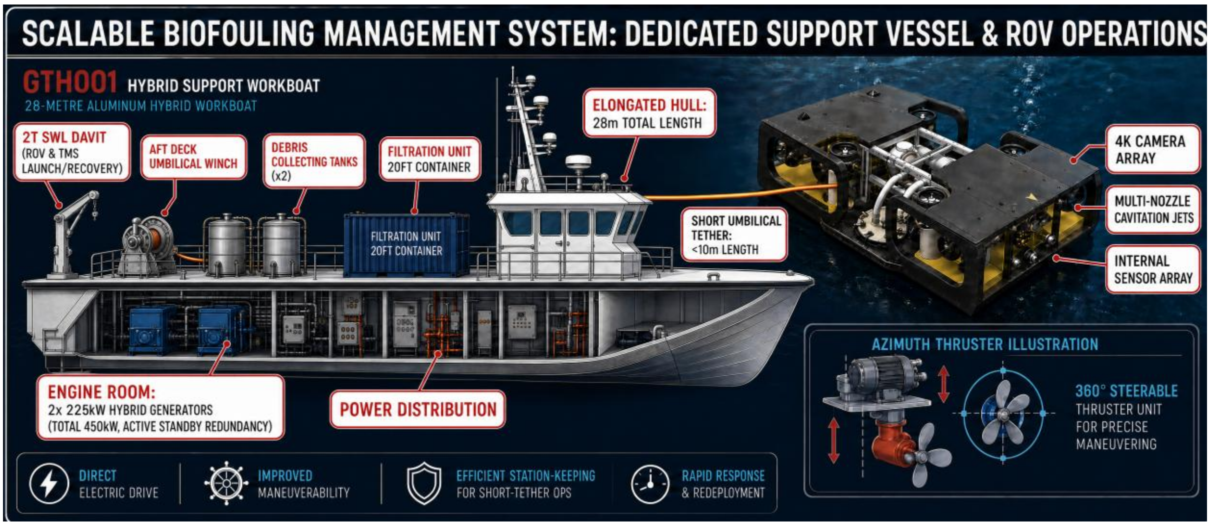

Fig.1: Support vessel and ROV

3. Commercial Scaling Strategy: Localized Operational Joint Ventures

International scalability must address diverse port-specific regulations, crew licensing, and logistical needs without exposing core technical IP. Our proposed model does not involve technology licensing or franchising. Instead, we propose localized operational Joint Ventures (JVs).

- The Technology Partner: Provides the standardized, purpose-built GTH001 support vessel and the advanced robotic cleaning technology, ensuring global technical quality.
- The Local Port Partner: Handles harbour manoeuvring, regional safety compliance, crew staffing for the support vessel, and terminal scheduling.

This approach allows rapid duplication of a standardized technical service footprint across international hubs while leveraging deep local operational expertise.

4. Safety, Redundancy, and Low-Emission Operations

4.1. The Role of N+1 Power Redundancy in Safety

Safety is paramount in port waters. Interruption of power to a magnetic crawler or vacuum system can lead to loss of station-keeping, risking collision with the vessel's hull or neighbouring harbour infrastructure. By prioritizing active redundancy rather than reactive standby, the GTH001 ensures no power interruption can result in an uncontrolled ROV event.

4.2. Low-Emission and Zero-Emission Operating Modes

To satisfy future port-specific emissions restrictions (such as FuelEU Maritime or the phasal inclusion of shipping in the EU ETS), the support vessel operates on zero-emission battery power while anchored for up to 16 hours. In active operational mode, the hybrid generators use high-efficiency, biocide-free cleaning principles while maintaining B100 biodiesel compatibility, offering a truly sustainable, near-zero footprint solution.

5. Results and Discussion

Our technical analysis indicates that the integrated GTH001 support system achieves three primary scaling goals:

1. Commercial Continuity: Redundant power ensures cleaning operations are completed within scheduled windows, meeting classification society safety and redundancy standards.
2. Technical Integrity: Direct, standardized supply chains for the workboat ensure identical service delivery standards globally.
3. Environment Compliance: Integrating a zero-emission mooring mode and B100-ready generators positions the service as a leader in environmentally sustainable port management.

6. Conclusion

The effective and widespread scaling of robotic hull cleaning requires robust operational solutions that extend beyond the cleaning robot itself. By utilizing a dedicated, highly manoeuvrable support workboat (GTH001) with a highly redundant 450 kW parallel power grid and localized operational joint ventures, Oceanis Robotics provides a scalable blueprint for the maritime industry. This model addresses the core requirements for commercial uptime, technical quality, and stringent environmental compliance, paving the way for standardized port-wide proactive biofouling management across global high-traffic hubs.

Acknowledgement

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Towards an Understanding of the Environmental Risk Posed by Biofilms and Proactive In-Water Cleaning: A Practical & Real-World Approach

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Abstract

The presence of harmful pathogens in ship biofilms is well documented and may even be less desirable than the release of some non-native macrofouling species. Debates around the need to capture debris removed during proactive cleaning continue, with little evidence to back up either side of the argument. Here we present a test method to investigate a) the pathogenic microbial assemblage composition of biofilm on an in-service commercial vessel using a DNA metabarcoding approach, b) the detectability of that assemblage in the water column during a proactive cleaning event and c) the background microbial assemblage for comparison. Ultimately, we aim to generate a real-world, data-based understanding of any ecological risk associated with biofilm release during proactive cleaning to enable port authorities and other parties to make informed decisions about hull management procedures.

1. Background

Perceptions about what is acceptable can change rapidly. What is deemed as "environmentally acceptable" in terms of industrial practices is changing at pace as the general public become more environmentally aware and the impacts of a changing climate become more obvious to all.

In relation to the shipping industry, the days of steaming with fouled hulls are numbered. Local, regional, and national regulation, and international policy and legislation are all moving towards tighter controls on hull fouling, for a whole host of very justified reasons.

Fortunately, decades of effort from industrial chemists in various coating manufacturing companies have produced a market of antifouling coating products which, in some cases, provide remarkable reduction in hull fouling, despite the significant challenges of fighting against immense biological processes.

However, coatings alone will not achieve our end goal. Cleaning will always be required when vessels fall outside of the operational profile of the coating, or if unexpected coatings issues arise. Reactive cleaning without capture (the industrial norm in most places) when conducted with care can temporarily reduce the macrofouling challenge but will always be associated with levels of biofouling debris, paint particles and in most cases release of soluble biocides to such an extent that this approach can't be justified as a long-term solution in today's changing world.

Reactive cleaning with capture will undoubtedly play a key part of the puzzle and is likely to be the only practical and environmentally responsible way of dealing with a macro fouled hull, especially one that is known to support high risk species within the fouling. However, the ability to scale this sophisticated technology to meet the global cleaning requirement that is expected once IMO ratify a legally binding convention on managing ships biofouling, will be extremely expensive and challenging.

This leaves a gap.

How do you manage hull fouling on a global scale with technology that can be triggered by the vessel at a suitable time and minimise the risks of contamination and damage to ship's coatings? The answer may be in proactive cleaning, with devices installed on individual vessels.

Proactive cleaning can provide the opportunity to manage hull fouling at the micro or biofilm level, before development into macro fouling. It can be achieved with hardware that can be owned or operated by the vessel, reducing the reliance on complex planning and logistics of bringing cleaning hardware to the vessel.

This approach is not perfect. It won't be suitable for all areas of the hull or all coating types. If used incorrectly it still has the capacity to negatively impact the performance of the coating, although in most cases this risk will be less than an incorrectly operated, or incompatible reactive approach.

However, in theory, when combined with a compatible coating system, the proactive approach provides a scalable, economically favourable option to provide long term biofouling management to assist vessels with being compliant and also reducing their operating costs in a world where hull scrutiny and the requirement for hull efficiency is only going to increase.

The question is, do we also need to capture the microbial biofouling that proactive systems will release?

This overarching question covers a range of key sub-questions:

1. What level of environmental threat does the microbial fouling released during a proactive clean pose?

2. Which organisms reside in a ship hull biofilm, and how likely are these to cause negative impacts in a receiving environment?

3. Can we link the organisms that commonly reside in microbial biofouling to known historical negative environmental impacts in ports and anchorages?

4. How does the release of biofilm during a proactive clean compare to the loss of biofilm that occurs under normal operational conditions (i.e. coatings sloughing off biofilms as they move and encounter different salinity and temperature gradients)?

PML Applications is working with Jotun to answers these questions.

2. Tests & Methods

PML Applications is working with Jotun and the Port of Southampton to conduct a field-based trial to examine the microbial assemblage composition of biofilms on a vessel, as well as the detectability of the vessel's biofilm during a proactive hull-cleaning operation.

The purpose is to better understand the relative environmental risk of any organisms released during the pro-active cleaning of a vessel's hull using the HullSkater cleaning solution, in comparison to background environmental conditions.

To examine the microbial community within the ship hull biofilm and the surrounding environment, samples will be collected and analysed using two methods:

1) Viable colony-forming unit (CFU) plate count method to quantify numbers of viable, culturable and potentially pathogenic bacteria of Vibrio cholerae, Escherichia coli and Enterococcus spp., and

2) Metabarcoding of biofilm associated algae, protists and invertebrates.

The project will involve a number of different steps:

- Optimising and testing the water sample collection method to attach to the HullSkater cleaning device to allow water sample collection during a pro-active clean.

- Logistics and planning to enable the sample collection process within the port (Southampton).

- Pilot study to test both the plate count and molecular methods for biofilms removed from a vessel coated in a copper containing biocidal coating.

- The actual pro-active cleaning operation and sample collection at the identified port.

  Sample collection within the Port will include:

  - Biofilm taken directly from the main vessel's hull,
  - Water samples from the HullSkater device during cleaning,
  - Water from the surrounding vicinity of the vessel before the cleaning operation begins,
  - Biofilm samples from underwater structures within the port,
  - Biofilm samples from a support vessel's hull that is coated in a similar biocidal coating and operates within the local area.

- Quantification of potentially pathogenic bacteria using viable CFU counts for Vibrio cholerae, Escherichia coli and Enterococcus spp.

- Molecular analysis of sample DNA, targeting biofilm associated algae and protists. This will also provide relatively coarse information (family/order level) for invertebrates such as ascidians, barnacles, bryozoans, molluscs and polychaetes.

- Bioinformatics, data analysis and reporting. A full report will be produced that includes methods, results and discussion, focusing on microbial community composition and differences between sample types, as well as highlighting any significant findings related to the presence or abundance of potentially harmful species/taxa.

3. Conclusion

This work will answer vital questions that will enable a data-based view to be taken on whether or not it makes environmental sense to capture microbial fouling released during a pro-active clean. If this, and other programmes of work suggest that capture of microbial fouling during a proactive clean makes sense, then that would be a valuable outcome for the project.

However, if capture is required alongside pro-active cleaning, many of the key benefits of this approach (vessel owned, economically favourable) are less obvious, and the wide scale solution to our global hull fouling challenge, becomes much more challenging.

Consequently, making the right environmental call at this stage needs to be a high priority to enable the commercial shipping industry to maintain compliance in more demanding world.

Proactive Grooming Validation & Efficacy Across Coating Categories

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Abstract

As the IMO moves toward a legally binding biofouling management framework, the design choices and incentives built into that framework will shape how ambitiously the industry can act on biofouling. A common concern in emerging regulations is coating compatibility, the assumption that gentle brush grooming is only appropriate for certain antifouling categories and should be limited accordingly. This paper challenges that assumption, drawing on operational data from over 2,000 commercial cleans, alongside in-situ water quality testing and submerged panel testing. The same data also challenges prevailing assumptions about cleaning cadence: keeping fouling at manageable levels requires grooming intervals of weeks, not months. At this frequency, fouling stays light and coating integrity is maintained throughout the grooming service.

1. All coatings are groomable

Coating compatibility has become a recurring point of contention in the development of in-water cleaning standards, including in the IMO's In-Water Cleaning Guidance (MEPC.1/Circ.918) and the correspondence group process currently developing a legally binding Biofouling Management Convention. This assumption shapes the regulatory choice ahead.

One way is to regulate by coating category. This approach is broad by design. It does not account for how adjustable modern grooming technology already is. Brush hardness, contact pressure, and cleaning frequency can all be set per clean. A category-based rule cannot capture this. It risks limiting which technologies reach commercial use, without a clear link to the outcome regulators care about.

A better way is to focus on outcomes: undamaged coatings, minimal biofouling. Proposition: utilise technology to make grooming very adjustable, and regulate for outcome rather than category. Through operational and empirical evidence, this paper shows that proactive grooming, when gentle and controllable, is compatible with all coatings:

- Operational field data: +2,000 commercial cleans over 3 years across global fleets and range of industry leading coatings
- In-situ water quality testing grooming on self-polishing copolymer (SPC): with independent third-party (SGS Marine Services) during proactive grooming operations
- Tailored operations: adjusting variables to ensure compatibility on all coatings

These data points show that various coating categories, both hard and soft, are groomable over months and years with measurably minimal risk. This is reinforced by Hullbot's accelerated life cycle testing presented at last year's PortPIC (2025), which simulated five years of proactive grooming on hard coatings, foul release coatings (FRCs) and ablative coatings, with no measurable change in coating integrity.

Coating damage risk is also driven by how much fouling has built up, not only coating type itself. How often a hull is cleaned determines how much fouling has built up, and that level of fouling then determines the brush type and pressure needed to remove it. Because fouling load is largely a function of cleaning frequency, regulation is better targeted at the fouling level a hull is allowed to reach, rather than at coating type or cleaning methodology directly.

2. Fleet-Scale Real Life Operational Data

2.1. Dataset across 2,000 cleans under real-life conditions

To date, more than 2,000 proactive commercial hull-grooming operations have been completed across ferries, cruises and commercial vessels operating in Australia, Asia-Pacific, Europe and North America (as of August 2026). Grooming has been carried out on vessels using all major coating brands, with no coating-damage incidents recorded by proactive grooming, Table I.

Table I: Headline figures from Hullbot's grooming dataset, as of August 2026

Documented cleans	Cleans/Month	Unique vessels	Cleaning coating damage	Coating damage (not caused by Hullbot, section 2.2)	Fuel reduction measured	CO2e reduction measured
+2,000	+100	91	0	25	2,676,883 L	8,298,153 kg

Table II summarises a documented subset by coating category, alongside the fuel-efficiency improvements measured and reported after adopting proactive grooming. Efficiency variation is not a reflection of cleaning or coating success, but due to a range of variables, including different global fouling pressures.

Table II: Grooming data by coating category, showing number of vessels, documented cleans, and reported fuel efficiency gain from fouling removal

Coating category	Vessels	Documented cleans	Max Months of Cleaning	Total average hours groomed	Fuel efficiency gain
Hard	7	927	36 months	2,533	11 - 23%
FRC	41	893	40 months	6,866	7 - 26%
Ablative	18	214	13 months	1,225	9 - 14%

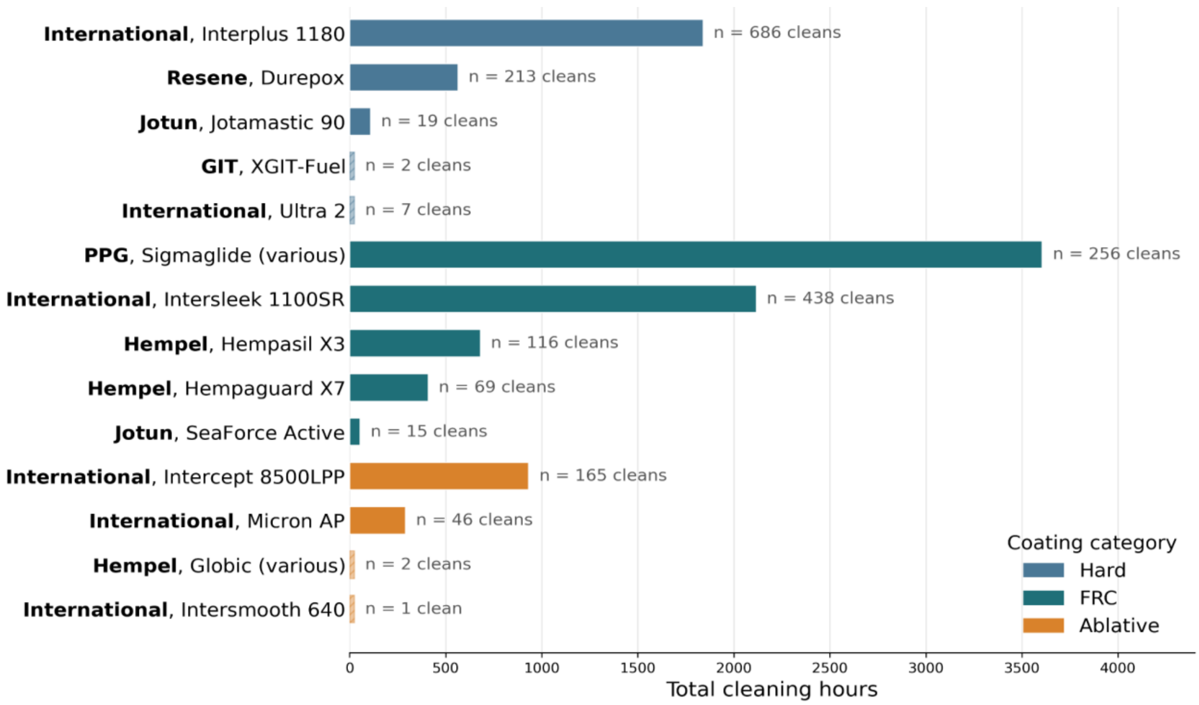


Fig.1: Documented cleaning history by coating product. Hatched bars are fewer than 80 hours of cleaning

Adjustable cleaning speed, brush type, and brush pressure allow the same grooming platform to be precisely adjusted per coating and fouling condition, rather than requiring a different tool for each coating category. Across the full grooming dataset, no coating damage has been attributed to grooming by the fleet operator or Hullbot. Where coating degradation has been observed at inspections, the cause has been documented. Examples include coating reaching end of life, dry dock blocks, or impact damage from grounding, fender contact, or anchor chain contact (Section 2.2)

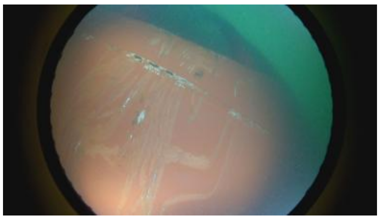
2.2. Subset examples of damage detection and coating degradation tracking

Marking paint failure

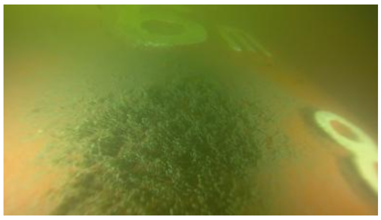
Docking block mark

Impact damage

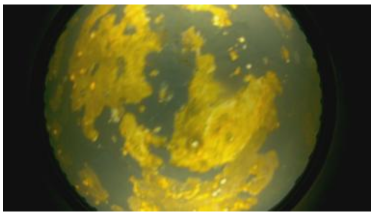
Transom Damage



Anchor chain scoring



Coating adhesion failure



Impact damage

Ablative failure

Diver brush scoring

3. Water quality testing results for ablative (SPC) coating grooming

Water quality testing was conducted during a proactive grooming operation on a SPC coating (Intersmooth 460), an antifouling type that relies on a controlled release of copper and zinc as its active ingredients. Fourteen water samples were taken at four stages of the trial, at the start, one third through, two thirds through, and at the end. Samples taken within 1m from the active cleaning system and 20m away were compared. Copper and zinc remained below detection limits throughout the whole cleaning operations in all samples, indicating that no measurable active ingredients were released from the coating, Fig.2.

In addition, suspended solids were measured as a proxy for cleaning residue. Values varied across the trial, with no consistent pattern. Because elevated solids show up in both background and near-operation samples, not just where cleaning happened, there is no clear link between the cleaning activity and the level of solids in the water, Fig.2.

Results show grooming does not strip or release measurable amounts of active ingredient from an SPC coating.

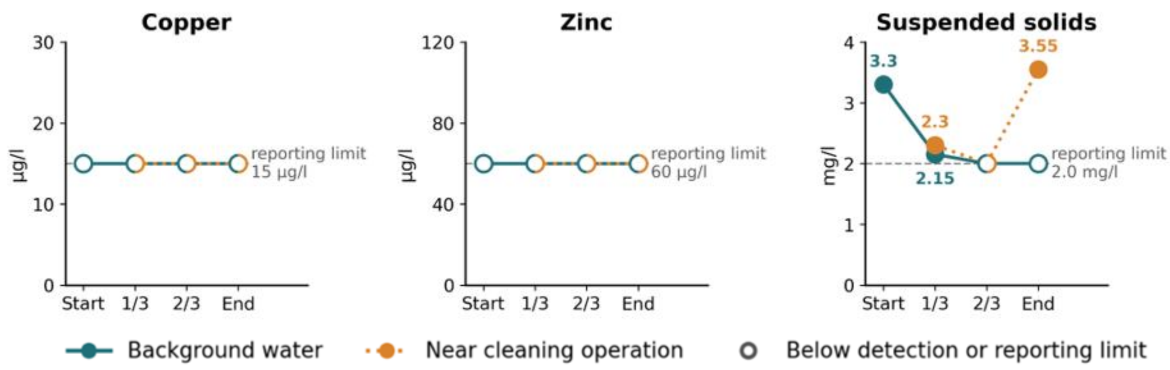


Fig.2: In-Situ water quality test results: Proactive grooming of an SPC coating

4. Compatibility is set by cleaning configuration, not coating

4.1. How cleaning variables and fouling level set the force required

Wear on a coating is a function of the force applied to it. Cleaning frequency, brush, contact, and coverage settings are all adjustable for every clean, Fig.3. Cameras and sensors monitor the clean as it happens. These settings are designed to apply the lowest force and abrasiveness needed at the coating surface. Fouling level on the hull matters too, since more fouling generally requires more force to remove. Fouling builds up between cleans, and cleaning frequency is the main lever that controls how much fouling builds up.

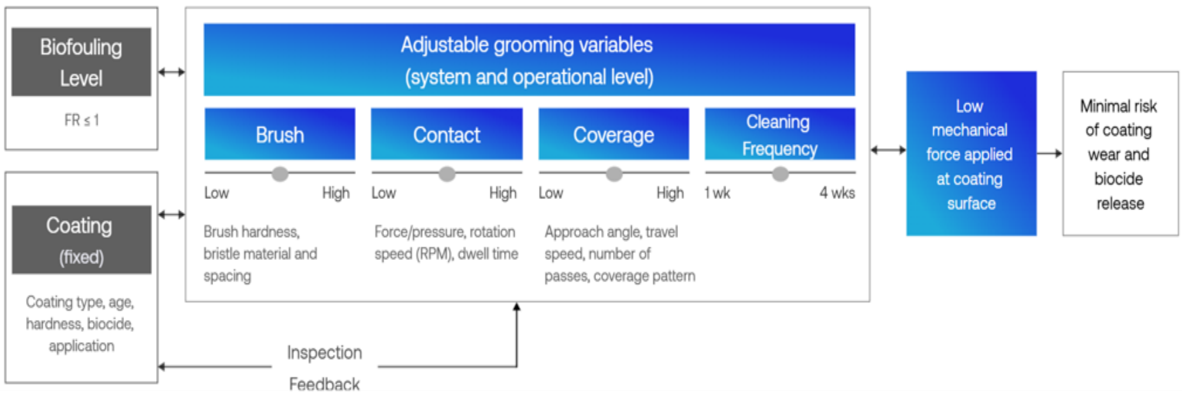


Fig.3: How adjustable cleaning variables and fouling level minimize force at coating surface

4.2. Fouling happens in weeks, not months or years

Without cleaning, slime forms within weeks on every coating category. This is supported by three years of field data and over 2,500 inspections from active vessels. Fig.4 shows a subset of vessels with fouling forming across water temperatures from 4°C to 29°C. These vessels span a range of coatings and are high-activity, regularly groomed vessels.

Fig.5 shows a submerged panel test of freshly painted coupons, tracking fouling formation over different grooming schedules. Four panels are tested, one per cleaning interval: two weeks, four weeks, eight weeks, and never cleaned, as a control. Each panel holds two coupons of each of seven industry leading coatings. This test does not compare which coating performs best. It tests whether a coating can be cleaned at these intervals, at the fouling level each interval produces, without damage. Eight weeks in, no panel shows statistically significant change in dry film thickness readings (DFT). The trial is ongoing. Further results upon completion of milestones in Q4 2026.

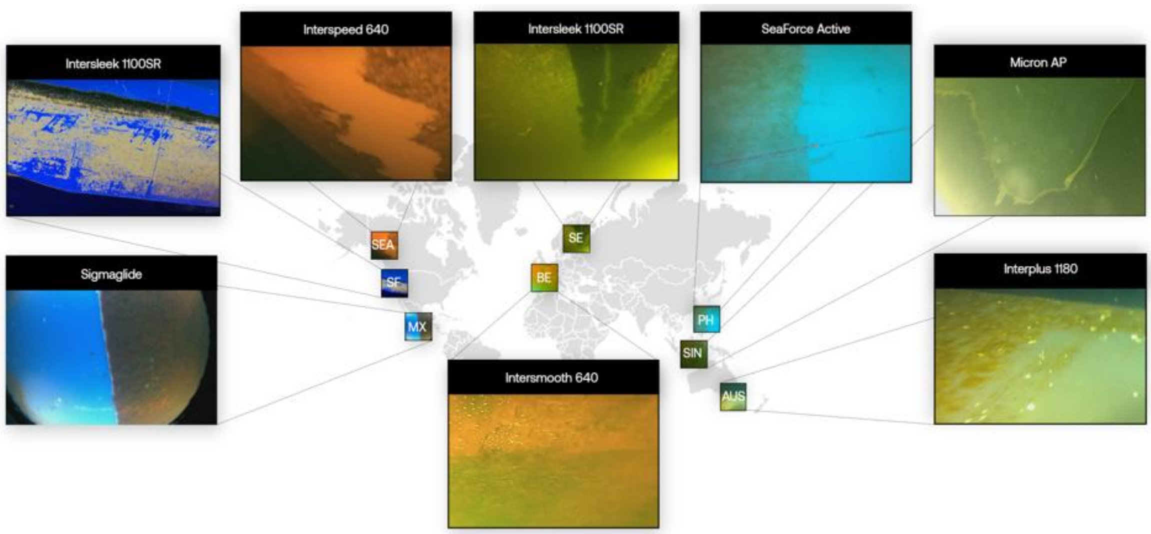
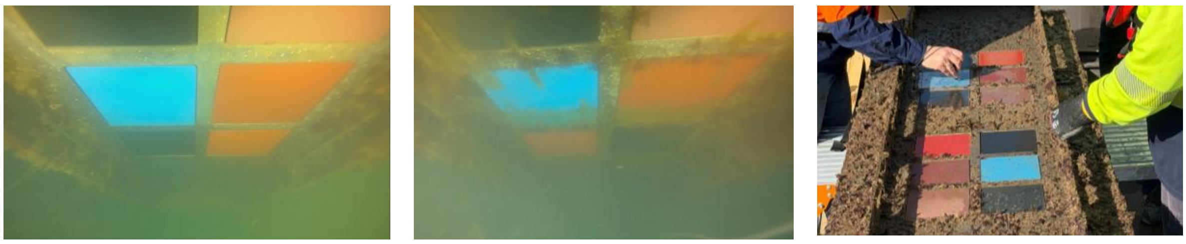


Fig.4: Slime detected on hulls globally on all coating categories



Mid-clean (2wk interval) Mid-clean (8wk interval) DFT measurement in progress

Fig.5: Panel fouling and inspection across grooming intervals

4.3. Frequent cleaning keeps force within range every coating can tolerate

Frequent cleaning keeps fouling from reaching levels that demand aggressive force. A hull cleaned every two weeks ensures only light biofilm is cleaned, not an established shell layer. This has a direct bearing on what regulation should target. A common assumption is that some coatings can tolerate grooming and others cannot. Where fouling is kept light through frequent cleaning, the force needed to remove it stays within the range coating categories are able to handle.

4.4. A wide range of settings is available, including brushes

Compatibility depends on two variables: how much force is applied, addressed in 4.1–4.3, and which brush is selected for a given coating, addressed below. A soft brush at low pressure suits a softer ablative or silicone system, a firmer brush at higher pressure suits a hard coating, Fig.6.

Fig.6: Subset of the 40 brush designs developed, varying in angle and Shore hardness to suit different coating types, increasing range from low abrasiveness to high abrasiveness.

We propose to assess coating damage risk from grooming using a decision matrix based on the vessel's biofouling level and coating type, to which the grooming characteristics can be adapted to minimise the risk, Fig.7. Light biofilm can be removed with a soft brush at low pressure on any coating, hard, FRC, or ablative.

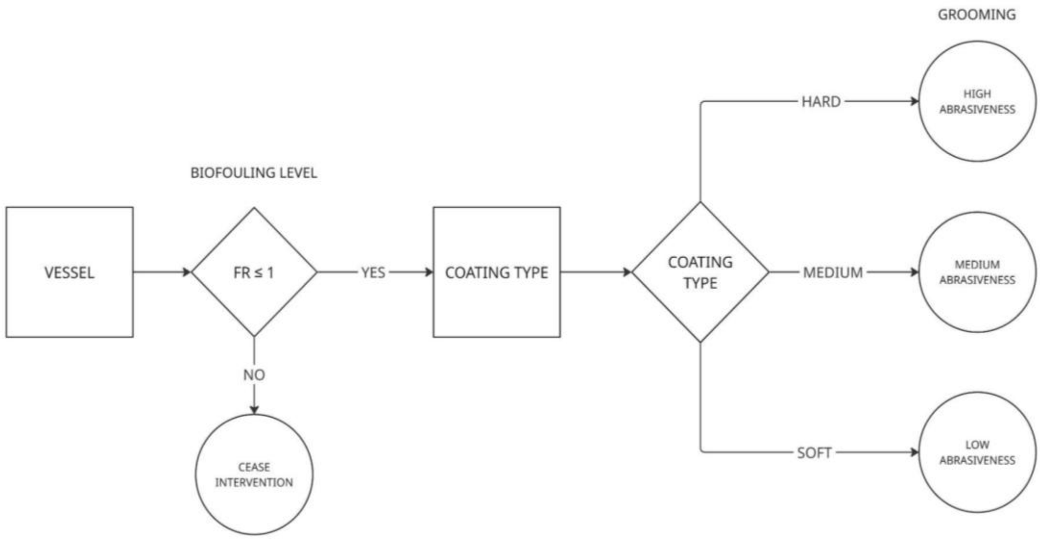


Fig.7: Grooming Abrasiveness Decision Matrix

5. Policy implications: Outcome focussed, not prescriptive

Proactive grooming data from over three years of fleet operations, independent submerged panel testing, and the water quality test together show that adjustable, controllable grooming is a successful way of cleaning across coating categories. The outcome that matters is a clean hull without coating damage or a measurable increase in harmful substances released to the water. This is achievable across coating categories because grooming can be adjusted to keep fouling from ever reaching a level that needs anything more than gentle, non-abrasive cleaning. A framework built around this outcome could accommodate a wide range of successful and environmentally friendly fouling prevention and intervention approaches, across coating categories and future cleaning technologies. A framework prescribing what can be cleaned and how, by contrast, would need constant revision to keep pace with new technology.

Acknowledgement

Thank you to the Defence Science and Technology Group (DSTG), Australia, for project partnership and scientific support, and SGS Marine Services for professional water quality testing.

Improving Antifouling Performance in Vessel Sea Chests Through Controlled Surface Preparation and Application

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Abstract

This paper describes the significance of controlled surface preparation and application in achieving effective fouling control within vessel sea chests, which are semi-enclosed seawater intake structures. Owing to their complex geometry and variable hydrodynamic conditions, sea chests are recognized as high-risk niche areas that present persistent biofouling and biosecurity challenges for ship owners. Surface preparation is identified as a critical factor for coating adhesion and long-term durability, as complex corners and internal features can increase the risk of premature coating failure and expose unprotected surfaces for fouling to settle on. Previous studies have demonstrated that improved surface preparation can enhance the performance of protective coating systems in comparable applications. Accordingly, in-service testing has been initiated to investigate the effect of controlled surface preparation and application on the antifouling performance of operational sea chests, with the objective of generating real-life data to support improved preparation practices as a primary means of enhancing coating performance in this challenging niche area.

1. Introduction

Biofouling remains a persistent operational, environmental and biosecurity challenge for commercial vessels—and an area where improved coating practice can create measurable value. It begins shortly after immersion and may develop as microfouling, such as slime layers, or as macrofouling, including barnacles, tubeworms, mussels, algae and other visible organisms. Beyond increasing hull resistance and fuel consumption, biofouling is recognised as a pathway for the transfer of invasive aquatic species. The International Maritime Organization (IMO) therefore highlights the need for ship-specific biofouling management practices, including the selection, installation, inspection and maintenance of antifouling systems for both hull and niche areas, *IMO (2011,2023)*. Recently, *Georgiades et al. (2026)* referred to the niche areas as the "Trojan seahorse", to describe the risk of spreading invasive species by overlooking the impact of fouling in niche areas. The definition of niche areas is very broad, but the study presented in this paper will focus solely on sea chests.

The need for targeted sea chest management is well documented. Sea chests and associated gratings may retain fouling even when the exposed hull is comparatively clean. In a survey of the passenger ferry Spirit of Tasmania, the submerged hull was largely clean, while sea chests and other sheltered areas contained significant macrofouling and non-indigenous species, *Coutts et al. (2003)*. In a separate investigation of 30 merchant vessels in New Zealand, dry-docking support strips and sea chest gratings generally had among the highest levels of mature fouling and were identified as important locations for biosecurity surveillance, *Coutts et al. (2004)*. These findings underline why sea chests should be treated as priority performance areas rather than secondary sections of the hull. Niche areas are more susceptible to biofouling than the main hull because they combine structural complexity, variable hydrodynamic conditions, reduced accessibility and increased risk of coating damage or incomplete coating coverage. Sea chests are especially demanding because they are semi-enclosed seawater intake structures with internal surfaces, grates, corners, pipes, brackets and areas of locally variable flow. This makes them a particularly relevant probing ground for application quality and coating robustness.

Antifouling performance in sea chests is therefore governed by more than product selection alone. Operational profile, vessel speed, time in port, trading route, water temperature, salinity and maintenance history all influence fouling pressure and the ability of an antifouling coating to perform as intended, *IMO (2011,2023)*. However, local flow conditions inside sea chests may differ substantially from those along the main hull. Areas of low flow may reduce polishing or biocide release, while areas of high local turbulence may increase coating wear. Consequently, sea chests require coating systems and application practices designed for the local niche environment rather than following the specification for the larger areas of the hull and the predicted average sailing speed, *Georgiades et al. (2018)*.

Surface preparation and application quality are central to coating performance. Robust preparation supports coating adhesion and durability by removing residual biofilm, biofouling residues, loose paint and other contamination before coating application. This has also been shown for coated steel surfaces, where pre-treatment error, low dry film thickness, especially edge and weld retention were identified as the most common causes for coating failure by *Knudsen et al. (2023)*. Even though that study focused on corrosion on painted steel structures, the MPI guidance also emphasises that coating service life is influenced by surface preparation and that good application with suitable thickness on all surfaces within sea chests is essential, *Georgiades et al. (2018)*. Experimental studies have further shown that coating durability depends not only on film thickness but also on the quality of the prepared substrate surface. Higher surface roughness generally improves coating adhesion and reduces coating undercutting and degradation during extended exposure, provided that the coating can fully wet the surface, *Roper et al. (2006)*. Similarly, in an extensive review by *Croll (2020)* it was highlighted that surface geometry, wetting and interfacial integrity influence both adhesion and resistance to corrosion creep, and that complex geometries can make it more difficult to form continuous, defect-free coating. Although the surface roughness play an important role it is also imperative to choose a coating with the appropriate features and level of fouling protection for the niche areas.The IMO guidance similarly recommends that sea chest grates and internal surfaces should be protected by antifouling systems suitable for local flow conditions, with particular attention to corners, edges, blowout pipes, holding brackets and grate bars during surface preparation and coating application, *IMO (2011,2023)*.

Despite their importance, sea chest conditions are difficult to document in service. Access may be limited by sea chest geometry, local port restrictions, diver safety considerations, visibility and available inspection time. Diver photographs and videos therefore provide valuable practical evidence of coating condition and fouling development, but they must be interpreted together with vessel operation and environmental exposure. The 2023 IMO guidance recommends risk-based inspections, fouling ratings, reporting of antifouling coating conditions, and documentation of operational deviations such as extended idle time, coating damage or operation outside the specified profile. Fig.1 show examples of sea chests with significant fouling both internally and on the outer gratings.

This study was initiated to assess whether controlled surface preparation and application excellence can deliver improved antifouling performance in operational vessel sea chests. The work is based on real-life in-service exposure on trading vessels, where one sea chest was prepared and coated according to a specified procedure and the corresponding reference sea chest was treated according to normal yard practice. Additional vessels were included to compare selected commercially available products when applied under controlled preparation and application conditions. The objective was to generate practical, field-based evidence on whether improved preparation and ensured integrity of the coating can reduce fouling development in sea chests, while interpreting the results in light of vessel trade, speed, temperature exposure and inspection limitations.

Fig.1: Examples of biofouling inside sea chests and on gratings applied following normal yard application practices and with an antifouling product from the main hull

2. Methodology

The testing presented in this paper was carried out on vessels in service and with the explicit permission of the vessel owners. This real-life approach was selected because it captures the complexity that ultimately determines performance in the field: dry-dock conditions, variation in surface preparation, application workmanship, vessel operation, trade routes, seawater temperature, inspection opportunities and the practical limitations of diver access. While laboratory and test-facility studies offer better control, in-service testing provides evidence under the conditions that matter most to ship operators. The results therefore provide insight into both fouling pressure and the practical antifouling protection delivered by the tested systems.

2.1. Surface treatment and application excellence

For any coating to deliver value, it must be continuous, well adhered and present on the surface it is intended to protect. During dry-docking, time pressure is high and attention is naturally directed toward large planar hull surfaces, propellers and externally visible niche areas. Sea chests, however, combine operational importance with complex geometry and high fouling-management difficulty. They are also difficult and sometimes unsafe to inspect, because divers may need to enter confined structures to collect photographs or videos and, where required, perform cleaning. In some ports, entry into sea chests is not permitted, limiting inspection to the external gratings only. Grating condition can indicate the fouling pressure experienced by the vessel, but it does not necessarily represent the condition inside the sea chest, where local flow and coating access differ substantially from the external hull. To evaluate the potential value of surface preparation and application excellence, specific requirements were defined and implemented during dry-docking of Vessel 1 and Vessel 2. On each vessel, sea chests on one side were prepared and coated according to the specified procedure, while the sea chests on the opposite side were treated according to normal yard practice for reference. Table I shows he test matrix.

Table I: Test matrix. Tests are positioned in both Low Sea Chests (LSCs) and High Sea Chests (HSCs) depending on the vessel configuration. * The exposure duration is reported as of June 2026.

Vessel	Test Description	Portside	Starboard	Expo-sure*
Vessel 1	Application excellence	Test Prod A - LSC	Ref Prod A - HSC	39 mths
Vessel 2	Application excellence	Test Prod A - LSC	Ref Prod A - HSC	39 mths
Vessel 3	Application excellence & product testing	Test prod B - LSC	Test prod C - HSC	26 mths
Vessel 4	Application excellence & product testing	Test prod B - LSC	Test prod C - HSC	15 mths
Vessel 5	Application excellence & product testing	Test prod D - HSC	Test prod C - LSC	9 mths
Vessel 6	Application excellence & product testing	Test Prod C - HSC	Test prod B - HSC	9 mths
		Test Prod A - LSC	Test Prod A - LSC	

2.2. Product evaluation

Once surface preparation and application have been controlled, product properties may also influence performance. To compare selected coating technologies under realistic service conditions, four commercially available Jotun products were included in the in-service study and are referred to as Products A, B, C and D.

For all product comparison vessels, the specified preparation and application procedure was implemented to provide a strong foundation for comparison. Representative photographs of the sea chests and gratings were taken by professional divers from different diving companies and in different locations. In some ports, internal sea chest access was not allowed; in those cases, only external photographs, mainly of the gratings, could be obtained. The testing is ongoing, and not all vessels have yet been inspected.

3. Results and Discussion

The photographic inspections confirm that fouling development varies between sea chests and between vessels, as expected for niche areas exposed to different local flow, temperature, trade and inspection conditions. Within this variability, however, the results reveal a consistent and practically important trend: sea chests prepared according to the specified procedure showed lower visible fouling than comparable areas prepared according to normal yard practice.

3.1. Controlled Surface Preparation and Application - Vessel 1 and 2

The first inspection of Vessel 1, after 22 months in service, provided the clearest paired comparison and is summarized in Fig.2. During this period, the vessel traded frequently in waters of varying temperature and without significant idling. The trade pattern, temperature exposure and speed profile are shown in Fig.3. The vessel spent substantial time in relatively warm waters but also completed long voyages and frequently operated above 10 kn. This combination provides a relevant field setting for evaluating whether improved preparation and application can support coating performance under demanding service conditions.

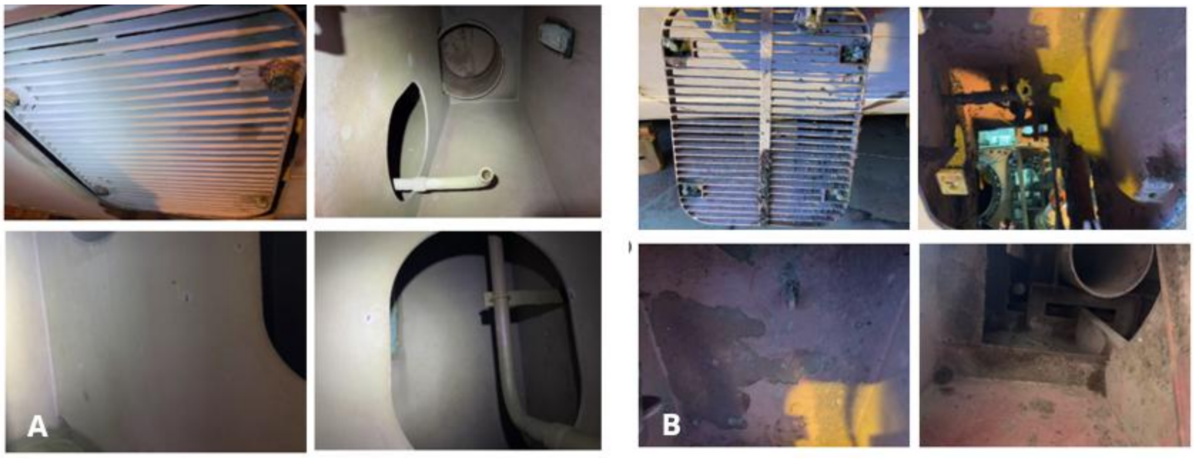

Fig.2: Vessel 1. A) LSC on portside, following specified surface treatment and application excellence procedure. B) HSC on starboard side, following "normal" procedures after 22 months in service.

Fig.2A shows the coating performance inside the sea chest and on the gratings. On Vessel 1, the portside low sea chest prepared according to the specified procedure showed only light slime or microfouling after 22 months, with no visible macrofouling on the grating or inside the sea chest. After approximately 36 months, the same area showed increased slime, Fig.4, but still no significant barnacle fouling. In contrast, the starboard high sea chest prepared according to normal practice showed coating detachment and barnacle fouling at the first inspection, Fig.2B, with barnacle fouling still evident after the longer exposure, Fig.4. Vessel 2 showed the same general trend after 20 months, Fig.6: the portside low sea chest prepared according to the specified procedure appeared cleaner and had less slime than the starboard high sea chest, although the difference in sea chest position and draft height means that the comparison should be interpreted with caution.

The coating detachment shown in Fig.2B is particularly important. Once coating integrity is compromised, exposed or poorly adhered areas can become preferential settlement sites for barnacles and other macrofouling organisms. *Roper et al. (2006)* showed that surface roughness can strongly influence coating performance, and although that study was not conducted in marine environments, it supports the broader link between surface condition and coating durability. The observation is also consistent with *Georgiades et al. (2018),* who found that the service life of antifouling coatings is influenced by surface preparation quality. Residual biofilm, biofouling residues, flaking paint and other contaminations should be removed before the coating application to secure adhesion and durability. The present in-service observations therefore strengthen the practical case for controlled surface preparation and application as a risk-reduction measure in sea chests.

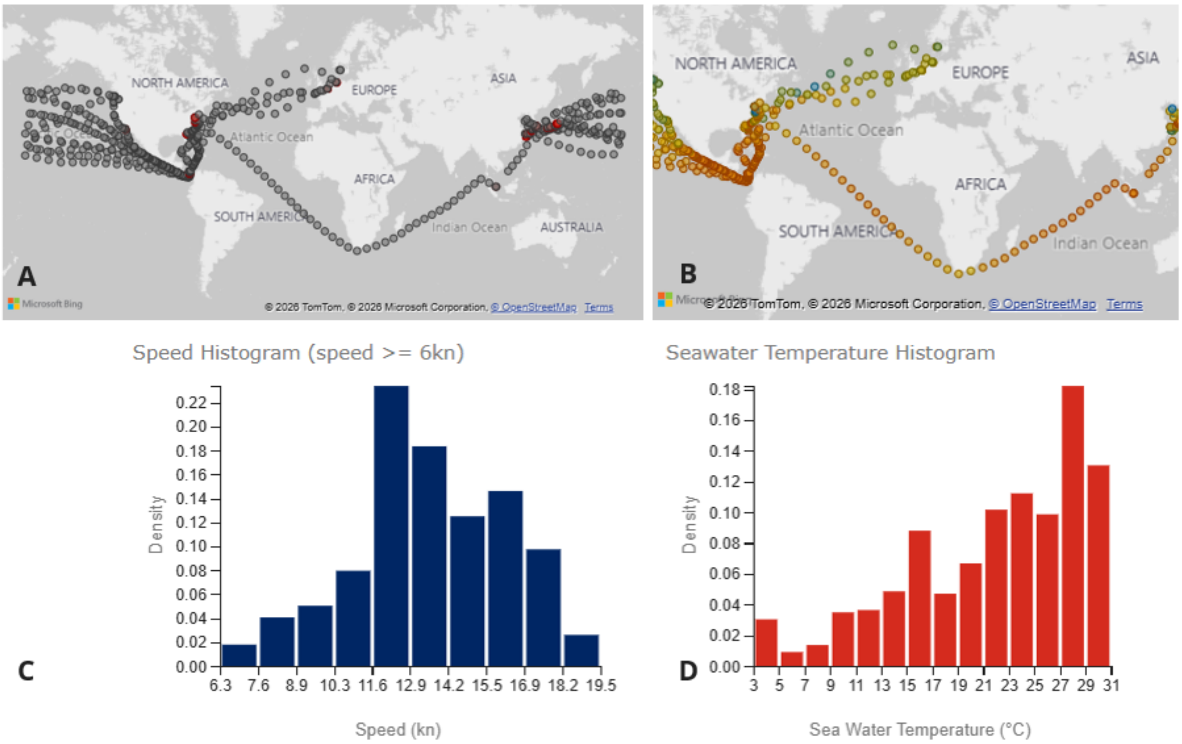

Fig.3; Vessel 1: A) trade, B) temperature patterns, C) speed histogram for speeds > 6 kn and D) seawater temperature between start of exposure and the first inspection, after 22 months in service

The trade and temperature patterns shown in Fig.3 and 7 indicate that Vessels 1 and 2 operated in warm waters, including periods above 25 °C, for a significant amount of time. Warm-water exposure increases biological fouling pressure and can increase the operational sensitivity of internal seawater systems. *Davidson et al. (2023)* showed that internal seawater systems are more likely to become blocked at higher ambient seawater temperatures, the risk increasing above approximately 25 °C. Against this background, the absence of significant macrofouling in the best-practice sea chests is a promising field result.

The speed histograms show that Vessels 1 and 2 often operated in the medium-speed range and did not experience major idling periods during the first inspection intervals. These are generally favourable conditions for the main hull because hydrodynamic forces can help remove weakly attached fouling. However, this effect should not be assumed inside sea chests. Flow inside sea chests is governed by intake demand, grating geometry, suction pipe position and internal obstructions, and may include both high-shear zones and low-flow pockets. *Piola et al. (2022)* demonstrated that sea chest geometry can influence the performance of self-polishing coatings, supporting the interpretation that vessel speed alone cannot explain the low fouling observed in the best-practice sea chests.

Local coating conditions, coverage and adhesion are likely important contributors. *Georgiades et al. (2018)* also emphasizes the importance of suitable film thickness on internal sea chest surfaces, which are more prone to fouling because of variable hydrodynamic forces and incomplete coating coverage. Thus, performance in sea chests depends on the full operating profile, including speed, activity level, temperature, salinity, trading route and regional fouling pressure, *Georgiades et al. (2018), IMO (2023)*.

Fig.4: Vessel 1: A) LSC on portside, applied according to specified surface treatment and application procedure, B) HSC on starboard side, following "normal" procedures, after 36 months in service.

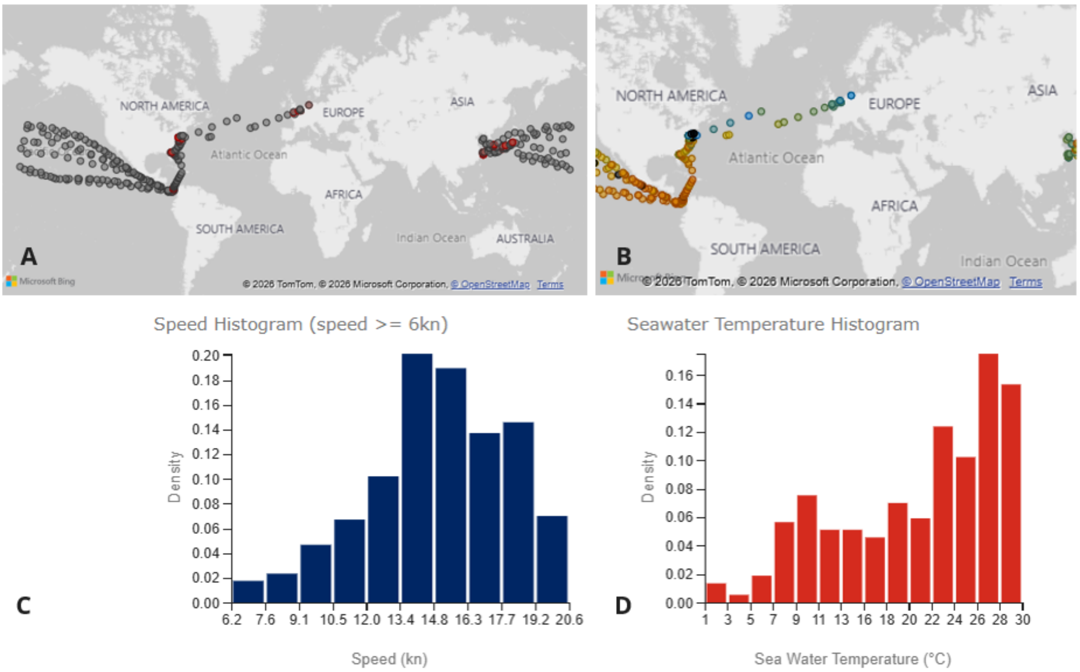

Fig.5: Vessel 1: A) trade, B) temperature patterns, C) speed histogram for speeds > 6 kn and D) seawater temperature between first inspection and second inspection, after 36 months in service

Vessel 2 was prepared according to the same principles and showed the same overall trend during the first inspection, as shown in Figure 6. The low sea chest on the port side, where the specified procedure was used, performed better than the corresponding reference sea chest on the starboard side. Based on the collected photographs, less slime was observed inside the portside sea chest. Because the compared sea chests are positioned at different draft heights on the vessel, variations in light exposure and water flow may impact the results. Nevertheless, the result supports the trend observed on Vessel 1.

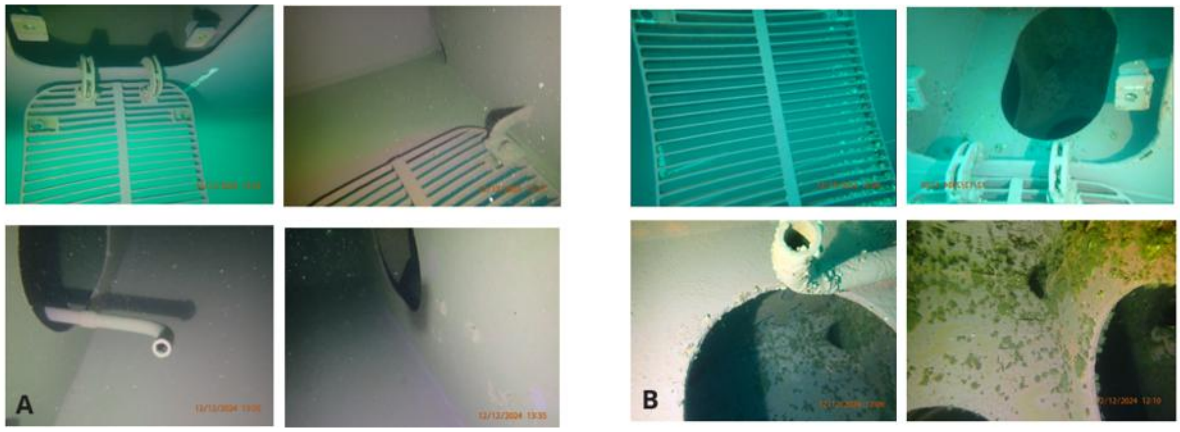

Fig.6: Vessel 2. A) LSC on portside, following specified surface treatment and application excellence procedure. B) HSC on starboard side, following "normal" procedures after 20 months in service

Vessel 2 also followed a worldwide trading pattern between test start and first inspection. The speed and temperature histograms, Fig.7C–D, show frequent operation above 11 kn and repeated exposure to seawater temperatures above 25 °C. These data confirm that the observed low fouling on the best-practice side was obtained under realistic and biologically relevant exposure conditions.

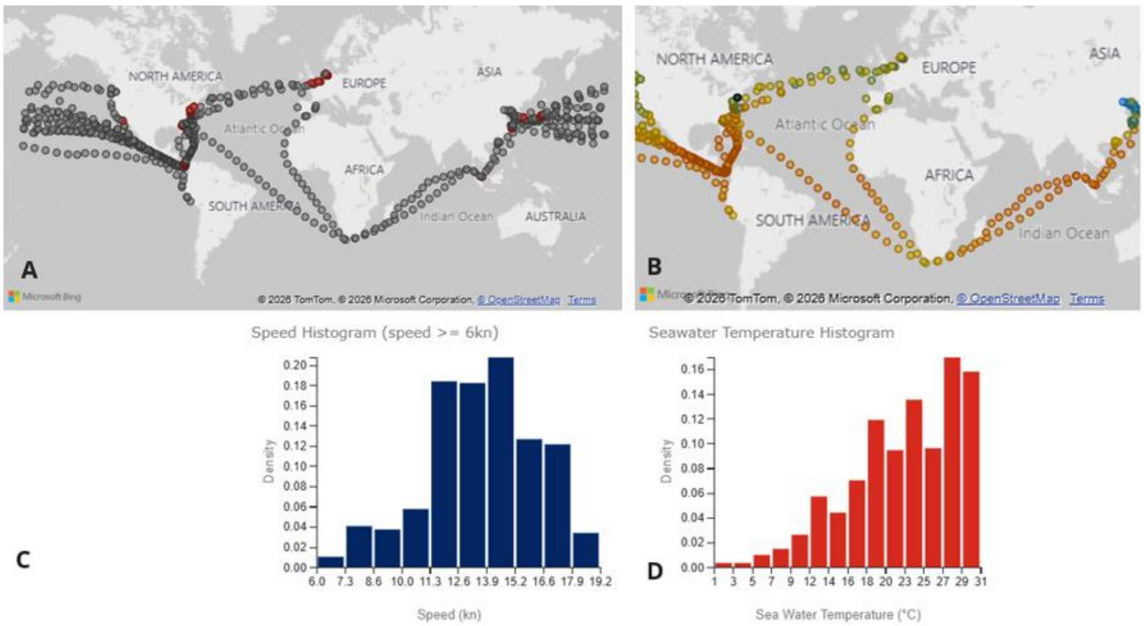

Fig.7: Vessel 2: A) trade, B) temperature patterns, C) speed histogram for speeds > 6 kn and D) seawater temperature, between first inspection and second inspection, after 20 months of in service

The results align with the broader understanding that sea chests are high-risk niche areas where antifouling systems are challenged by complex geometry, variable flow, corners, grates and sheltered internal surfaces. *Coutts et al. (2007)* reported that samples taken from sea chests from 42 vessels contained 150 different organisms and that older antifouling paints and longer in-service periods were associated with a larger number of organisms. In another study by *Coutts et al. (2003)* the hull condition of a passenger ferry called Spirit of Tasmania was inspection. The inspection showed that the exposed hull was mostly clean while sea chests and other sheltered areas contained substantial macrofouling, including mussels, tubeworms, hydroids, barnacles, bryozoans and mobile organisms. This passenger ferry was in regular service, operated at approximately 18 knots and carried an effective SPC antifouling paint. Yet the sea chests still supported biologically significant fouling communities because they were protected from strong laminar flow. *Coutts et al. (2003)* therefore reinforces a key message from the present study: high vessel activity and speed may help maintain the exposed hull, but sea chest performance depends on local coating quality, geometry and flow. Consistent with this, *Roper et al.*

(2006) showed that the substrate surface characteristics have an impact on the durability of the coating. Surfaces exhibiting higher peak-count roughness generally provide stronger adhesion and less degradation of the coating during extended exposure compared to more smooth surfaces. These findings suggest that local variations in coating application and coating integrity may contribute to the reduced antifouling performance often observed in complex, sheltered structures such as sea chests.

3.1. Performance of selected products - Vessel 3 - 6

To investigate whether specific products may offer advantages in sea chest service, four commercially available products were applied in the sea chests of four additional test vessels. Figs.8 and 10 show the performance after 12 and 21 months in service, respectively, for Vessel 3. The low sea chest on the port side was applied with Product B and the high sea chest on the starboard side with Product C. In both sea chests, the specified surface preparation and application procedure was used to ensure that product comparison was not confounded by avoidable preparation deficiencies.

For Vessels 3 and 4, the available inspection evidence is still too limited to rank the products with confidence. The inspections do not provide complete photo coverage of both sea chests and gratings, and the exposure durations differ between vessels. In addition, low and high sea chests may experience different fouling pressure because of draft position and local flow. The product results should therefore be considered preliminary until more inspections have been carried out and additional photographs are available. At this stage, the most robust finding remains the value of controlled surface preparation and application excellence as the foundation for performance.

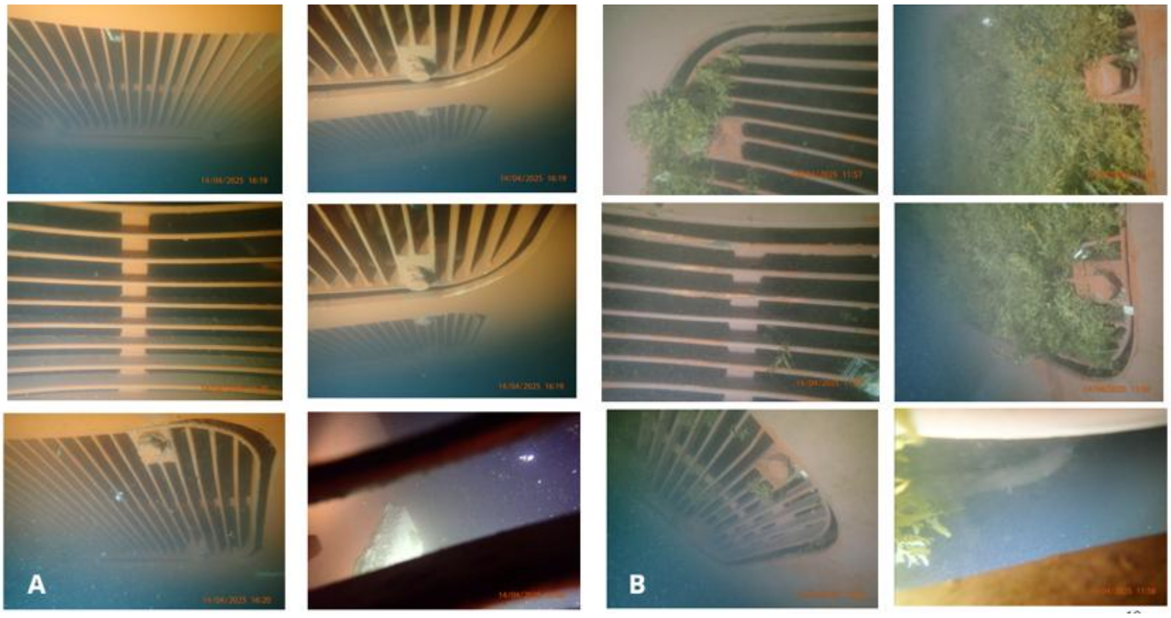

Fig.8: Vessel 3. A) LSC on port side, applied with Product B, and B) HSC on starboard side, applied with Product C, after 12 months in service

Figs.9 and 11 show the trade and temperature patterns and the speed and temperature histograms for Vessel 3 for the two different time periods; from start of exposure to the first inspection, Fig.9, and between the first and the second inspection, Fig.11. The operational profile for Vessel 3 is similar to that of Vessel 1 and 2. Figs.12 and 13 show the corresponding first-inspection results for Vessel 4 after only 6 months in service. The presence of barnacles on the gratings on both port and starboard sides highlights the potential influence of operational parameters and local exposure on coating performance, even at relatively short exposure time. Both the *IMO (2011)* and *IMO (2023*) guidelines state that antifouling systems should be selected for the ship's operating profile and for the specific submerged area. They also recommend tailored antifouling strategies for niche areas rather than assuming that one hull coating approach is optimal everywhere.

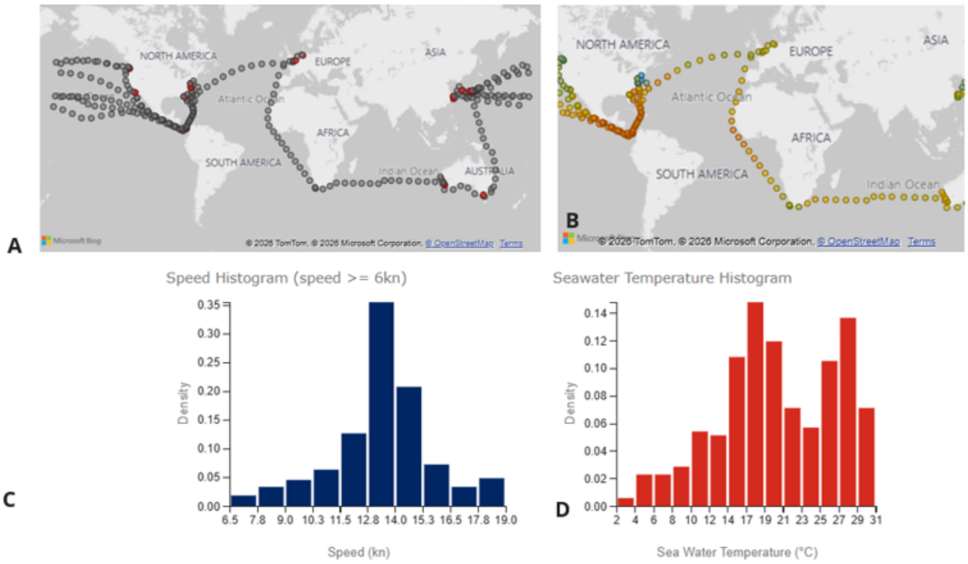

Fig.9: Vessel 3. A) trade and B) temperature patterns, C) speed histogram for speeds > 6 kn and D) seawater temperature between start of exposure and the first inspection, after 12 months in service

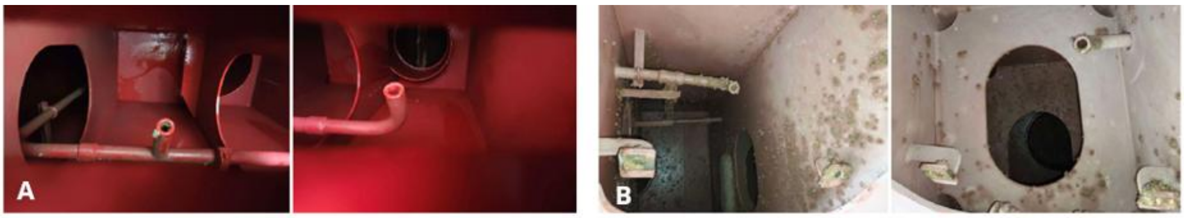

Fig.10: Vessel 3. A) LSC on portside, applied with Product B, and B) HSC on starboard side, applied with Product C, after 21 months in service. Photos of the gratings are not available.

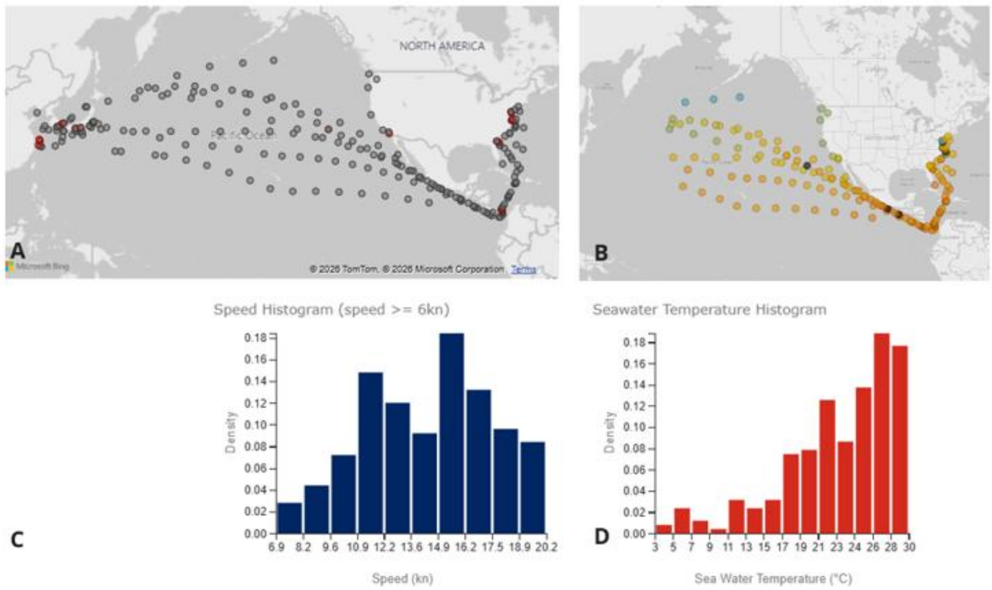

Fig.11: Vessel 3. A) trade, B) temperature patterns, C) speed histogram for speeds > 6 kn and D) seawater temperature between first and second inspection, after 21 months in service

The regulatory documents also highlight the importance of inspection and documentation when interpreting in-service performance. The *IMO (2023)* revision recommends risk-based monitoring, inspection intervals, fouling ratings, antifouling coating condition reporting, MGPS condition reporting and documentation of contingency actions. Going forward, more detailed documentation of niche areas such as sea chests can strengthen Biofouling Management Plans and support more informed maintenance decisions.

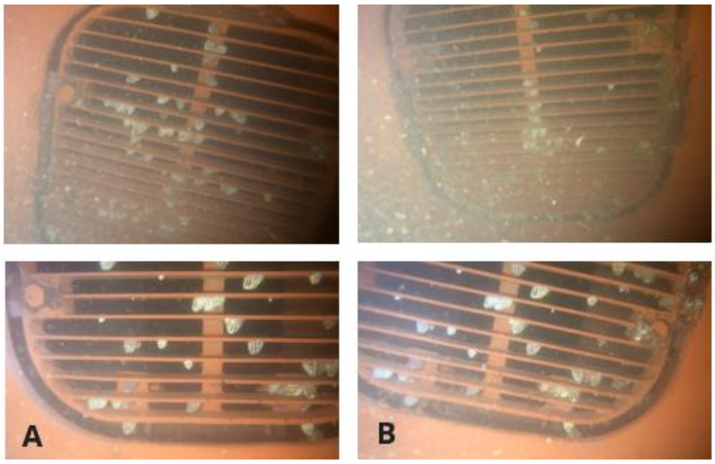

Fig.12: Vessel 4. A) LSC on portside, applied with Product B, and B) HSC on starboard side, applied with Product C, after 6 months in service. No photos of portside or from inside are available.

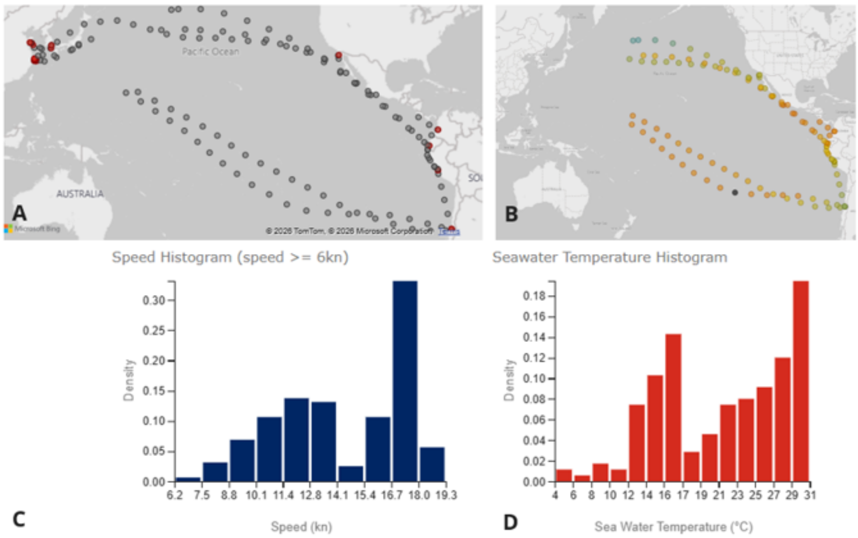

Fig.13: Vessel 4. A) trade and B) temperature patterns, C) speed histogram for speeds > 6 kn and D) seawater temperature between first and second inspection, after 6 months in service

The results from this study also have operational and biosecurity relevance. *Davidson et al. (2021)* reviewed how biofouling in internal seawater systems can restrict flow, reduce heat transfer, contribute to corrosion and the spread of invasive species. *Growcott et al. (2017)* concluded that sea chests and internal pipework remain difficult to manage preventively and that reactive systems may be needed in addition. Preventing fouling establishment through improved surface preparation and coating application is therefore a highly attractive first line of defense that may reduce the need for, or extend the time before, reactive treatment is required.

4. Conclusions

The in-service results show that controlled surface preparation and application excellence can improve antifouling performance in vessel sea chests under demanding operating conditions. The trade, temperature and speed data indicate that the low fouling observed in the best-practice sea chests cannot simply be attributed to favourable exposure. The vessels operated in conditions where fouling could reasonably occur, and the absence of significant macrofouling in the best-practice sea chests indicates that the specified preparation and application procedure contributed to coating performance. A clear difference between microfouling and macrofouling was observed. Sea chests prepared according to the specified procedure generally showed light slime or microfouling, while the normally prepared sea chest on Vessel 1 showed visible barnacle fouling and coating detachment. The product-comparison results from Vessels 3–6 remain preliminary because the available inspections cover different exposure durations, sea chest positions and incomplete photo documentation. The present dataset therefore does not allow ranking of Products A–D.

The results strongly indicate that sea chests should be assessed independently from the main hull. Vessel speed and general hull activity may support coating performance on exposed hull areas, but the photographs and analysis show that sea chest geometry, local flow, coating coverage and surface conditions strongly affect fouling development inside these structures. Grating condition can provide useful evidence of fouling pressure, but it should not be used as the only indicator of internal sea chest condition when internal inspection photographs are unavailable.

Overall, this field study supports the hypothesis that surface preparation, coating adhesion, application quality and documented inspection quality are critical prerequisites for successful fouling control in sea chests. The early in-service results indicate that controlled preparation can reduce macrofouling risk, even in warm-water and global-trading service. Continued inspections are required to confirm long-term performance, clarify any product-related differences and determine whether the observed performance advantages persist over the full intended service period.

Acknowledgement

We would like to thank the participating vessel owners, technical managers, dry-dock teams, applicators, divers and colleagues who enabled the in-service testing and inspection work. Their cooperation made it possible to collect practical field evidence from challenging operational sea chest environments.

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Developing Non-Biocidal and Microplastic-Reduced Self-Polishing and Cleanable Hard Coatings (BioSHIP) – Initial Results of Laboratory and Field Testing

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Abstract

The BioSHIP project focuses on developing two different antifouling coating systems: Self-polishing marine coatings (SPCs) and cleanable hard coatings – both with a minimised release of biocides and microplastics. The aim is a more sustainable way to keep ships free of fouling and ensure they remain fully operational. In view of increasing restrictions on the use of biocides in marine coatings, as well as limited options for cleaning ships affected by biofouling, there is a clear need for a solution that reduces the environmental and climate impact of antifouling systems.

1. Introduction

Biofouling on ship hulls has been a concern for many centuries for a variety of reasons, including reduced manoeuvrability, the invasion of new species, and increased fuel consumption. Furthermore, more greenhouse gases are released into the atmosphere.

Usually biocides are used to prevent biofouling. Over the years, the entry into force of the Biocidal Products Regulation (EU) No 528/2012 has led to the banning of numerous legacy biocides. Even the biocides that are currently still authorised cause damage to the marine environment, and not just to the target organisms on the ship's hull. Further bans in the future cannot be ruled out. For this reason, research into non-biocidal alternatives is ongoing. Foul-release coatings, self-polishing coatings or cleanable hard coatings are the focus here.

In addition to reducing the release of biocides, efforts are also being made to reduce or prevent the release of microplastics into the marine environment. The BioSHIP project was launched to develop self-polishing and self-cleaning hard coatings that pose little or no ecotoxicological risk to marine organisms, are more biodegradable, and can be broken down by organisms in the environment without remaining in the sea or accumulating there.

2. Methods

Dr. Brill + Partner GmbH (DBP) has been conducting performance tests on coatings developed by Momentive Performance Materials GmbH and Fraunhofer IFAM, in different salinity levels and climate zones during the summers of 2025–2027 in both hemispheres. The large number of test sites will provide valuable insights into differences in coating effectiveness and durability under various conditions. In addition, dry and wet Taber tests and elution tests using the Mini RotoMarin are being conducted at DBP and are sent to Hydrotox GmbH for further biodegradability and ecotoxicity analysis.

2.1. Field tests

Field tests are carried out in various locations in both hemispheres, Fig.1, mostly in the North Sea, near Norderney and Helgoland. The location for testing in freshwater is Grohn, near Bremen, on the Lesum. The remaining test sites are in the Mediterranean (Hyères/Port du Niel, France), the Red Sea (Eilat, Israel) and the Tasman Sea (Tauranga, New Zealand). All test sites except Helgoland are covered by DBP. The test panels off Helgoland are tested and analysed by IFAM. The season starts in April and ends around October, except in Israel and New Zealand. So far, one full season of testing has been completed.

The test panels are exposed statically and dynamically in the harbour at Norderney in sizes of 10x10 cm, 20x20 cm, and in the form of discs fitting onto the RotoMarin®. In Grohn and Hyères/Port du Niel, the static test panels are 20 x 20 cm and in Israel and New Zealand they are 10 x 10 cm. The test coatings are applied to PVC panels. In addition, an initial screening of the effectiveness of the coatings against barnacle settlement is carried out using a rapid test at the beginning of the season, in April and May, on coated PVC microscope slides.

Photo documentation and the ASTM D6990-20 'Standard Practice for Evaluating Biofouling Resistance and Physical Performance of Marine Coating Systems' are used to analyse the test panels, which are then shared with the project partners to aid the development of new coatings.

Each set of test panels is exposed alongside two biocidal, commercial, self-polishing reference panels (excluding Israel and New Zealand), one non-biocidal, commercial, hard coating, and one negative reference: an uncoated PVC panel. Due to strict regulations in both countries, only non-biocidal coatings can be tested in Israel and New Zealand. Therefore, no biocidal commercial positive reference can be used in these locations.

On Norderney and Helgoland, the inspections for the statically exposed test panels are done monthly, the dynamic test on Norderney and the exposed test panels at the remaining testing sites, are inspected every two months.

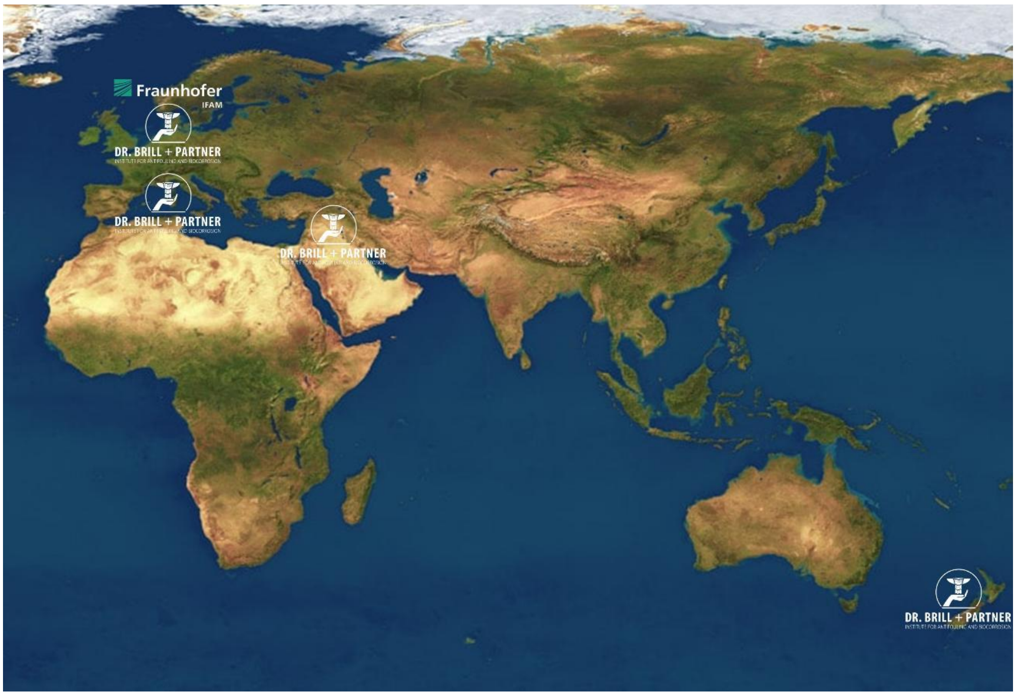

Fig.1: DBPs test locations in Norderney, Grohn at the Lesum, the Mediterranean Sea, the Red Sea, and the Tasman Sea in the northern and southern hemisphere and IFAMs exposure site in Helgoland

2.1.1. Rapid test on barnacle settlement

The rapid test on barnacle settlement was developed by DBP to provide an initial screening of the effectiveness of newly developed coatings. Three replicates of each coating are exposed in different orientations in the intertidal zone of Norderney harbour, alongside three uncoated PVC negative references, Fig.2. During high tide, the panels are underwater; during low tide, they fall dry for a few hours. Barnacles mainly settle onto hard structures in these areas. The test coatings remain in place until the negative references are covered by at least 500 barnacle larvae. The results are then analysed and evaluated using ImageJ and CellCounter and visualised in a graph created in Excel. Due to the number of test panels, BioSHIPs test panels were exposed in two deployments. This year’s first deployment took place from 24 April to 21 May 2026, and the second from 27 May to 2 June 2026. The difference in exposure time is due to the late settlement of barnacle larvae during the first deployment.

Fig.2: Testing location for rapid test on barnacle settlement

2.1.2. Cleanable hard coatings

DBP has developed a testing station for the cleanability of hard coatings on Norderney. Since 17 April 2026, the coatings developed by MPM and IFAM have been statically exposed on 20x20 cm test panels in the harbour of Norderney. Every four weeks, one half of each test panel is cleaned for five seconds using an extra-soft white brush connected to an underwater screwdriver, Fig.3, while the other half is cleaned only every eight weeks. Inspections are carried out every four weeks on both panel halves separately. A set of replicate panels has also been exposed to ensure comparability of the effects of regular 'proactive' cleaning and no cleaning activities. At the end of the season, the replicate test panels are cleaned with a harder brush to simulate 'reactive' cleaning after six months of static exposure.

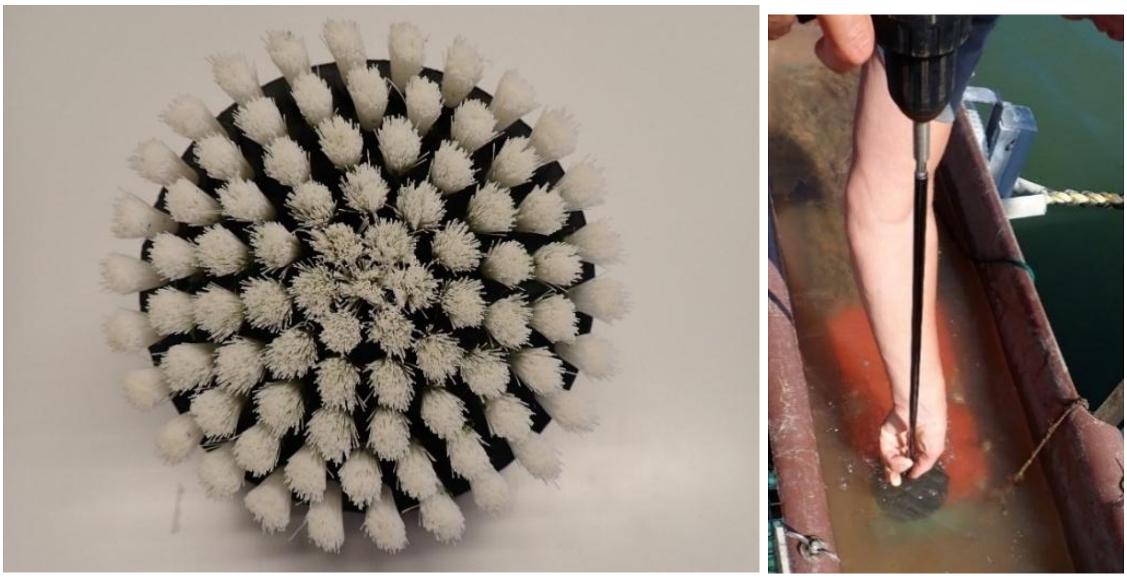

Fig.3: Cleaning of test coating with extra soft white brush (left) connected to a screwdriver underwater (right)

2.1.3. Dynamic field tests on Dr Brill's RotoMarin® test rig

Another field test used to determine the effectiveness of coatings is the dynamic test on Dr Brill's RotoMarin® test rig, *Daehne et al. (2016,2018)*. The coated test panels are screwed onto a disc-shaped structure, Fig.4, which rotates at different speeds throughout the day, reaching a maximum speed of 14.2 kn. As the plates run on the disc, the speed varies from the innermost to the outermost area of the test panel, providing more insight into the speed at which a coating becomes effective. The inner part of the panels runs at speeds ranging from 1.2 to 8.0 kn, while the outer part runs at speeds ranging from 8.0 to 14.2 kn. The RotoMarin® operates during the day and is idle at night, simulating the navigation profile of a coastal-operating vessel. ASTM D4939-89 (reapproved 2020) is followed for deployment, ASTM D6990-20 for evaluation, and pictures are taken and edited, and graphs are created in Excel for visualisation. The test panels were exposed on 8 May 2026 and are inspected every two months.

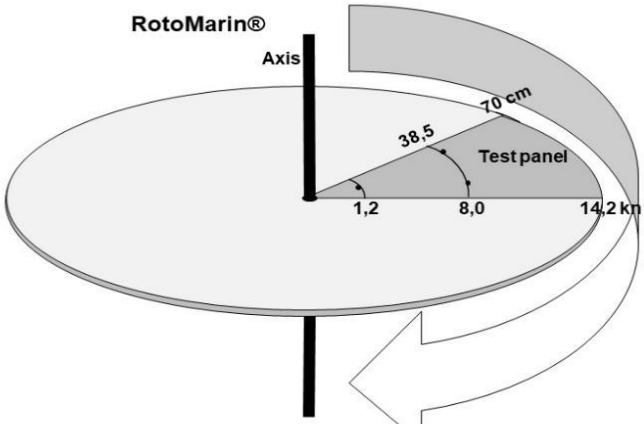

Fig.4: Dr Brill's RotoMarin® test rig

2.2. Ecotoxicology and Biodegradability tests

Ecotoxicological and biodegradability tests are carried out in close collaboration between DBP and Hydrotox. DBP prepares elution tests inside the Mini RotoMarin and Taber wet and dry tests for biodegradability testing and then forwards the probes to Hydrotox for ecotoxicity and biodegradability analysis. The Mini RotoMarin, Fig.5, was developed by DBP in a previous research project (Haptocheck, No. KK5193801KS0). It is a smaller version of the RotoMarin® field test rig and functions similarly. For this test, the Mini RotoMarin was set to run continuously at 400 rpm and 6.2 m/s for 64 days. One coating was tested per setup, enabling two coatings to be tested simultaneously. Expanded PVC sheets were used to cover each aquarium to prevent dust or other external factors from influencing the results.

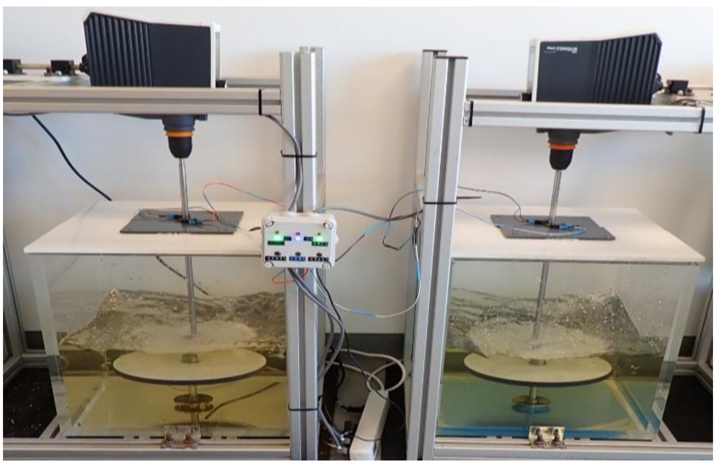

Fig.5: Mini RotoMarin test rig running inside Dr Brill's laboratory

The design of the Mini RotoMarin elution test is based on the Blue Angel DE-UZ 221 award criteria for "Underwater coatings and other antifouling systems", *Daehne et al. (2023)*. The eluates are obtained via Mini RotoMarin extraction from the coatings. Samples are taken at two time points: the first after 24 hours, and the second after 64 days. The testing is carried out using luminescent bacteria, algae, Daphnia, fish eggs and Umu tests, together with the eluates of the coatings to be tested, Table I.

Table I: Test species and criteria for elution tests on ecotoxicity

Test species	Test standard	End point	Criterion
Luminescent bacteria(*Vibrio fischeri*)	EN ISO 11348-1	Luminescent	GL ≤ 8
Algae *(Raphidocelis subcapitata or Desmodesmus subspicatus*)	EN ISO 8692	Growth	GA ≤ 4
Crustacean (*Daphnia magna*)	EN ISO 6341	Mobility	GD ≤ 4
umu-Test (*Salmonella typhimu-rium TA 1535/pSK1002*)	ISO 13829	Mutagenic potential	GEU ≤ 1,5

Biodegradability tests are carried out at Hydrotox in accordance with the Manometric Respirometer Test (OECD 301 F). To do this, a sufficient quantity of particles from the coating must be provided for testing. In order to test a substance's biodegradability in water, the substance is added to the water as the sole source of carbon. Microorganisms degrade the substance and consume the oxygen, which is measured. CO_2 is absorbed by NaOH and sequestered, enabling precise O_2 balance via measurement of pressure decrease. The test is carried out in closed bottles for a standard duration of 28 days, though this can be extended to 60 days. The evaluation measures how much oxygen was required in 28 (or up to 60) days. If more than 60% of the theoretical oxygen requirement is used within 28 days, the substance is considered 'readily biodegradable'. Less than 60% indicates that the substance is not completely degradable. As a control, a blank probe without a test substance is used, and sodium acetate is used as a positive control as it is easily degradable.

The final test carried out on the developed coatings by MPM and IFAM is the Taber abrasion test, *Daehne et al. (2025)*. This test determines the resistance of the developed coatings. As distinct differences in resistance were found under dry and wet conditions in the Taber Abraser, the coatings were tested under both conditions. The coatings were applied to two steel plates measuring 9.8 mm x 9.8 mm x 1 mm with a centre hole. The wet and dry tests correspond to the standard Taber abrasion test (ASTM D 4060), except that under wet conditions, grinding dust is not vacuumed off; instead, the test plates are covered in water. For the test, CS-17 abrasive wheels were used together with a 1000 g weight for 1000 cycles. The abrasive wheels were reconditioned with P150 sandpaper for 50 cycles after 500 cycles. For the dry tests and reconditioning of the abrasive wheels, the vacuum was set to 100% power.

3. Results

Considering they are non-biocidal coatings, the first exposure season (2025–26) produced promising results. Dynamic field tests using Dr Brill's RotoMarin® test bench, Daehne et al. (2016,2018), and static cleaning tests demonstrated the effectiveness and durability of the developed coatings. Static exposure in conjunction with proactive cleaning using a soft brush on a monthly or bimonthly basis produced particularly promising results in some cases.

3.1. Field tests

All test coatings have been exposed in time around April or May at this 2026 season at almost all DBP test sites. The test panels in the Red Sea in Israel and the Tasman Sea in New Zealand will be exposed by September 2026.

3.1.1. Rapid test on barnacle settlement

The rapid test on barnacle settlement showed promising results, indicating that all test coatings had less barnacle larvae coverage than the negative reference (NR PVC) by the end of the screening period, Fig.6. The test panels 2006, 2007 and 2009 had the best overall results, with an average of 177, 231 and 359 barnacles per slide, respectively.

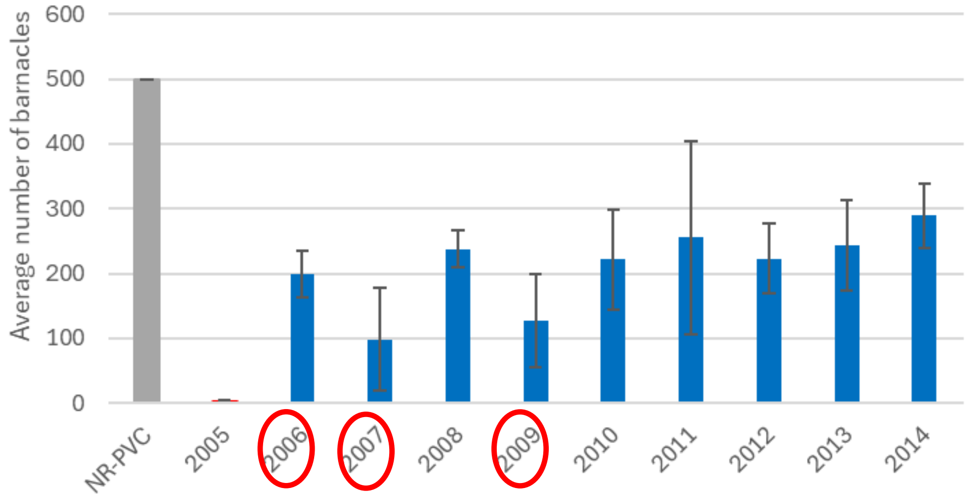

Fig.6: Results of this year's second deployment rapid test on barnacle settlement. On this graph, the NR PVC was downscaled to 500 barnacles/slide for better readability, and the test panels were downscaled accordingly. Test panel 2005 is one of the biocidal self-polishing commercial positive references.

3.1.2. Cleanable hard coatings

Even the 20x20 cm test panels that are regularly 'proactively' cleaned are already showing promising results in some cases. As the fouling pressure is particularly high in the North Sea, many test panels show signs of macrofouling after just a few days.

The main fouling organisms that settle on the panels are barnacles and algae. These can be easily cleaned off the panels when the barnacles have not grown too large and the algae filaments are not too long to get caught in the brush. Some of the coatings, such as the one on the far right in Fig.7, received a perfect Fouling Rating after cleaning, as all organisms could be removed by the brush on both sides of the test panel. This coating exhibits antifouling properties and produces good results in static exposure tests. The fourth panel from the left cannot be inspected anymore as the topcoat was lost during the first cleaning interval.

Fig.7: Some of the 20x20 cm test panels at the fourth inspection on 04th August 2026 after 109 days of exposure. that are cleaned in a 4- and 8-weekly cleaning cycle per panel half. The test panel on the left is one of the biocidal self-polishing commercial positive references. The upper picture is before cleaning; the lower picture is after cleaning with an extra soft white brush for five seconds/panel half.

3.1.3. Dynamic field tests on Dr Brill's RotoMarin® test rig

The first inspection of the test panels was carried out after 46 days of exposure, Fig.8. Coating 1786-6 had lost its topcoat entirely and could therefore no longer be inspected. The remaining test panels were covered in various fouling organisms, resulting in similar fouling ratings. The inner part of the panels, which moved more slowly, was more heavily fouled than the outside. Both the inner and outer parts of the panels were predominantly covered by hydroids. Encrusting bryozoans were only the dominant fouling organisms on the outer part of panels LBS18-6 and LBS19-6.

Test panel 1784-6 had the best Fouling Rating of 80 on the inside, while 1787-6 had the best Fouling Rating of 98 on the outside.

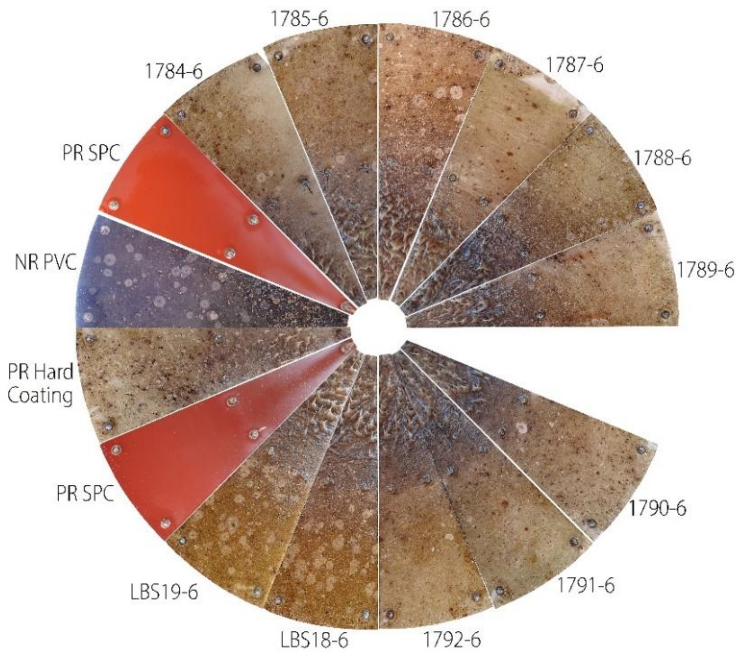

Fig.8: Dynamic test patches and their positive/negative reference(s) at first inspection after 46 days of exposure

3.2. Ecotoxicology and Biodegradability tests

The eluates of the Mini RotoMarin were analysed at Hydrotox, showing that one coating had no ecotoxicological effect on any of the tested organisms, Table II. Some of the coatings tested were toxic to algae and/or daphnia, though the remainder showed no toxic effects. Further tests will be conducted to determine which component of the coating resulted in the toxic effect on the organisms.

Biodegradability tests were conducted using particles sent directly from MPM and IFAM to Hydrotox. One substance was found to be readily biodegradable by 60.4% after 28 days. Another substance tested achieved a degradation rate of 43.8% after 28 days.

Table II: Preliminary results of the ecotoxicity testing of the first four coatings. Samples were taken after 24 hours and after 64 days.

Description	Algae LID_A	Daphnia LID_D 48 h	Fish egg LID_{Ei} 48 h	Luminescent bacteria LID_{lb}	Umu LID_{EU}	Conductivity (µS/cm) mean	pH mean
Eluate LBS 8- 24h	≤ 2	≤ 3	≤ 3	≤ 4	≤1.5	13.7	6.8
Eluate LBS 11- 24h	= 4	≤ 3	≤ 3	≤ 4	≤1.5	21.7	6.7
Eluate LBS 8- 64d	≤ 2	≤ 3	≤ 3	≤ 4	≤1.5	30.5	6.9
Eluate LBS 11- 64d	≤ 2	≤ 3	≤ 3	≤ 4	≤1.5	66.8	6.8
Eluate 2002- 24h	> 6	= 6	≤ 3	≤ 4	≤1.5	415.8	8.3
Eluate 2003- 24h	≤ 2	= 4	≤ 3	≤ 4	≤1.5	419.3	8.5

Lastly, the Taber Abraser test produced interesting results regarding the abrasion resistance of the test coatings when dry and wet tests were compared, Fig.9. Coatings 1686 and 1689 achieved the best results with abrasion in µm/1000 cycles of -34.36 µm and -44.73 µm, respectively, during the wet tests. Even the positive reference of the commercial hard coating had stronger abrasion during the dry and wet tests, at -31.36 µm and -67.03 µm, respectively.

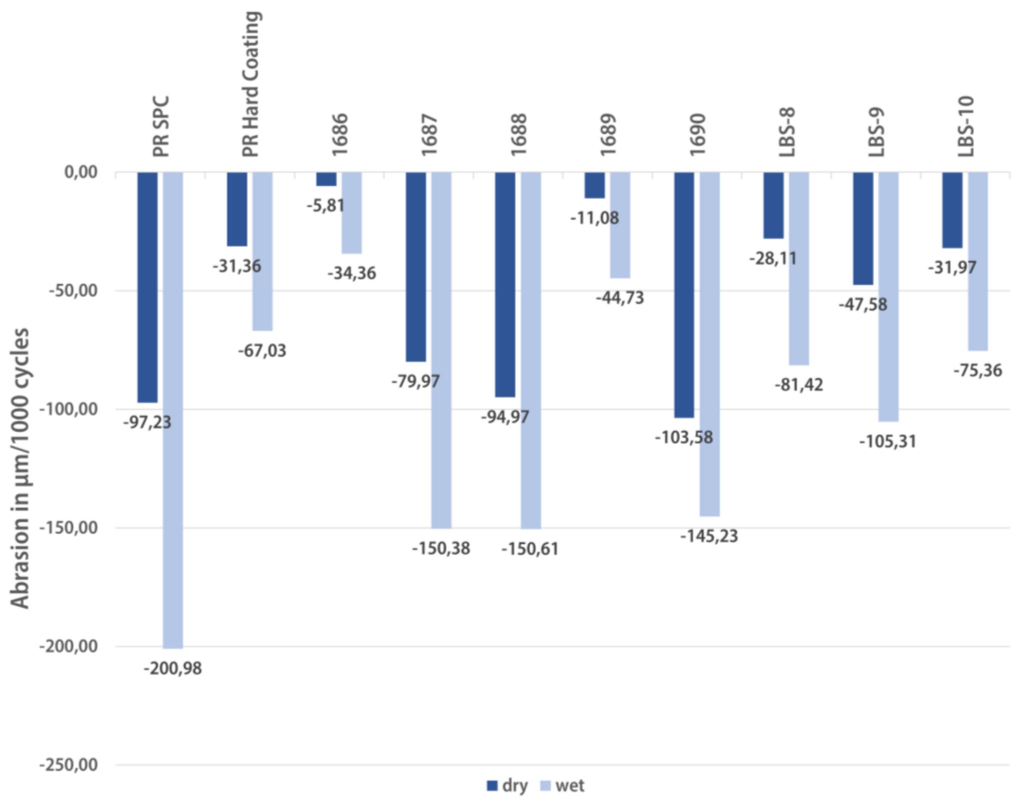

Fig.9: Results of the Taber Abraser dry and wet tests. The dark blue shows the dry abrasion in µm/1000 cycles, the light blue shows the wet abrasion of each test coating.

4. Discussion

Conducting exposure tests of the same coatings in various locations around the world provides a better insight into the effectiveness of each coating. This is because every location has different external factors influencing the coating and the activity of organisms at the site. In some locations, the fouling pressure is much higher than in others, even though the conditions are better, such as warmer waters. As the fouling pressure is highest in the North Sea, many coatings are unable to withstand the strong pressure exerted by sessile marine organisms. However, in locations such as the Red Sea in Israel, or freshwater in Grohn at the Lesum, the coatings perform much better. Therefore, it is crucial for the paint and additive developers MPM and IFAM to get a broader image of the antifouling properties each coating exhibits.

In addition, the initial screening of the effectiveness of the antifouling properties against barnacle larvae during the rapid test on barnacle settlement at the beginning of the season in Norderney provides an initial indication of the areas to focus on in terms of paint development. The results of this year's first screening have been much better than the negative references and therefore the developed coatings definitely exhibit antifouling properties. The next step is to focus on the effectiveness of each coating over a longer period of time, as sometimes the effectiveness diminishes after a short period due to the complete leaching of the antifouling properties from the coating into the marine environment.

In terms of cleaning, many of the coatings demonstrate good abrasion resistance, with minimal damage evident after brush cleaning with an extra-soft brush. Comparing proactive cleaning at two different time points with reactive cleaning of an uncleaned replica over the same exposure time will clarify the cleaning interval required for each coating. Some of the coatings, such as 1686, could not be cleaned; even the slightest force removed the entire topcoat, making the entire test panel uninspectable. 1787, on the other hand, has similar antifouling properties to 1686 in static conditions; nevertheless, it is more stable and can withstand the pressure of soft brush cleaning. The optimal cleaning frequency must be determined to ensure the coatings perform at their best. As fouling pressure is high in the North Sea around Norderney, cleaning more frequently at first can create space for other sessile organisms, which reduce the fouling rating more than cleaning less frequently would. However, allowing barnacles to grow to a size of around 4–6 mm usually means that they cannot be cleaned off with a brush, but require high-pressure water or stronger cleaning equipment. More frequent cleaning does not always result in cleaner coatings.

In the dynamic test setup, it was observed that the coatings did not yet have sufficient antifouling properties to remain free from fouling throughout the operation of a coastal vessel. At lower speeds of 1.2 to 8.0 kn at the inner part of the panels in particular, the coatings were covered in various species of macrofouling and could not withstand the intense fouling pressure. On the outer part of the panels, where the disc runs at speeds from 8.0 to 14.2 kn, the coatings were fouled less, with 1787 achieving very good results again. However, on the inside, the fouling rating was close to zero. Test panel 1784 achieved better fouling ratings on both the inner and outer parts of the panel, though this may be due to the neighbouring biocidal panel, which can affect the settlement of marine organisms in its vicinity. The reason the test coatings are not functioning well within the dynamic test setup could be due to the fast leaching of antifouling properties, accelerated by the speed of the RotoMarin®, resulting in reduced effectiveness after short exposure.

Some of the tested coatings and substances already show promising results in terms of low ecotoxicological risk to various tested organisms, with one substance being readily biodegradable after 28 days. The abrasion resistance tested using the Taber Abraser also shows promising results for the hard coatings designed for this purpose. For example, abrasion was lowest for coatings 1686 and 1689, which performed far better than the commercially available hard coating used as a positive reference under dry, as well as wet conditions. This suggests that fewer microplastics could end up in the marine environment if abrasion scenarios occurred, as the coatings can withstand strong pressures.

5. Summary

The BioSHIP project is working to develop more sustainable, self-polishing, as well as cleanable hard coatings that pose little to no ecotoxicological risk and release fewer persistent microplastics. These coatings must also possess effective antifouling properties and be biodegradable. These formulations are developed in line with industry standards and application conditions. New biodegradable components are identified, adapted and, where necessary, integrated into the coating matrices. The coatings are tested worldwide under realistic static and dynamic conditions to assess their antifouling performance, the effects of cleaning, and their biodegradability and ecotoxicity. The results of these tests inform the further development of the coatings. The results of studies into the biodegradability and ecotoxicity of additives and polymers are to be supplemented by a systematic database and literature search.

The results of the second exposure season are promising, indicating progress towards a highly biodegradable, antifouling coating with minimal ecotoxicological risk.

Acknowledgement

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Biofouling Regrowth Following In-Water Cleaning: Influence of Cleaning Conditions on Recolonization Dynamics

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Abstract

In-water cleaning is increasingly applied to maintain vessel performance and reduce the environmental impacts associated with marine biofouling. While cleaning efficiency has been widely investigated, considerably less attention has been given to the regrowth of fouling following cleaning. In the present study, biofouling regrowth was evaluated under controlled laboratory conditions using different cleaning technologies and cleaning intensities. Regrowth behavior was quantified through image-based fouling assessment and related to changes in coating surface properties The results demonstrate that cleaning conditions significantly influence recolonization dynamics and that more intensive cleaning does not necessarily result in slower regrowth. Changes in coating surface properties and the extent of residual biological material were both found to influence subsequent fouling development.

1. Introduction

Marine biofouling, defined as the accumulation of microorganisms, algae, and marine invertebrates on submerged surfaces, remains a persistent challenge for the maritime industry. Fouling accumulation on ship hulls increases hydrodynamic drag, resulting in higher fuel consumption, greenhouse gas emissions, and operational costs, *Dobretsov (2009), Yebra et al. (2004)*. In addition, biofouling on ship hulls facilitates the transfer of non-indigenous species (NIS) between ecosystems, posing ecological and economic risks to coastal environments, *Chan et al. (2022)*. Consequently, fouling control coatings, hull maintenance strategies, and biofouling management programs are essential for maintaining vessel efficiency while reducing environmental impact, *Demirel et al. (2022)*. The increasing recognition of these challenges is reflected in recent regulatory developments by the International Maritime Organization (IMO) and national maritime authorities, which place growing emphasis on sustainable and effective biofouling management practices, *IMO (2023), Winthrop (2023)*.

In-water cleaning (IWC) has become an increasingly important component of modern biofouling management, *Song et al. (2020)*. By removing fouling directly from submerged surfaces, cleaning can restore hull performance without the need for dry-docking and thereby reduce fuel consumption and associated emissions, *Oliveira et al. (2020)*. Recent developments within the industry have further shifted attention towards proactive cleaning approaches, where early-stage fouling is removed before significant macrofouling can develop. Such strategies aim to maintain high hull performance while minimizing the risk of invasive species transfer, coating damage and maintaining compliance with emerging regulations, *Swain et al. (2022)*.

While considerable research has focused on cleaning efficiency, coating compatibility, and environmental releases during cleaning operations, comparatively little attention has been given to the fouling development that occurs after cleaning, *Scianni et al. (2023)*. The removal of biofouling does not necessarily restore a surface to its original condition. Depending on the cleaning method and operating parameters, cleaning may alter surface roughness, coating morphology, residual biofilm coverage, and the distribution of biological and coating-derived residues, *Bork et al. (2026)*. These changes may influence the subsequent attachment and growth of fouling organisms and therefore affect the long-term effectiveness of a cleaning operation.

Furthermore, regrowth may originate from residual viable organisms, remaining biofilm structures, detached biological material, or newly arriving propagules from the surrounding environment, *Floerl et al. (2004)*. Previous studies have demonstrated that fouling communities can rapidly re-establish on submerged surfaces and that environmental factors such as temperature, water quality, nutrient availability, and hydrodynamic conditions play important roles in recolonization dynamics, *Davidson et al. (2008)*. As proactive and routine cleaning become increasingly adopted within hull maintenance programs, understanding the factors governing post-cleaning regrowth becomes increasingly important. The objective of this study was therefore to investigate biofouling regrowth following simulated IWC under controlled laboratory conditions. Different cleaning strategies and intensities were applied to fouled coating samples prior to re-exposure in a natural seawater environment. The subsequent fouling development was monitored with particular focus on how cleaning-induced surface changes influence regrowth dynamics and recolonization behavior.

2. Biofouling Regrowth Following In-Water Cleaning

2.1. Biofouling Regrowth After In-Water Cleaning

The removal of biofouling during in-water cleaning does not necessarily eliminate all biological material from a submerged surface, *Floerl et al. (2004)*. Following cleaning, viable microorganisms may remain attached to the coating surface in the form of residual biofilms, microbial colonies, or microscopic fouling fragments. In addition, detached organisms and propagules released during the cleaning process may remain suspended in the surrounding water and subsequently resettle on nearby surfaces, *Lim et al. (2023)*. As a result, recolonization can originate both from biological material remaining on the cleaned surface and from dispersed fouling fragments present within the local marine environment.

The earliest stages of fouling (re-)growth are typically dominated by bacteria and microalgae, which rapidly form conditioning layers and biofilms that facilitate the settlement of subsequent fouling species, *Qian et al. (2022)*. Previous investigations have demonstrated that viable microorganisms can remain detectable both on cleaned surfaces and in cleaning effluents, even when cleaning systems achieve high debris-capture efficiencies, *Hyun et al. (2024)*. These findings indicate that complete removal of biological material is difficult to achieve and that even small quantities of residual biological matter may initiate recolonization. Depending on local hydrodynamic conditions, these fragments can be transported through the surrounding water and potentially settle on nearby surfaces, where they may act as sources for renewed fouling development. Consequently, the extent of regrowth is not solely governed by cleaning efficiency but also by the persistence and viability of biological material remaining after the cleaning process.

2.2. Factors Influencing Regrowth

The condition of the coating surface after cleaning is expected to play an important role in determining subsequent recolonization dynamics. Depending on the cleaning technology employed and the operating parameters applied, cleaning may alter surface roughness, coating morphology, residual biofilm coverage, and other surface properties known to influence biological settlement, *Bork et al. (2026)*.

Aggressive cleaning conditions can improve immediate fouling removal but may simultaneously modify the coating surface through local abrasion, removal of conditioning layers, or exposure of fresh coating material. Such changes may influence the attachment behavior of microorganisms and early-stage fouling species by altering the physical and chemical characteristics of the substrate, *Bork et al. (2026)*. Conversely, insufficient cleaning may leave residual biological material that can serve as a nucleus for recolonization, *Floerl et al. (2004)*. The balance between effective fouling removal and preservation of the coating surface is therefore likely to influence the long-term outcome of the cleaning operation.

For fouling control coatings, surface characteristics such as roughness, wettability, and surface energy are important parameters governing settlement and adhesion strength of marine organisms, *Cao et al. (2023)*. Changes to these properties during cleaning may therefore affect both the initial attachment of microorganisms and the subsequent development of more mature fouling communities.

Although increasing cleaning intensity generally improves the immediate removal of fouling, it does not necessarily result in reduced fouling accumulation over longer time scales. More severe cleaning may alter the coating surface sufficiently to create favorable conditions for recolonization, while gentler cleaning may preserve the original surface properties but leave behind viable biological material. The relationship between cleaning intensity and long-term regrowth is therefore not expected to be linear and remains insufficiently understood. Understanding this balance is essential for identifying cleaning strategies that not only remove existing fouling effectively but also delay subsequent recolonization.

In addition to surface-related factors, environmental conditions strongly influence recolonization dynamics. Water temperature, salinity, nutrient availability, light intensity, hydrodynamic conditions, and local fouling pressure determine both the availability of colonizing organisms and their subsequent growth rates, *Davidson et al. (2008), Qian et al. (2022)*. Consequently, regrowth should be regarded as the result of interactions between residual biological material, the condition of the cleaned surface, and the environmental conditions during subsequent exposure.

3. Experimental Investigation of Post-Cleaning Regrowth

3.1. Controlled exposure of fouling control coatings

Biofouling development and post-cleaning regrowth were investigated through natural seawater exposure at the CoaST Maritime Test Centre (CMTC) in Hundested, Denmark (see Fig.1a). The facility provides representative marine conditions and supports the development of naturally occurring Baltic Sea fouling communities. Environmental parameters including temperature, salinity, and dissolved oxygen were continuously monitored throughout the exposure period from March 2025 until December 2025.

a)

b) **c)**

Fig.1: a) CoaST Maritime Test Centre (CMTC) in the Baltic Sea, b) rotor set-up for dynamic exposure and c) set-up for static exposure in natural sea water

Different commercially available fouling control coatings were included in the present study. The coatings were selected to represent major fouling control strategies currently employed within the maritime industry, including a fouling-release coating, a self-polishing antifouling coating, a hard antifouling coating, and an inert reference coating. All coatings were applied in accordance with the respective manufacturers' specifications and subsequently exposed. The selected coating systems encompass a broad range of fouling-control mechanisms and surface characteristics, thereby enabling investigation of regrowth dynamics across different coating technologies.

Coating samples were initially exposed to promote the development of representative marine biofouling suitable for subsequent cleaning experiments. Following simulated IWC (see Chapter 3.2), the samples were re-immersed under the same environmental conditions to allow recolonization. This approach ensured that all samples experienced comparable environmental exposure before and after cleaning, enabling differences in regrowth behavior to be attributed primarily to the applied cleaning conditions. The exposure facilities at CMTC enable both static and dynamic exposure conditions, thereby simulating vessel idle periods and transit conditions, respectively (see Fig. 1b-c), *Pedersen et al. (2023)*. Exposure durations before and after cleaning were selected to achieve the desired fouling development and to monitor subsequent regrowth dynamics.

3.2. Simulated In-Water Cleaning under Laboratory Conditions

Laboratory-scale cleaning was conducted using various experimental cleaning devices constructed to reflect actual operating conditions with the flexibility of adjusting and measuring all relevant parameters during the cleaning simulation, *Guth et al. (2025)*. These systems enable the controlled simulation of IWC under highly reproducible conditions while allowing individual cleaning parameters to be adjusted independently. The laboratory-scale setups employed in this study are shown in Fig. 2a-c and facilitate the simulation of brush cleaning, water-jet cleaning, and proactive ultrasonic cleaning.

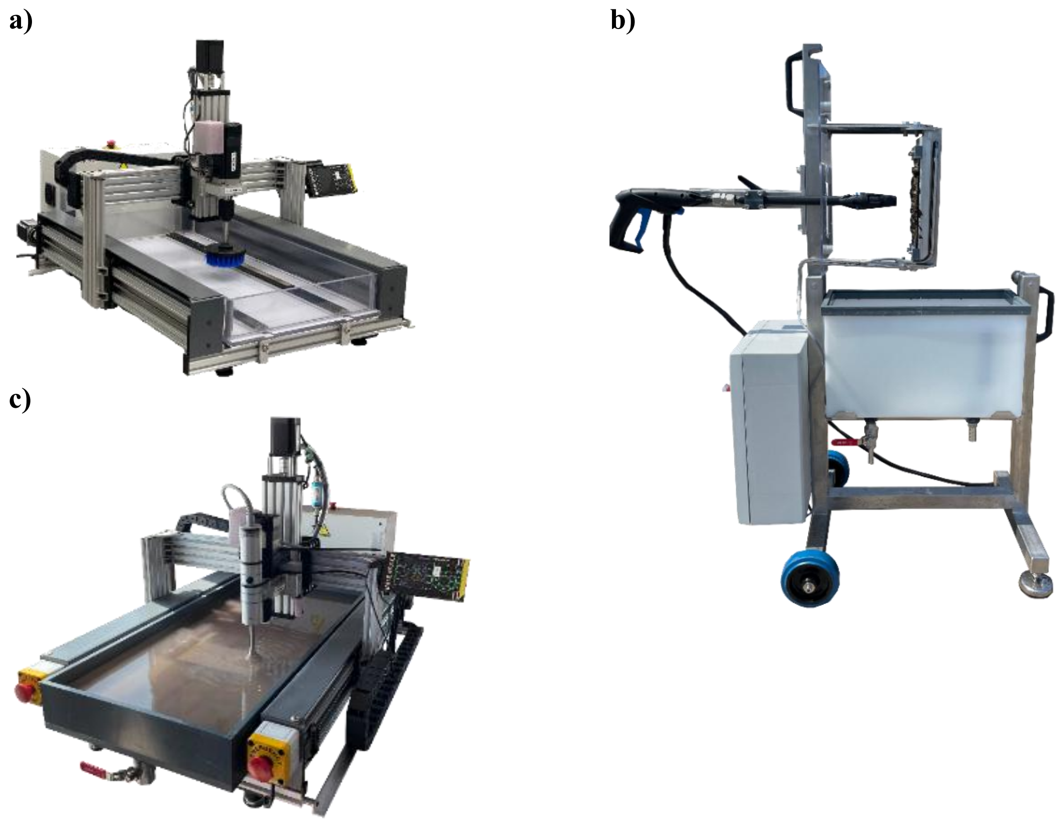

Fig.2: a) Automated in-water brush cleaning device, b) semi-automated in-water water-jet cleaning device and c) automated in-water proactive ultrasonic cleaning device

Cleaning conditions were selected to represent different levels of cleaning intensity and to generate varying post-cleaning surface conditions while achieving comparable levels of visible fouling removal. A detailed description of the cleaning systems, associated instrumentation, and operating principles is provided by *Guth et al. (2025)*. To facilitate comparison between the investigated cleaning scenarios, four representative cleaning parameters were selected. The parameters were chosen to generate different post-cleaning surface conditions while maintaining comparable levels of visible fouling removal. An overview of the cleaning parameters investigated and their qualitative characteristics is provided in Table I.

Table I: Cleaning parameters applied during the study and their qualitative characteristics with respect to cleaning technology and cleaning intensity

Description	**Abbreviation**	**Properties**
Cleaning parameter 1	CP1	Contactless ultrasonic cleaning, high cleaning intensity
Cleaning parameter 2	CP2	Contact-based brush cleaning, soft bristles, low cleaning intensity
Cleaning parameter 3	CP3	Contactless water-jet cleaning, high cleaning intensity
Cleaning parameter 4	CP4	Contact-based brush cleaning, hard bristles, high cleaning intensity

3.3. Evaluation of Regrowth

The development of biofouling following cleaning was monitored through visual inspections and digital image acquisition. Images were collected at weekly intervals before and after laboratory-scale IWC to document the progression of surface recolonization and fouling development. Fouling coverage was quantified using a machine-learning-based image analysis approach developed for biofouling assessment, *Anani et al. (2026)*. For each assessment point, the percentage surface coverage was determined and used as a quantitative measure of regrowth progression (see Fig.3). In addition, representative images were evaluated to identify differences in fouling morphology and settlement patterns between cleaning conditions.

To facilitate comparison between cleaning strategies, regrowth rates were determined from the temporal evolution of fouling coverage. Particular attention was given to the initial recolonization phase following cleaning, as this period is expected to be most sensitive to cleaning-induced changes in surface properties. The resulting regrowth behavior was subsequently analyzed in relation to the applied cleaning parameters and the corresponding post-cleaning surface condition. Fouling surface coverage was defined as the combined surface coverage of all classified fouling categories, while areas classified as clean surface were excluded from the calculation.

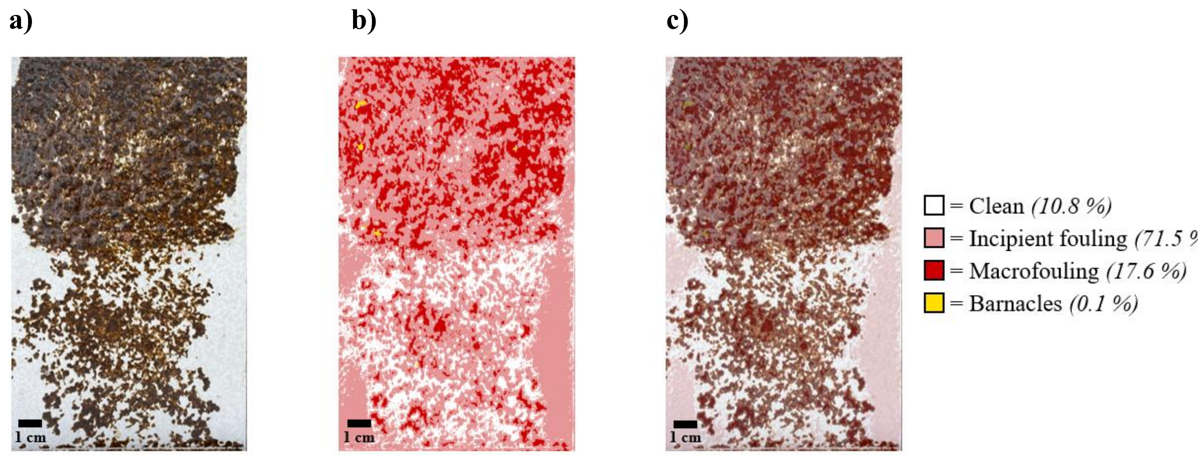

Fig.3: a) Original image taken of a sample, b) processed image with classification map and coverage in percent and c) overlapped original image with classification map

To investigate the influence of cleaning on coating properties, complementary surface characterization was performed on identical coating samples exposed under laboratory conditions in artificial seawater without biological fouling. This approach avoided interference from residual fouling and ensured reliable surface measurements. Surface roughness was measured using an optical 3D profilometer (3D-profilometer 3100 VR, KEYENCE International NV/SA), with the arithmetic mean square roughness (Sq) selected as the primary roughness parameter. Surface wettability was evaluated using a drop shape analyzer (DSA30E, A. KRÜSS Optronic GmbH) and deionized water as test liquid. The resulting contact angles were used to assess changes in surface wettability induced by the different cleaning conditions and overall exposure of different fouling control coatings to seawater.

4. Results and Discussion

4.1. Regrowth Dynamics Following Cleaning

Fig.4 illustrates the evolution of fouling coverage following IWC. For all cleaning conditions, recolonization of the cleaned surfaces was observed shortly after re-immersion, indicating that complete suppression of fouling regrowth was not achieved. However, clear differences in regrowth rates were identified between the investigated cleaning intensities.

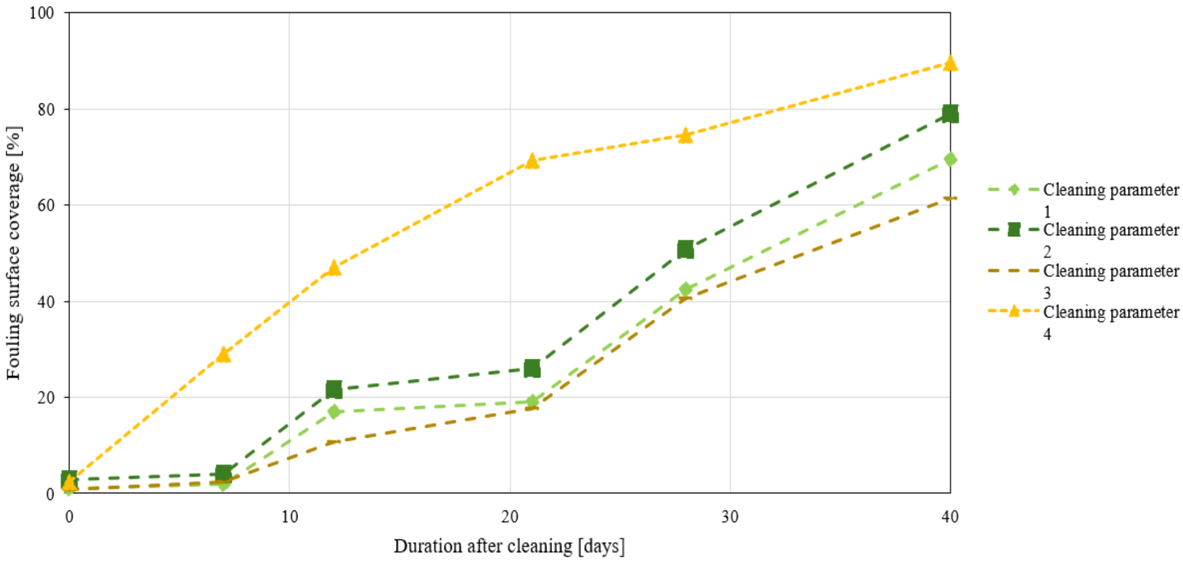

Fig.4: Evolution of biofouling surface coverage following re-immersion in natural seawater (CMTC in Hundested/Denmark) of a cleaned fouling control coating subjected to four cleaning strategies

Cleaning conditions generally associated with higher cleaning intensities (Cleaning Parameters 1 and 3) resulted in lower fouling coverage throughout the re-exposure period compared to the less intensive Cleaning Parameter 2. The largest differences were observed during the first 20 days following cleaning, during which more intensively cleaned surfaces exhibited delayed recolonization and slower fouling accumulation. This observation suggests that more effective removal of residual biofilms, microorganisms, and fouling fragments can reduce the availability of biological residues responsible for the initiation of regrowth.

An exception to this trend was observed for Cleaning Parameter 4. Despite representing the most severe cleaning condition investigated, this parameter resulted in the fastest recolonization and fouling development. As shown in Chapter 4.2, Cleaning Parameter 4 also produced the largest changes in surface roughness and wettability, indicating substantial modification of the coating surface. This suggests that while increased cleaning intensity can reduce residual biological material and thereby delay regrowth, excessive cleaning may simultaneously alter surface characteristics in a manner that promotes recolonization.

Following approximately 30 days of re-exposure, the differences between cleaning conditions gradually diminished as fouling communities developed on all surfaces and surface coverages approaches 100 % coverage. The results therefore indicate that post-cleaning regrowth is governed by the combined effects of residual biological material and cleaning-induced surface modifications, rather than by cleaning intensity alone. For clarity, only one representative coating system is shown here as the observed trends were consistent across all investigated coating technologies.

4.2 Influence of Cleaning Conditions on Surface Properties

To investigate whether the observed differences in regrowth behavior were associated with changes in surface properties, surface roughness and wettability measurements were performed on identically cleaned coating samples.

Fig.5 presents the root mean square roughness (Sq) measured before and after the different cleaning conditions presented here. The results demonstrate that the applied cleaning scenario influenced the surface roughness of the investigated coating system to varying degrees. While Cleaning Parameter 2 resulted in Sq values comparable to those of the uncleaned reference panels, indicating no measurable alteration of the surface condition, the remaining cleaning conditions produced more pronounced changes in roughness. Depending on the cleaning method and parameter selection, both increases and decreases in Sq compared to the uncleaned reference were observed, suggesting modification of the coating surface through removal of surface layers, abrasion, or localized erosion of coating material. The largest deviations from the reference condition were associated with cleaning parameters 1, 3, and 4, indicating that the more aggressive cleaning conditions applied here can significantly alter the surface morphology. These findings confirm that cleaning intensity not only affects fouling removal but may also influence coating surface properties that are known to affect subsequent biofouling settlement and regrowth.

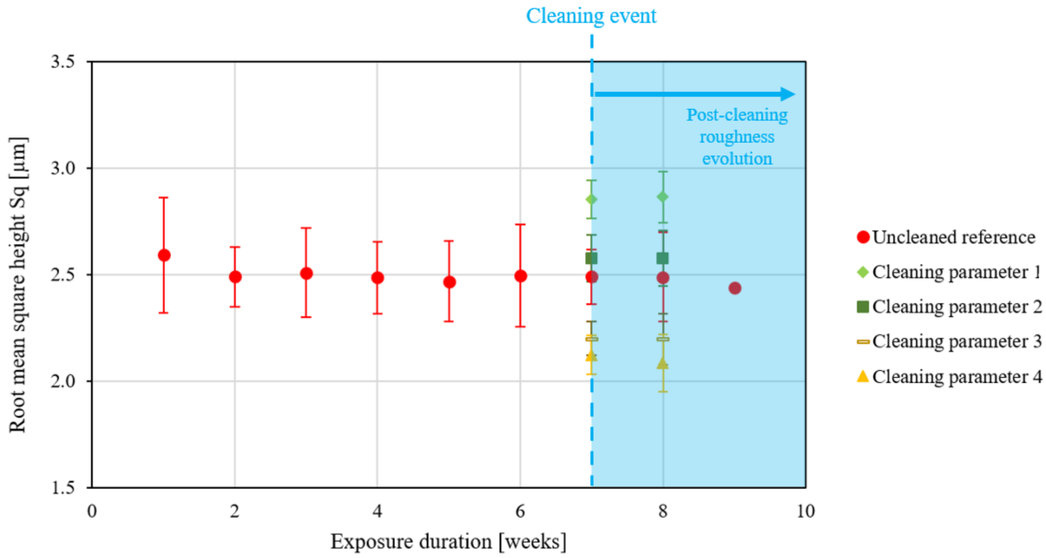

Fig.5: Evolution of root mean square height (Sq) for an uncleaned reference surface and four cleaning strategies, including post-cleaning roughness changes (week 7) and roughness progression during re-exposure (week 8)

Fig.6 presents the evolution of surface wettability following the different cleaning conditions. Similar to the surface roughness measurements, the applied cleaning parameters resulted in varying degrees of change in wettability immediately after cleaning. Cleaning Parameter 2 produced wettability values comparable to those of the uncleaned reference surface, whereas Cleaning Parameters 1, 3, and 4 resulted in larger deviations, indicating a more pronounced modification of the coating surface. However, in contrast to the roughness measurements, these differences were only temporary. Following re-exposure, wettability rapidly returned towards the values observed for the uncleaned reference surfaces within one week after cleaning. This suggests that while cleaning can induce short-term changes in surface wettability, the effect can be largely reversible under the investigated exposure conditions and is therefore unlikely to explain the longer-term differences observed in biofouling regrowth behavior.

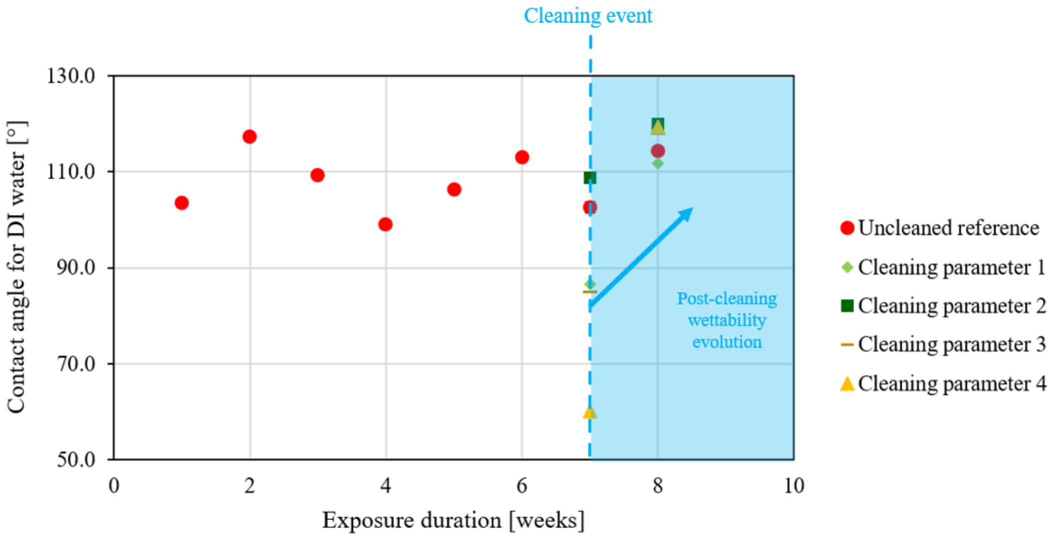

Fig.6: Evolution of contact angle (demineralized water) for an uncleaned reference surface and four cleaning strategies, including post-cleaning wettability changes (week 7) and wettability progression during re-exposure (week 8). Error bars show ± 1 standard deviation (max. standard deviation = 0.53 °) and are therefore not visible.

Overall, the surface characterization results demonstrate that cleaning conditions can significantly influence coating surface properties. More aggressive cleaning parameters resulted in larger deviations in both surface roughness and wettability immediately after cleaning, indicating increased modification of the coating surface. However, while changes in wettability were found to be temporary and returned to levels comparable to the uncleaned reference within one week of re-exposure, changes in surface roughness persisted for longer periods and remained dependent on the applied cleaning condition.

5. Conclusion and Outlook

The present study investigated biofouling regrowth following simulated IWC under controlled laboratory and field exposure conditions. Although all investigated cleaning strategies successfully removed visible fouling, substantial differences in post-cleaning recolonization behavior were observed.

Cleaning conditions associated with higher cleaning intensity generally resulted in slower regrowth rates during the initial stages of recolonization. These findings suggest that the amount of residual biological material remaining on the surface following cleaning may play an important role in governing subsequent fouling development. At the same time, more aggressive cleaning conditions produced greater deviations in surface roughness and wettability, indicating increased modification of the coating surface. The results demonstrate that evaluating cleaning technologies solely through immediate cleaning efficiency may overlook important differences in long-term performance. The observation that the most severe cleaning condition resulted in the fastest regrowth further indicates that increasing cleaning intensity alone does not guarantee improved long-term cleaning performance. Instead, cleaning effectiveness should be assessed as a balance between fouling removal, coating preservation, and the resulting regrowth behavior.

Future work will focus on improving the understanding of how residual biological material, surface modifications, and environmental exposure interact to influence the recolonization processes. Such knowledge may support the development of cleaning strategies specifically designed not only to remove existing fouling, but also to delay subsequent regrowth and thereby extend maintenance intervals while maintaining vessel performance and minimizing environmental impact.

Acknowledgement

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Technologies Against Biofouling – The More, the Merrier?

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Abstract

Marine biofouling is increasingly managed through combinations of coatings, marine growth prevention systems and in-water cleaning technologies. Information about their individual efficacy is not sufficient: compatibility, operational limitations and unintended environmental effects must also be understood. These questions can be addressed proactively through bench-scale, ex-situ and in-situ testing. Based on DHI test examples, this article illustrates how different test scales can assess biofouling prevention, coating durability, cleaning impacts, capture and filtration performance, and environmental releases.

1. Introduction

Biofouling management increasingly relies on combinations of technologies, including antifouling coatings, marine growth prevention systems (MGPS) and in-water cleaning systems. Combining technologies may improve overall performance, but it can also introduce interactions, limitations or environmental effects that are not apparent when each technology is considered independently, creating unforeseen maintenance time or decreased lifetime of equipment.

Meaningful performance claims therefore need measurable criteria and defined operating boundaries. Statements such as “the technology works” or “nothing is released” are of limited value unless the conditions under which these claims apply are specified. A technology may perform well under one set of environmental or operational conditions and differently under another set of conditions. Understanding these limitations requires testing at an appropriate scale and under sufficiently varied conditions.

DHI performs independent testing at its environmental laboratory in Hørsholm and at the Maritime Technology Evaluation Facility (MTEF) in the Port of Hundested, Denmark. Depending on the technology readiness level and the question being addressed, testing can range from bench-scale experiments to controlled ex-situ trials and full in-situ evaluations. Existing standards and guidelines are applied where available and relevant, while customized test protocols can be developed for technologies or questions not yet covered by standardized methods.

2. Bench-scale testing

Bench-scale testing is useful for isolating specific mechanisms or effects under highly controlled conditions. Smaller experiments are generally less resource-intensive and allow more replicates to be included, increasing the robustness of the results. Examples include leaching tests in beakers, ecotoxicity testing of biocidal substances or effluent water, and detailed analytical measurements on small samples. Some sensitive analytical methods are also most practically applied at this scale, particularly when investigating coating-related releases or effects.

Bench-scale tests can therefore provide an efficient first step in determining whether a suspected effect is measurable, identifying relevant parameters and defining the conditions that should subsequently be tested at a larger scale. Their main limitation is representativeness: a mechanism demonstrated in a small, controlled system still needs to be shown to remain relevant when the technology is operated under more realistic conditions.

3. Ex-situ testing

Ex-situ testing provides a bridge between small-scale laboratory experiments and full in-situ trials. Environmental and operational conditions can still be controlled, while technologies can be tested at a more representative scale and under realistic biofouling or cleaning conditions.

DHI's facilities enable control or adjustment of relevant abiotic and biotic test-water characteristics, including suspended material, organic matter, bacteria and plankton. Once these conditions have been quantified, technology performance can be evaluated against defined test conditions and performance criteria. Test tanks ranging from small experimental units to volumes of up to approximately 1,000 m^3 allow testing at different scales, including high-flow applications and ex-situ cleaning of coated panels, including storage of cleaning effluent. Representative geometries, including structures simulating vessel niche areas, can be incorporated where required, as for example in the Global TestNet guidance for evaluation of MGPS; *Global TestNet (2025)*.

A great advantage of ex-situ testing is the ability to increase or standardize the biological challenge. Naturally occurring organisms can be concentrated from ambient water and introduced into exposure tanks, or selected organisms such as barnacle larvae can be added where a specific fouling group is of interest. This can strengthen the biological challenge during the relatively short Scandinavian fouling season and improve comparability between tests. Ex-situ testing is especially suited when operation of the technology could result in an environmental release or another unintended effect. Containment allows such effects to be investigated without directly exposing the surrounding marine environment. This may be relevant, for example, when investigating technologies producing sound or other forms of energy for which effects outside the treated surface should be considered; *Madsen et al. (2025)*.

3.1 Compatibility between coatings and cleaning systems

If an antifouling coating and a cleaning system is not compatible, any pollution is much easier to handle in a test tank than in the real environment. A cleaning technology may successfully remove biofouling but still alter the coating surface in a way that affects its subsequent performance. To investigate this, DHI has developed a laboratory-scale in-water cleaning system in which either a brush or water jet is applied to coated test panels using a gantry system, Fig.1, with similar equipment described by *Guth et al. (2025)*. The test panel is mounted on a force and torque sensor, allowing the load applied during cleaning to be quantified. Detailed surface imaging before and after cleaning can then be used to identify changes in coating topography and surface roughness.

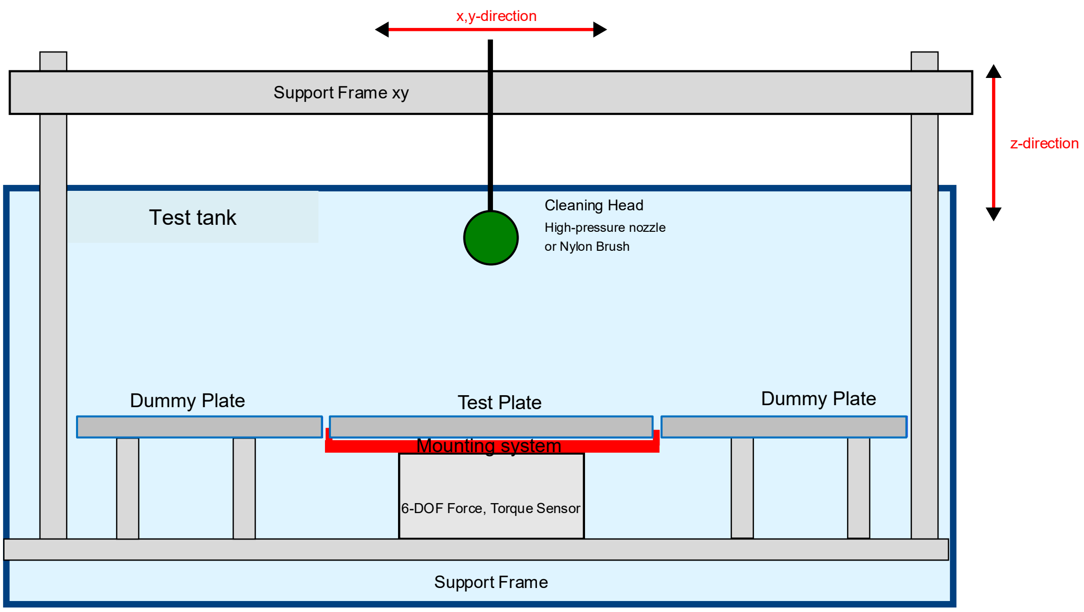


Fig.1: System for lab-scale in-water cleaning of coated test panels by either brush or water jet

3.2 Capture and treatment of removed material

During in-water cleaning, removed material may be captured to limit its release to the surrounding environment. Ex-situ testing provides favourable conditions for evaluating such capture and treatment systems, as water can be sampled under controlled conditions without interference from currents or wind.

Fig.2 shows an example from three rounds of ex-situ propeller polishing performed by a client, with DHI supporting the sampling programme. Concentrations of metals and total suspended solids were generally highest in the captured water and were reduced to varying degrees after treatment. The results also illustrate the importance of characterising the test water before cleaning: in round A, the initial copper concentration was already high, limiting the extent to which subsequent copper concentrations could be attributed to the polishing process itself.

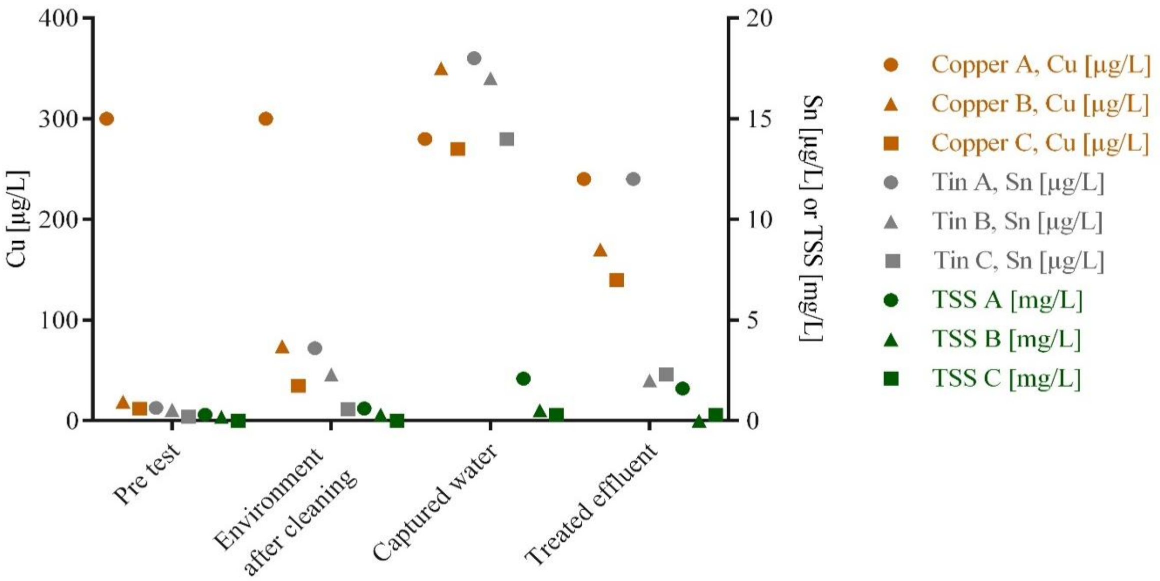


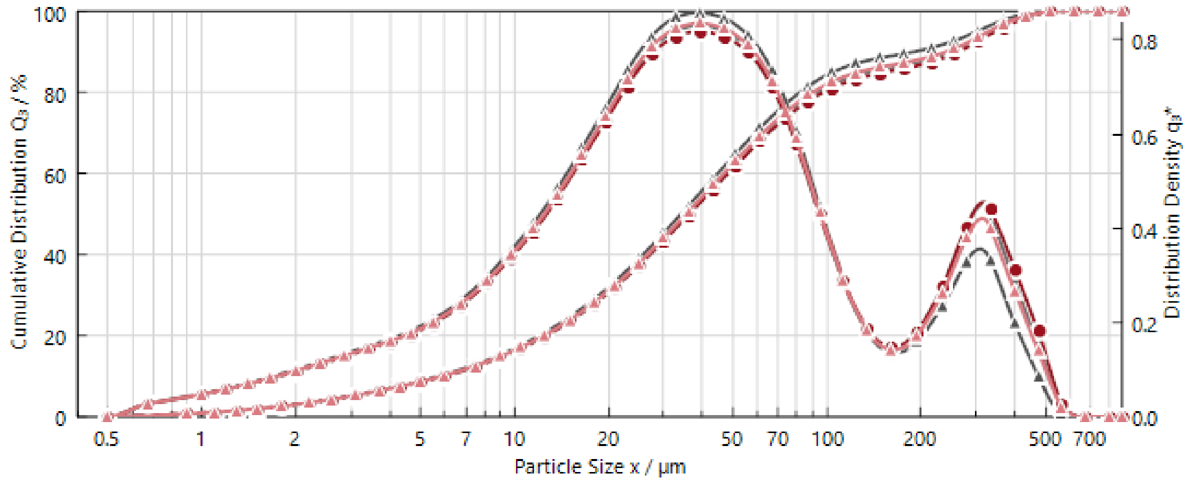
Fig.2: Concentrations of copper, tin, and total suspended solids during rounds A, B, and C of an ex-situ propeller cleaning. Note the two y-axes and two units.

Once material removed during cleaning has been captured, the next step is to assess how effectively it can be retained and treated. Filter performance is commonly evaluated against a defined particle-size threshold, but performance may depend strongly on the nature of the material being filtered. At DHI, filter testing therefore includes both performance and endurance testing using biotic or abiotic loads.

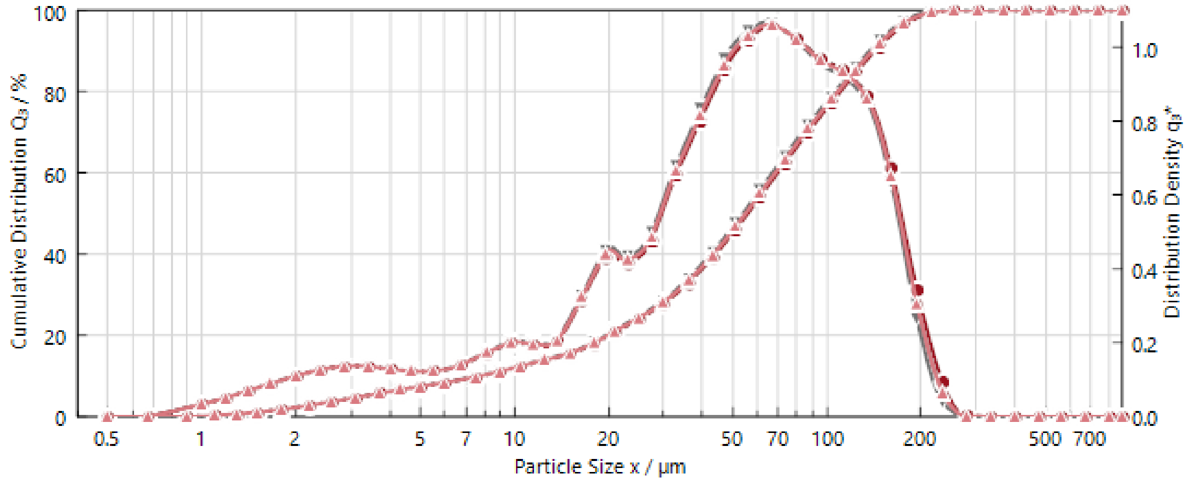
Fig.3 shows an example using a high concentration of naturally occurring organic material. Particle size distribution (PSD) is used together with total suspended solids (TSS), as PSD describes the relative size distribution of particles but does not quantify their total concentration. In this example, filtration substantially reduced the coarse fraction, as 90% of the particles was smaller than 235 ± 40 µm before filtration, whereas 90% was smaller than 140 ± 3 µm after filtration.

A separate phenomenon occurs during filtration itself. Material retained on the filter surface can form a filter cake, which may increase the retention of particles smaller than the nominal filter pore size. Conversely, soft biological material may deform and pass through openings smaller than its apparent dimensions. Performance established with sediment or other rigid particles therefore cannot necessarily be assumed to represent performance with biological material.

Endurance is another important aspect of filter performance. Repeated operation, filter loading and backwashing may challenge even well-performing filters, and the practical operating time between manual maintenance events can be as important to the operator as the initial retention efficiency.



x10 = 5.9 ± 0.2 µm x50 = 35 ± 1 µm x90 = 235 ± 40 µm



x10 = 7.8 ± 0.1 µm x50 = 55 ± 1 µm x90 = 140 ± 3 µm

Fig.3: Particle size distribution of organic load test, averaged from three measurements. The upper panel shows the distribution before the filtration and the lower panel after filtration. x10, x50 and x90 indicate the particle size below which 10%, 50% and 90% of the measured particle volume are found, respectively.

4. In-situ testing

In-situ testing provides the most operationally representative assessment of a technology, but interpretation of the results can be more difficult because many environmental and operational variables cannot be controlled. Successful performance under field conditions therefore provides strong evidence of practical applicability, whereas poor performance may be difficult to attribute to a single cause.

Ultrasound provides an example of this challenge. Under controlled exposure conditions, a clear reduction in biofouling can be observed, as illustrated in Fig.4. Results from installations on board vessels are more variable and can be more difficult to interpret; *Madsen et al. (2025), Mølris (2025)*.

Continuous operation is an important consideration for this type of technology, as the system should be active before the protected surface is immersed and remain operational throughout the exposure period. Ultrasound has also been investigated at laboratory scale as a cleaning method; *Bork et al. (2025)*. In the tests performed by DHI to date, coating damage associated with exposure to biofouling-preventive ultrasound has not been observed.

Fig.4: Test panels after two months of exposure to biofouling in Perth, Australia. Both panels were coated by an aliphatic acrylic polyurethane paint; the panel on the left was additionally exposed to ultrasound throughout the test.

Water sampling during in-water cleaning presents another challenge for in-situ testing. Sampling requirements vary between standards and port guidelines; e.g. *Sigvaldsen et al. (2026), ISO 20679 (2025), BIMCO and ICS (2023),* and *Port of Antwerp Bruges (2019)*; while currents, vessel geometry and movement of the cleaning equipment can make representative sampling difficult.

Fig.5 shows results from an in-water cleaning event on a vessel coated with an antifouling system containing copper and zinc. Metal concentrations were substantially higher in samples associated with the cleaning unit than in ambient samples, supporting the conclusion that coating-associated metals were released during the cleaning operation.

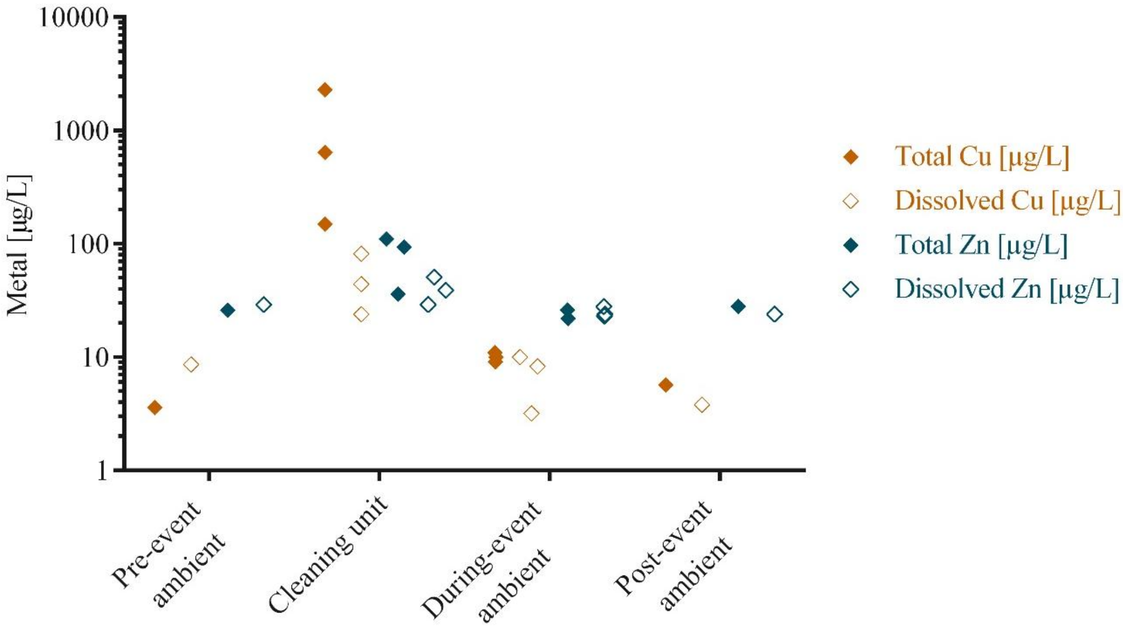


Fig.5: Concentrations of copper (Cu) and zink (Zn) during an in-situ in-water cleaning event.

The distinction between total and dissolved metal concentrations is important when interpreting such results. In this example, subsamples were filtered through a 0.45 µm membrane before analysis of the fraction reported as "dissolved". This is an operational definition: filtration separates particles larger than approximately 0.45 µm from the analysed fraction, but does not imply that the metal itself has been removed from the water. Preparing sufficient filtered sample volume can also be challenging when samples contain concentrations other suspended material.

5. The More, the Merrier?

As biofouling management increasingly combines preventive and cleaning technologies, compatibility becomes an important part of performance evaluation. Antifouling coatings, sound- or light-based prevention systems and other MGPS may ultimately be used together with brushes, water jets, heat or other cleaning technologies if fouling develops despite preventive measures.

New technologies may improve biofouling management, but only if they work together as intended. A cleaning technology should not compromise the coating it is intended to maintain. A prevention system should not introduce unacceptable environmental effects. A capture system must not only collect removed material but also retain or treat it effectively under realistic loading conditions.

No single test scale can answer all of these questions. Bench-scale experiments are useful for isolating mechanisms and identifying specific effects. Ex-situ testing allows interactions to be investigated under controlled and reproducible but more representative conditions. In-situ testing then provides evidence of how the complete technology or technology combination performs under actual operating conditions.

The objective is therefore not simply to demonstrate that each individual technology works, but to understand its operating boundaries, interactions and potential side effects. In biofouling management, more can indeed be better — provided that the combination has been demonstrated to be effective, compatible and environmentally acceptable.

Acknowledgement

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Effective Biofouling Control at Risk in Europe

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Abstract

Antifouling coatings are essential for biofouling control but face increasing regulatory pressure under the EU Biocidal Products Regulation. Key biocides such as Zinc Pyrithione and Medetomidine are now recommended for non-approval, narrowing available chemistries as the IMO moves toward stricter macrofouling rules. Using Zinc Pyrithione as a case study, this paper shows how hazard-based exclusion and limited alternatives threaten effective coatings. Without reliable antifouling solutions, Europe risks invasive species transfer, operational disruption, and failure to meet decarbonization, biodiversity, and competitiveness goals. Coordinated action is urgently needed to safeguard biofouling control.

1. Introduction

Biofouling is the accumulation of microorganisms, plants and animals on submerged surfaces, including ship hulls and marine infrastructure. It develops in stages, from microfouling by bacteria, diatoms and biofilms below one millimetre to macrofouling by algae, barnacles and mussels above it. Its rate and composition are driven by temperature, salinity, nutrient availability, hydrodynamics, light and substrate, which together produce strong spatial variability: fouling pressure differs markedly between European sea basins and between operating profiles.

The consequences are measurable. A slime layer alone raises fuel consumption by 5-10%, that heavy fouling raises it by 30-40%, and that a 10% increase corresponds to roughly 400 tons of additional carbon dioxide per vessel each year. Shipping also accounts for up to 78% of marine alien species introductions in some regions, and the global cost of aquatic invasive species has been estimated at USD 345 billion. The International Maritime Organization has responded by moving from guidance towards obligation: the 2023 Biofouling Guidelines call for a ship-specific management plan and record book, selection and maintenance of an antifouling system and proactive inspection and cleaning, and at PPR 13 in Feb. 2026 it was agreed to develop a legally binding framework covering fouling thresholds for the main hull and niche areas. Higher standards for immersed surfaces raise the demands on the coatings that must deliver them, while European regulatory practice moves the other way.

2. On The Importance of Antifouling Chemistries for Biofouling Control

No single antifouling technology can deliver optimal performance on immersed areas of all ships and boats operating across all geographies, on all vessel types with varying operational profiles. Products are deliberately formulated as combinations of complementary actives — copper compounds for hard fouling paired with co-biocides such as Copper or Zinc Pyrithione for soft fouling — to optimize efficacy while minimizing emissions. Copper-free products can be formulated with organic biocides that are active against hard fouling. These products are suitable for use in waters where there is concern over elevated copper concentrations.

The importance of biocide chemistries for antifouling products is further demonstrated by a review of the Lloyds Register for Antifouling Coating Type Approvals. Fig.1 shows the distribution of products and chemistries as listed in 2023. Only 3.2% of all products are biocide-free with a large majority of products based on copper compounds to manage macrofouling and co-biocides to manage microfouling, mainly Copper Pyrithione (CuPT), Zineb, DCOIT and Zinc Pyrithione. As the ship owner's first line of defense against biofouling, effective antifouling paints will be critical to minimize the risk of translocation of invasive species and prevent disruption to shipping operations.

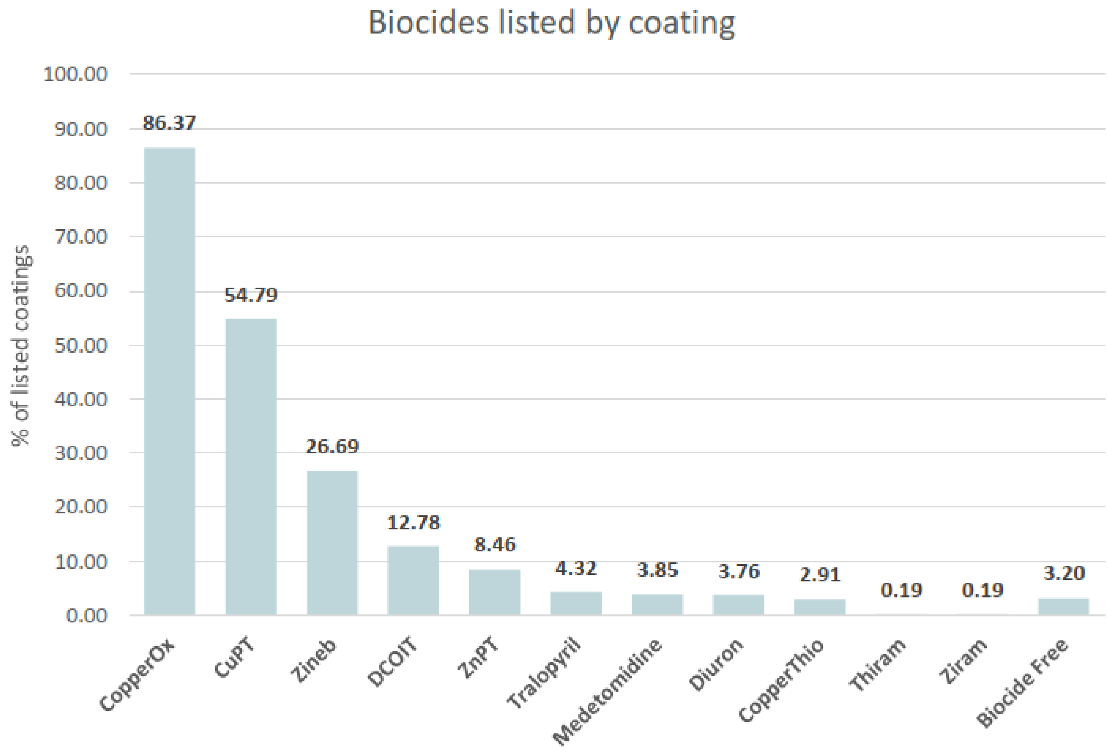

Fig.1: Snapshot of the Lloyds Register Antifouling Coating Type Approvals – Alistair Finnie, International Antifouling Conference, Gothenburg 2023

3. Regulatory Framework: The Two-Step Logic of the BPR

The BPR regulates biocides in two sequential steps. An active substance is evaluated by a Member State competent authority and, after peer review in the European Chemicals Agency Working Groups and the Biocidal Products Committee, approved or refused at European Union level; only then may products containing it be authorized and sold on the market. A single decision on an active substance therefore determines the fate of every product formulated with it, however those products differ in composition, application method, vessel type or region of use.

The first antifouling approvals were granted from 2015 for ten years, and all of those substances are now in renewal under evaluation practice that has become substantially more conservative in the intervening decade. Antifouling chemistries are typically hazardous substances and can be classified as carcinogenic, mutagenic or toxic for reproduction, as endocrine disruptors, or as persistent, bioaccumulative and toxic meet exclusion criteria. Based on the hazard profile they potentially cannot be approved by standard process, but only if specific derogation criteria are met, e.g. essentially use or based on socio-economic reasoning. Conversely, biocide-free products require no prior approval under biocidal product law and their non-biocidal safety in use or emissions need not be disclosed.

Notably, that asymmetry in regulatory burden does not necessarily track a difference in hazard or risk. Researchers at Chalmers University of Technology and the IVL Swedish Environmental Research Institute reviewed formulation data for 212 topcoat products from six major EU manufacturers and found biocides in 83% of ship coatings and 88% of yacht coatings, dominated by inorganic copper, *Hou et al. (2026)*. Their product hazard potential metric varied by up to three orders of magnitude across biocidal coatings, with some alternative organic biocides among the highest scores and non-biocidal constituents such as zinc oxide and bisphenol A epoxy resins driving the hazard of certain products, including biocide-free ones. The BPR, they concluded, requires comprehensive assessment, but only for biocides and zinc.

4. The Zinc Pyrithione Decision Explained

Zinc Pyrithione is a substance effective against soft fouling organisms including algae, bacteria and fungi. In antifouling coatings it is typically used as a co-biocide alongside a copper type compound. The manufacturers applied for European approval in 2006. Sweden was tasked with of examining the case, sent its report to the European Chemicals Agency in September 2025, and the expert committee that reviews such cases agreed its opinion on 27 May 2026. The answer was no: the substance should not be approved for use in antifouling products.

3.1. Why the substance was ruled out and outlook for other chemistries

European law works from a list of properties that automatically disqualify a substance, regardless of how carefully it is used. One of them is being classified as reproductive toxic in the more serious of the two categories, which Zinc Pyrithione is and it is also classed as possibly capable of causing organ damage after repeated exposure. Once a substance falls into that group, the only way it can still be approved is through a narrow exemption or derogation, which has to be argued and proved case by case. Critically, most if not all antifouling chemistries carry a classification of similar hazard or remain in evaluation, which means that the challenges on renewals are comparably high across all antifouling chemistries. For example, Medetomidine or Selektope has already received an opinion for non-approval and recommendation to remove all products containing the chemistry from the market with a final decision possible already early October 2026.

3.2. Proving efficacy for co-biocides

A biocide can only be approved if it is shown to work. Here the committee accepted that Zinc Pyrithione is inherently effective and that paints containing Zinc Pyrithione together with a copper compound do keep fouling off a hull. What it did not accept was evidence of how much of that result comes from the Zinc Pyrithione itself rather than from the copper. Additional information supplied during the assessment did not settle the question, and the committee also found it could not judge whether fouling organisms might become resistant over time.

This is a demanding test to set. A paint is designed as a recipe in which the ingredients work together, much as a medicine may combine two drugs because the pair does more than either alone. Separating out the share of the result attributable to one ingredient, across the whole range of organisms that settle on a hull and over a service life of several years, is difficult to demonstrate. The effect of the test in this case was also uneven: when the committee later compared Zinc Pyrithione with possible replacements, it assumed the substance does work, yet the same missing evidence was used to conclude that it is not essential. The European Chemicals Agency seems to understand the difficulty on what is asked and has put a task force in place to resolve the issues. An industry working group has joined the efforts to support the development of suitable guidelines.

3.3. Who is at risk, and where

The assessment looked separately at occupational and environmental risk in use. For workers, it examined the scenarios in which someone comes into contact with antifouling paint during handling, application and removal of coating products. In general, sale to consumers is ruled out for all substances in high hazard classes and can no longer be sold for do-it-yourself use. However, for Zinc Pyrithione a safe use was identified and further refinement of the assessments remains possible at product authorization stage.

The Zinc Pyrithione picture for the environment and releases to water is quite different and very favorable. Using a standard model, the assessors calculated concentrations of the substance and its breakdown products in a commercial harbour, a marina and a shipping lane. The results were within safe limits everywhere as required. In short, the risk to the marine environment and waters during the years a coated ship is in service was found to be acceptable. The recommendation to refuse approval rests on exposure of workers during painting, on the unresolved question of how much the ingredient contributes, and on the view that substitutes exist, rather than on damage to the marine environment in normal use.

3.4. Are there substitutes?

Because Zinc Pyrithione meets BPR exclusion criteria and standard approval is not possible, the committee had to ask whether the market could manage without it. A public call for views in late 2024 drew many responses, from companies and trade bodies in eight countries, all saying the substance is needed, particularly in low-biocide silicone coatings, in copper-free paints and on aluminum hulls. The committee then carried out its own comparison. A summary of their conclusions and possible market impact is shown in Table I.

Table I: Marine antifouling chemistries, hazard categories and potential removal from EU market

Alternative assessed	Hazard category	Removal from EU market
Copper compounds	Under evaluation	Potential removal proposal
Copper Thiocyanate	Under evaluation	Potential removal proposal
Copper Pyrithione	Under evaluation	Potential removal proposal
Zineb	Endocrine disruptor	Removal proposal likely
DCOIT (Seanine 211)	Under evaluation	Potential removal proposal
Zinc Pyrithione	Reproductive toxicity Cat. 1	Removal proposal in place
Tralopyril (Econea)	Potential PFAS	Removal proposal likely
Medetomidine (Selektope)	Endocrine disruptor	Removal proposal in place
Non-biocidal hard coatings	Unknown	Not applicable
Silicone-based coatings	Unknown	Not applicable
Ultrasonic systems	Unknown	Not applicable
In-water cleaning	Unknown	Not applicable

Two things stand out. The first is that the list of chemical substitutes includes substances that are themselves up for renewal, facing a withdrawal proposal, or dependent on the same narrow exemption that Zinc Pyrithione was refused. The second is that the comparison was made almost entirely on hazard and not risk in use. The committee acknowledged that no single option, including Zinc Pyrithione, covers every type of fouling and every use, and that the alternatives, including non-biocidal alternatives should be seen as a toolbox rather than as replacements one for one.

What the committee failed to acknowledge is that the number of available chemistries is already very limited, and that the variability in environmental conditions (e.g. temperature, salinity, fouling pressure), diversity of vessel types (commercial shipping, leisure craft, offshore structures, aquaculture) and differences in operational profiles (e.g. speed, idle time, maintenance cycles) require different chemical solutions. The committee also failed to acknowledge that non-biocidal solutions may not be effective, do not act as preventative treatment, may not be widely available or not be suitable for certain vessel types. The committee did not take into account at all the effectiveness of non-biocidal solutions, costs and potential impact on human health or the environment.

4. Shortcomings of the Current Evaluation Practice

Two features of the Zinc Pyrithione evaluation recur across the ongoing renewals of the other antifouling chemistries. The first is the accumulation of conservatism: assessment factors are layered to cover severity, vulnerable subpopulations, interspecies and intraspecies variation and, explicitly, deficiencies in the data. Each step is individually defensible, yet the combined effect is that restrictions are put in place limiting the use and application spectrum. The second is the evidentiary standard applied to co-biocides: requiring a component to demonstrate its contribution in isolation from the system in which it functions does not correspond to how antifouling technology is designed, tested or used, and a standard no combination product can meet operates as a de facto prohibition.

The third concerns the analysis of alternatives, where suitability was assessed largely on toxicological profile, not risk in use, with efficacy differences acknowledged qualitatively rather than tested. Alternatives whose own regulatory futures are unresolved were counted as available, while the limitations of non-biocidal options were treated as manageable because other options exist. The industry evidence points the other way: antifouling systems must be selected and adapted on a case-by-case basis, combining different technologies within a broader biofouling management approach.

The fourth is the cumulative arithmetic. Decisions are taken substance by substance, but their effect is felt at portfolio level. Industry estimates the current renewals could see more than 40% of antifouling paint products withdrawn from the European market, yet no single opinion assesses that aggregate effect.

5. Consequences for Biofouling Management

The regulatory contraction is occurring precisely as performance requirements rise. Advanced hull coatings are recognised in IMO MEPC 80/INF.10 as a key energy efficiency technology available now, and emission intensity targets under MARPOL Annex VI apply from 2028 towards a 20% reduction in greenhouse gas emissions by 2030. A binding biofouling framework will set expectations for immersed surfaces that a diminished set of coating options cannot meet, particularly in niche areas.

The environmental consequence of insufficient fouling control is not neutral. Reduced coating performance increases fuel consumption and therefore emissions, forces premature in-water cleaning or dry-docking, and raises the risk of translocating invasive aquatic species. In-water cleaning is itself counted among the alternatives, yet the terms on which it will be permitted, including capture requirements, remain under negotiation at IMO. There is a competitiveness dimension as well: if the products that meet the coming IMO standards cannot be authorised in Europe, application and in time formulation and innovation will move to jurisdictions where they can.

6. Towards Constructive Cooperation

None of this argues for weaker protection of human health or the marine environment. The BPR exclusion criteria reflect a settled consensus. The argument is that the framework around those criteria, in particular the analysis of alternatives and the treatment of efficacy, is where current practice diverges from the outcomes the regulation is intended to deliver and needs of the market to meet wider sustainability objectives.

Several steps would narrow that divergence. An agreed methodology for demonstrating the contribution of a co-biocide within a formulated system, developed jointly by industry and evaluating authorities before rather than during an evaluation, would replace an unmeetable standard with a testable one. Analyses of alternatives should be evidence-based on performance as well as hazard and risk in use, drawing on field data across representative sea basins, vessel types and operating profiles, and should exclude options whose own approval is unresolved. The aggregate effect of sequential substance decisions on product availability should be assessed explicitly, so that overall availability of solutions is evaluated as a toolbox. Much of the necessary evidence rests with the wider marine industry beyond chemical suppliers and coatings formulators: shipowners, operators, ports, cleaning service providers and classification societies hold the operational data such analyses need.

7. Conclusions

The recommendation for removal of Zinc Pyrithione containing products from the European market is only the next completed evaluation of an antifouling active substance under current regulatory practice, and it is unlikely to be the last of its kind. Its reasoning, that hazardous substances can be removed as sufficiently suitable alternatives are listed on paper, is available to every renewal now in progress; applied consistently it would reduce the number of antifouling products available in Europe to a few copper-based chemistries and non-biocidal technologies whose performance is bounded by availability, costs and operating conditions. The environmental case for that outcome is not established, since acceptable risk to the environment was demonstrated for the service life of the substance. Reconciling this trajectory with an IMO framework under which macrofouling will not be permitted requires a regulatory practice that takes a holistic approach rather than eliminating chemistries in isolation, tests alternatives against field performance, and treats the prevention of biofouling as the environmental objective it is. European decarbonization, Green Deal, biodiversity, supply chain resilience and competitiveness agendas cannot be met if the maritime sector loses access to effective antifouling solutions containing key biocides chemistries. Urgent action across the marine value chain is needed to ensure effective biofouling control remains available in Europe.

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Testing In-Water Cleaning Systems with Capture: Development of a Practical Verification Procedure

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Abstract

Biofouling management increasingly requires in-water cleaning systems that can demonstrate effective removal while preventing the release of biological material and coating residues. This paper presents a Norwegian Green Shipping Programme pilot developing a practical verification procedure for in-water cleaning systems with capture. Ex-situ and in-situ trials were evaluated against ISO 20679:2025 and IMO MEPC.1/Circ.918. The results show that controlled ex-situ testing is best suited for quantifying capture efficiency, while in-situ testing is essential for verifying operational performance. The study proposes practical performance criteria and identifies key parameters for future independent verification and regulatory use.

1. Introduction

In-situ testing under real port conditions is subject to environmental variability, vessel movements, harbour activities, turbulence generated by cleaning equipment, and variation in background water quality. These factors may significantly affect sampling and complicate the quantitative assessment of material that escapes capture during cleaning. Conversely, controlled testing can provide more reproducible conditions but may not adequately demonstrate the operational performance of a cleaning system on an actual vessel.

To address this gap, the Norwegian Green Shipping Programme established the pilot project "Testing of In-Water Cleaning Systems with Capture", led by the Port of Bergen. The project brought together ports, authorities, research institutions, classification and cleaning technology providers. The objective was to develop a practical and representative procedure for independent verification of in-water cleaning systems with capture (IWCS), drawing on ISO 20679:2025 and IMO MEPC.1/Circ.918 while adapting the testing approach to practical operational and regulatory needs.

The study investigated two complementary approaches: controlled ex-situ testing and full-scale in-situ testing. The principal research question was whether these approaches could be combined to provide reliable evidence of capture efficiency, separation and treatment efficiency, cleaning performance, and potential environmental impact from release of coating residues.

2. Methodological Framework

2.1. International Guidance and Test Objectives

The project did not seek to replace ISO 20679:2025 or IMO MEPC.1/Circ.918 but to investigate how their principles could be translated into a practical verification procedure suitable for cleaning providers, independent verifiers and port authorities.

Four performance areas were identified:

1. capture efficiency during the cleaning operation;
2. separation and treatment efficiency for captured material;

3. cleaning efficiency and removal of biofouling; and
4. potential damage to, or release of material from, antifouling coatings.

A central premise of the study was that no single test environment is optimal for evaluating all four aspects. The project therefore investigated a combination of ex-situ and in-situ testing.

2.2. Ex-Situ Pilot Testing

The ex-situ trial was carried out at NIVA's Solbergstrand research facility. Steel plates with a surface area of 10 m² were exposed to natural seawater to establish representative natural biofouling. The plates were subsequently cleaned in a controlled 60 m³ seawater tank using a commercial in-water cleaning system with capture.

Water samples were collected before and after cleaning to quantify material not retained by the capture system. Parameters evaluated included total suspended solids (TSS), particulate organic carbon (POC), total suspended inorganic material, dissolved and total organic carbon, and ATP as an indicator of biological activity.

The controlled test environment allowed the mass of material released during cleaning to be evaluated with substantially less interference from external environmental factors than would be possible during shipboard testing.

2.3. In-Situ Pilot Testing

The in-situ trial was conducted on a cruise vessel berthed in the Port of Bergen. Two cleaning systems were tested during actual hull-cleaning operations, including cleaning of the main hull surface and a niche-area application.

Time-integrated continuous sampling was applied in accordance with the principles of ISO 20679:2025. Samples were collected from background water, water close to the vessel, close the cleaning unit, influent to the separation system and treated effluent. The analytical programme included TSS, POC, particle size distribution, selected metals and ATP-based measurements of biological activity.

The purpose of the in-situ testing was not only to measure environmental performance but also to assess whether the procedures could be implemented reliably under realistic port conditions.

3. Results and Lessons Learned

3.1. Ex-Situ Testing

The ex-situ testing demonstrated the value of a controlled environment for evaluating capture efficiency. Variations in TSS, POC and inorganic particulate matter provided useful information on the amount of material remaining in the test water following cleaning.

The study indicated that particle-based mass measurements provide a more robust basis for evaluating capture performance than changes in concentration alone. Particularly at low background concentrations, relatively small variations may result in large percentage differences without representing a meaningful environmental release.

TSS, POC and inorganic particulate matter were therefore identified as the most relevant parameters for assessment of non-captured material. Increasing sample volumes and using a larger filter pore size were identified as practical means of improving representativeness and analytical robustness.

ATP measurements provided useful supplementary information on biological activity but showed greater variability, particularly in samples containing hard sessile organisms. The results therefore indicate that biological measurements should complement, rather than replace, particle-based assessment of capture efficiency.

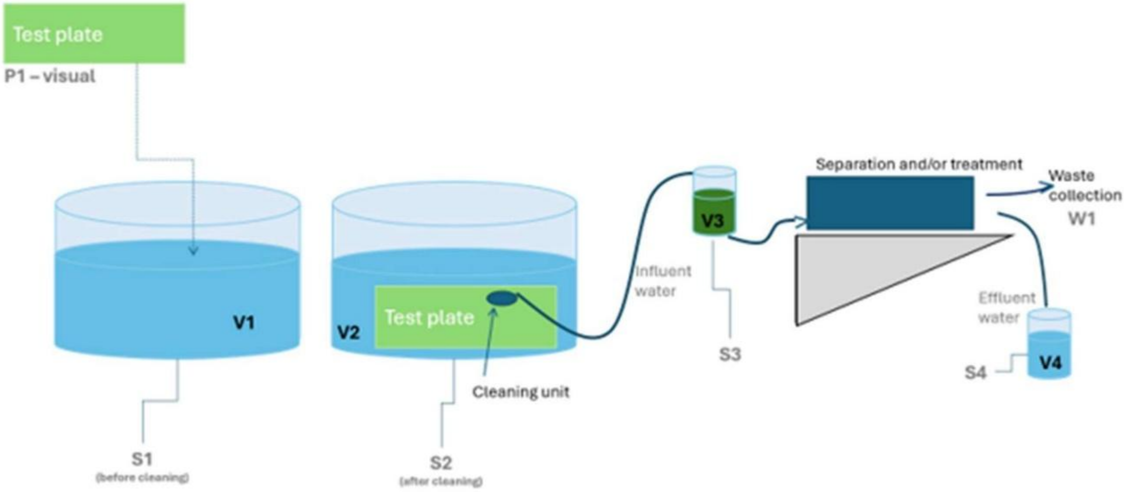

Fig.1: Illustrative presentation of ex-situ test set-up of an in-water cleaning unit, with a separation/ treatment unit. V1 is the volume of water present in the test tank prior to any cleaning. V2 is the volume after cleaning is completed. V3 is the captured volume that subsequently is transferred to volume 4 as managed water. S1-S4 are sample points.

3.2. In-Situ Testing

The in-situ trial demonstrated that full-scale testing is important for confirming operational capabilities and cleaning performance. Visual documentation before and after cleaning provided an effective method for assessing the removal of macrofouling.

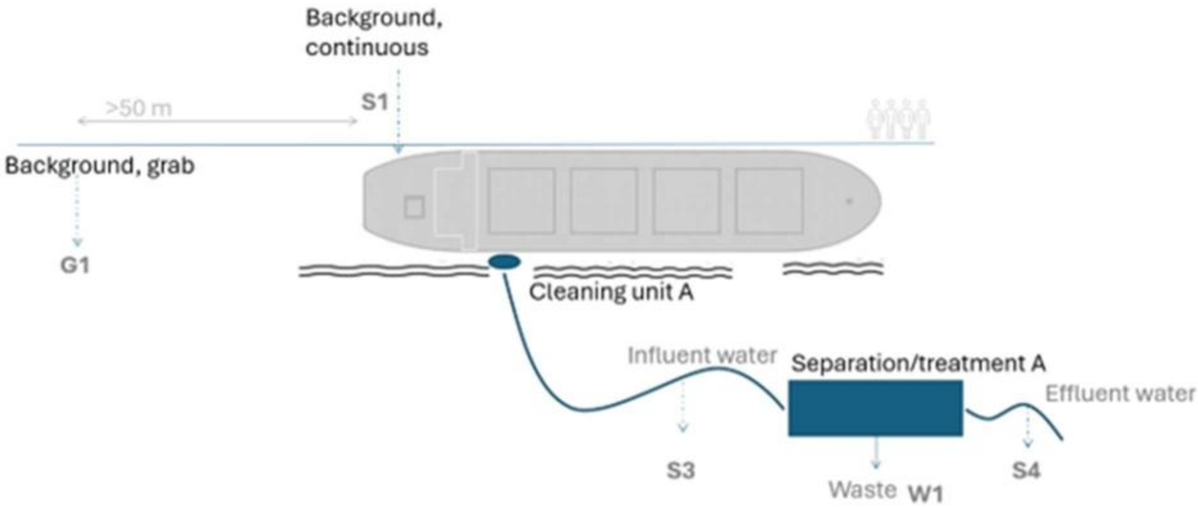

Fig.2: Illustration of in-situ test operations and sample locations (G1 and S1-S3). Collection of waste shall be weighed (W1)

However, the study also identified substantial limitations associated with using samples collected close to the cleaning unit to quantify capture efficiency. Turbulence generated by the cleaning and suction equipment made it difficult to demonstrate that such samples were representative of the material released during cleaning. Background water quality also varied during the test period, possibly due to accumulation of coating residues between the ship side and quay or other harbor activities. The results therefore support continuous characterization of ambient water conditions at the same side of the ship and same distance to surface as the cleaning equipment. A harbor background sample can indicate if the ship's coating has passive release of coating residues -not induced by the cleaning equipment.

Sampling of influent and effluent water during a cleaning cycle of at least 90 min or a full ship side was found to provide a suitable basis for assessing the performance of separation and treatment systems. TSS, POC, inorganic particles, particle size distribution and relevant coating-related metals were identified as useful parameters.

4. The Test Procedure

Based on the pilot results, the proposed verification procedure uses ex-situ testing as the primary method for determining capture efficiency:

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$$Capture\ efficiency\ A1: \frac{mass\ unintentially\ released: S2 * V2 - S1 * V1}{total\ mass\ disloged: (S2 * V2 - S1 * V1) + S3 * V3} * 100\ < 20\%$$

In-situ testing can be used for subsequent verification of operational performance:

$$Separation\ efficiency\ A2: \mathrm{S4} < 20\%\ \mathrm{of\ S3}$$

The pilot group proposed a benchmark performance level of at least 80% capture efficiency and at least 80% separation efficiency. These values should be regarded as pragmatic verification thresholds rather than as definitions of the maximum performance achievable by current technology. The procedure is intended to be refined as additional data, technologies and regulatory requirements become available.

5. Conclusion

One of the principal findings of the study is that test design must distinguish between what can theoretically be measured and what can be measured reliably under practical conditions.

International guidance provides a comprehensive framework for assessing the environmental performance of in-water cleaning systems. Nevertheless, applying sampling procedures directly around an operating cleaning unit introduces uncertainties that may limit the ability to quantify capture efficiency. The controlled ex-situ approach reduces these uncertainties and allows a mass-balance-based assessment of material not retained by the system.

At the same time, laboratory or tank testing cannot replicate all factors associated with cleaning a full-scale vessel. Operational competence, vessel geometry, hydrodynamic conditions and access to niche areas can only be adequately demonstrated under realistic conditions. A combined approach therefore provides a stronger basis for independent verification than either test method alone.

The findings also have implications for ports. Port authorities increasingly need to determine whether cleaning technologies may operate without creating unacceptable risks of invasive-species transfer or pollution. A transparent verification procedure based on measurable performance criteria can provide ports with a more consistent basis for permitting operations while allowing technology providers to demonstrate environmental performance.

Several areas require further development. In particular, additional work is required to establish robust procedures for evaluating compatibility between cleaning systems and different antifouling coatings. Cleaning of complex niche areas, internal structures and grid-like geometries also requires further investigation. Finally, this study focused on systems with capture; different risk assessment and verification approaches may be necessary for cleaning technologies operating without capture.

Acknowledgement

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Assessing the Net Climate Benefit of Proactive Hull Cleaning Solutions

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Abstract

Shipping must reduce greenhouse gas emissions while continuing to move most of the world's traded goods. One practical way to lower emissions is to keep ship hulls clean, since biofouling increases drag, fuel consumption and CO_2 emissions. This paper discusses how proactive robotic hull cleaning, combined with compatible anti-fouling coatings and systematic performance monitoring, can help maintain clean hulls and reduce fuel consumption. It highlights the importance of ISO 19030 as a common framework for measuring hull performance, while also emphasizing the need for independent third-party verification to build confidence in speed-loss and emission-reduction claims. Based on verified performance data, a proactive cleaning solution was shown to achieve no measurable speed loss over an average assessment period of 3.5 years. For one large container vessel, this corresponded to an estimated annual reduction of 17,300 tons of CO_2. The paper also considers the environmental footprint of the solution itself, including the coating system, underwater cleaning robot, and onboard station. The total installation footprint was estimated at approximately 423 tons of CO_2 equivalents, while the lifetime footprint over 25 years was estimated at about 2,036 tons. Compared with an estimated lifetime emission saving of 432,500 tons of CO_2, the avoided emissions clearly outweigh the footprint of the solution. These findings show that verified proactive hull cleaning can be a credible and practical contribution to maritime decarbonization when both avoided emissions and total solution footprint are assessed transparently.

1. Introduction

The shipping industry has been crucial for the globalization of modern society. Maritime transport is the backbone of global trade, moving over 80 % of goods traded worldwide, and is vital for industrial development and economic growth all over the world, *UNCTAD (2025)*. Although shipping is one of the most energy-efficient modes of transport, global shipping also comes at an environmental cost. In 2023, global shipping emitted 911 million tons of CO_2 and is thereby responsible for up to 3 % of the world's total CO_2 emissions, *UNCTAD (2025), Mao et al. (2025)*.

Emissions from maritime transport predominantly originate from the burning of fossil fuels. Increasingly strict regulations related to carbon emissions have resulted in growing industry interest in different approaches to reduce CO_2 emissions. Another important aspect is the economy related to emissions, not only through various carbon taxes such as the EU ETS, but simply because fuel costs money and is responsible for up to 50 % of the operational costs of a ship. Therefore, cutting carbon emissions through fuel preservation will have a double positive effect on the bottom line.

Biofouling on ship's hulls is a critical concern for the global shipping industry. Biofouling increases friction, leads to higher drag and increased fuel consumption. According to a report from Glofouling Partnerships Project from October 2022, protecting ships from biofouling would enable the industry to cut CO_2 emissions by as much as 19 % through fuel preservation, *Glofouling (2022)*. But biofouling is also a threat to marine biodiversity. Global shipping is contributing to the spread of invasive species by bringing foreign marine species into new areas, which can disturb the natural marine ecosystems.

The need to improve sustainability in the shipping industry is accelerating, *IMO (2025)*. The global industry must cut carbon emissions, protect marine biodiversity and reduce the total impact on the environment.

2. The standardization of hull performance

However, in order to improve we need to set a baseline, and we need to measure and monitor the progress. This is where ISO 19030 in 2011 came into the industry, *ISO (2016)*. This standard is commonly cited and has become the most widely accepted industry standard for hull performance monitoring. ISO 19030 provided a common language and understanding of quantifying the changes in hull and propeller performance. This changed the way the industry measured vessel performance and paved the way for performance guarantees of anti-fouling coatings and solutions. Linking average speed loss measurements to fuel consumption and greenhouse gas (GHG) emissions also enabled the industry to make better-informed decisions of how to reduce their emissions while also preserving fuel. However, although ISO 19030 is the most important foundation for performance monitoring, it has some limitations. As pointed out in a recent report, with more high-frequency data becoming available as well as advanced analytics, ISO 19030 does not provide the complete solution, but more the common starting point, *MacDonald and Stevens (2026)*.

3. The importance of third-party verification of emission reduction claims

In order to overcome the limitations of ISO 19030, third party verified data is becoming increasingly important. There is a growing disconnect between the un-verified and often over-optimistic marketing claims, and the practical fuel savings. This can lead to a credibility gap that ultimately results in a lack of trust and willingness to invest in solutions that can help decarbonizing the shipping industry. Independent third-party verifications provide transparent and credible claims that support the industry to accelerate decarbonization and invest in the solutions that is proven to have a practical positive impact on the performance of the vessel, ultimately leading to measurable fuel savings and reduction in emissions.

Lately a third party verified report from DNV states that a robotic proactive hull cleaning solution resulted in no measurable speed loss in accordance to ISO 19030, https://www.jotun.com/ww-en/news-and-insights/jotun-insider/jotun-hss-always-clean-hull-verified-by-dnv. The independent verification was based on in-water inspections of 33 vessels consistently showing absence of fouling and thereby confirming that the inspected hulls remained clean throughout the period of the assessment. In addition to physical inspections, performance monitoring data from 12 of the vessels were evaluated. Analysis of performance data confirmed that over the average period of 3.5 years, including a reference of one year as per ISO 19030, the clean hull condition resulted in no measurable speed loss. This third-party verification directly shows that well-documented inspections combined with systematic performance data analyses in accordance with ISO 19030 provides a clear and transparent method for proving speed loss claims. This also clearly shows that proactive cleaning solutions can provide hull performance beyond what can be achieved with more traditional anti-fouling technologies. This serves as an example of solutions and technologies that provide direct and measurable improvements in performance and, consequently, reduced GHG emissions. As an example, for one of the large container vessels included in the data set (based on high frequency data), this resulted in a reduction in emissions of 17.7 % or 17,300 tons of CO_2 in one year of sailing.

4. Everything comes with a footprint

A robotic proactive cleaning solution consists of three main components; the compatible anti-fouling coating system, the underwater cleaning robot and the onboard station.

Starting with the footprint of the anti-fouling coating system. A typical coating system including an anti-fouling coating compatible with proactive cleaning technologies, consists of three layers of paint; a primer, a tie-coat and the anti-fouling. The products used, the number of layers and thicknesses can all vary depending on e.g. the sailing routes and trading patterns of the vessel in question. However, it can be assumed that for a large container vessel an approximate amount of 40 – 50 000 liters of paint is consumed for the hull. Depending on the build-up of the coating system the thickness distribution between the different layers will be varying, however, for this example a system comprising 200 μm thick primer, followed by 100 µm of tie-coat and 350 µm of anti-fouling coating. The footprint of paint products can be easily found in environmental product declarations, EPDs, and should be readily accessible for a wide range of products from all paint manufacturers. Based on data from EPDs and the assumed paint consumption and thickness distribution of the different layers, the total footprint of the coating system including an anti-fouling coating compatible with proactive cleaning is estimated to be 407 tons of CO_2 equivalents.

A representative underwater cleaning robot consists of a large set of components. From metal frames, composite materials, electronics and cleaning brushes. It is therefore a complex matter to calculate the exact footprint based on each component. However, a simplified approach can be used to make an estimate using the weight of the main groups of components and use available general emission factors from verified third party sources for e.g. electronics, steel, composite materials etc. By summarizing the estimated footprint for the different main groups of components, an underwater cleaning robot used for this case shows a total footprint of approximately 1.1 tons of CO_2.

Lastly the onboard station of which the underwater cleaning robot is stored between missions, and where most of the electronics and equipment required for running the cleaning operation will also have a significant contribution to the footprint of the solution. For this example, a station weighing a total of nearly 4 tons comprising various modules and a base frame. By weight, the main component is structural steel, but also cabinets and electronics which have a higher footprint per kg material contributes to the total footprint. By again assessing the main groups of components and using available relevant general emission factors from verified third party sources, the total estimated footprint of such onboard station is 14.3 tons of CO_2.

The total estimated footprint of the components required for a proactive underwater hull cleaning solution including the compatible anti-fouling coating system is thereby in the range of 423 tons of CO_2. As described, these numbers hold some uncertainty, however, it is considered that this is accurate enough for the purpose of comparing the ratio between the total footprint of the solution and the reduced footprint due to reduction in fuel consumption as a result of the always clean hull. The footprint of the energy used to power the solution is deemed negligible and not considered in this study.

5. Comparing total footprint of proactive cleaning solutions with impact on reduced emissions

When comparing the total footprint of the proactive underwater robotic cleaning solution with the reduced emissions for one year as a result of an always clean hull, we find even with what we consider as conservative estimates, a 50:1 ratio. The main contributor to the footprint of the solution is the anti-fouling coating used, mainly due to the large volume. This volume is predominantly given by the area that is coated and is therefore more or less linearly dependent on the size of the ship. This coating system will be replaced during dry docking with five years intervals. The underwater cleaning robot and the onboard station have an expected lifetime of 10 years. This will likely depend on the number of missions etc. However, it is not expected that any major components will be replaced during the lifetime of the solution.

For a 25-year period, assuming this is the expected lifetime of the vessel, the coating system will have to be replaced four times (in addition to the first time of coating during new build) the under-water cleaning robot and the onboard station will be replaced once. The total footprint of the proactive cleaning solution over the lifetime of the vessel will then be approximately 2,036 tons of CO_2. If assuming that the fuel consumption is more or less the same year on year throughout the lifetime of the vessel, the total fuel savings will be 139 000 tons. This results in an accumulated 432,500 tons of CO_2 savings over 25 years. It is therefore very clear that the positive impact of reduced fuel consumption outweighs the negative environmental footprint of the proactive cleaning solution itself.

6. Conclusions

Global shipping is responsible for a significant contribution of global GHG emissions. Most of these emissions come from the burning of fossil fuels to power the ships. When a ship's hull starts to foul the friction increases and consequently the fuel consumption, and emissions, increases as well.

Although this has been well known for decades it was only with the introduction of the ISO 19030 that the industry gained a common understanding and method for measuring and monitoring hull performance. However, the standard itself only provides a framework, it is how it is being used and implemented that is the key to ensuring that hull performance is correctly assessed, and that e.g. speed loss claims are backed by data. Therefore, it is important to have third party verification of speed loss claims, backed by other data such as inspection data and high frequence data.

Using such methodologies proactive cleaning solutions have achieved a remarkable third party verified milestone, namely delivering "no measurable speed loss". This signifies the importance of and potential of proactive cleaning solutions as a means to effectively reduce the emissions from ships. However, all solutions come with a footprint, and it is therefore important to assess the negative environmental footprint of the solution with the positive impact that solution will have through fuel savings and reduced GHG emissions.

In this study it was shown that a proactive cleaning solution comprises three main components, the compatible anti-fouling coating system, the underwater cleaning robot, and the onboard station. The total footprint of the solution upon installation was calculated to be around 423 tons of CO_2. While the positive impact due to reduced emissions was estimated to be 17,300 tons of CO_2 for one year for one large container vessel. Over an assumed lifetime of 25 years the total emissions savings from the solution for the same large container vessel was estimated to be 432,500 tons of CO_2, while the footprint of the proactive underwater cleaning solution was estimated to be 2,036 tons of CO_2. Hence, based on this the negative footprint of the solutions is more than compensated for by the positive impact the solution will have. It is our opinion that third-party verified speed loss claims, together with assessments of the total footprint over the lifetime of the ships provides a good foundation for making well-informed decisions that reduces the total emissions of GHG in practice.

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When Safety Becomes a Commercial Variable

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Abstract

Underwater ship husbandry remains a highly fragmented local service market, where contractor selection is often driven by price, availability and local presence rather than by a transparent comparison of safety standards. Propeller polishing illustrates this dynamic well: although it can deliver measurable operational value, the service is typically procured from locally available providers competing within a relatively low-margin market. At the same time, industry expectations regarding safety, contractor assurance, documentation and operational control are increasing. This paper argues that vessel charterers, vessel owners and technical managers should adopt a minimum safety-baseline model for underwater maintenance, supported by procurement requirements, charterparty clauses and vessel assurance processes. Such a shift would improve safety performance across the industry while changing the economic comparison between diving and robotic alternatives. As the cost of compliant diving operations increases and robotic systems continue to benefit from automation and scale, the business case for robotics becomes progressively stronger.

1. Introduction

Underwater ship husbandry has historically been treated as a local and operational service, with varying levels of standardisation and governance, *Noordstrand (2020)*. Whether the task is hull cleaning, propeller polishing, underwater inspection or minor maintenance below the waterline, buyers typically compare availability, speed and price. Propeller polishing is a useful example of this broader market dynamic. It is a standardised service offered in ports and anchorages worldwide. Although it can create measurable value through improved vessel efficiency and reduced fuel consumption, the market rarely captures this through value-based pricing. Instead, charterers, ship owners and technical managers often influence or determine contractor selection based on local cost, timing and availability.

This commercial framing understates the nature of the work. Underwater ship husbandry is not a low-risk maintenance activity. It often involves commercial divers working around propellers, thrusters, sea chests, intakes, discharges, limited visibility, vessel movement and sometimes live systems. A failure in planning, communication, emergency readiness or contractor competence can have severe consequences, including serious injury or fatalities. The fact that the final output may look routine, such as a polished propeller or a cleaned hull section, should not obscure the operational risk involved in getting that result.

This market structure means that underwater ship husbandry is generally priced closer to cost-plus than value-based pricing. Because many contractors can offer similar services, contractors have limited pricing power and are pushed to compete on their local cost base plus the margin the market will accept. Lower costs may reflect legitimate advantages such as wages, efficient mobilisation, high vessel volume or lower overhead. However, they may also reflect a lighter safety setup, such as smaller teams, less equipment, limited standby capability, weaker emergency procedures or insufficient documentation. The commercial challenge is that the visible output may look similar to the buyer, while the underlying safety standard can be materially different.

This price-driven structure also helps explain why divers still dominate many underwater maintenance activities, even where robotic or semi-robotic systems could technically perform the work. For many standard tasks, diver-based services remain cheaper on a direct-cost basis, which has made it difficult for robotics startups and scaleups to build a profitable and scalable business case. Yet if the lowest-cost option reflects a lower safety-cost structure, the comparison is not fully like-for-like. The central issue is therefore not whether divers or robots are technically better, but that underwater ship husbandry is often bought as a commodity while the safety standard behind the service can differ materially between contractors, ports and regulatory environments.

2. The Safety Behind the Price

Price differences between ports are not automatically evidence of lower safety. A contractor in Rotterdam may simply have a higher cost base than a contractor in Las Palmas, Singapore or another high-volume maritime hub. Labour costs, employer charges, insurance, local regulation, port access, equipment availability and overhead can all differ materially. Lower wages or lower overhead do not automatically mean lower safety. A team in a lower-cost region can be highly experienced and operate professionally. Conversely, a higher price does not automatically guarantee a higher safety standard.

The market does not automatically solve this problem because buyers usually observe the final maintenance result rather than the safety system behind the operation. A polished propeller, cleaned hull section or completed underwater inspection may look similar in the final report, even when the underlying team composition, diving method, emergency readiness and documentation are materially different. Because the safety architecture behind the service is difficult to see and compare, it is also difficult to reward commercially. As a result, contractors that invest in stronger supervision, standby capability, emergency procedures, equipment and documentation may not always be clearly distinguished from contractors offering the same visible output at a lower price. This creates a risk that safety becomes an invisible commercial variable rather than an explicit procurement requirement.

The real issue is therefore transparency. A buyer may receive two quotations for the same underwater maintenance activity, while the operating models behind those quotations are materially different. If a lower price reflects lower wages, better utilisation or more efficient mobilisation, that is normal competition. But if it reflects fewer people, weaker emergency readiness, less suitable equipment or limited documentation, then safety has effectively become part of the commercial discount. Underwater ship husbandry should therefore not only be compared on price, but also on the safety standard behind the service.

Several safety-related factors have a direct impact on the cost of a diving operation, *IMCA (2024)*:

1. <u>Team size</u>
   A more robust dive operation includes a diving supervisor, working diver, standby rescue diver and two umbilical tenders. A larger team increases the direct cost of the job, but also improves supervision, emergency response capability and operational redundancy.
2. <u>Diving method</u>
   SCUBA-based operations are generally cheaper and easier to mobilise. Surface-supplied diving requires more equipment, communication systems, procedures and support personnel, but provides stronger control, communication and emergency readiness. The choice of diving method therefore has a direct impact on both cost and risk profile.
3. <u>Competence and certification</u>
   Properly trained commercial divers, qualified supervisors, medical checks, equipment maintenance and documented procedures all increase the contractor's cost base. These elements may not visibly improve the final cleaning or polishing result, but they materially influence the safety and reliability of the operation.
4. <u>Emergency readiness and procedures</u>
   The presence of a standby diver, clear rescue procedures, communication protocols, risk assessments and permit-to-work processes can significantly affect the ability to respond to an incident. These controls add preparation time and cost, but are central to reducing operational risk.
5. <u>Insurance and liability exposure</u>
   Insurance and liability costs are particularly relevant in highly regulated jurisdictions. They may not always be the largest cost item, but they reflect the broader legal and financial environment in which the contractor operates. Contractors working under stricter compliance regimes often carry higher overhead and risk-management costs.

The commercial challenge is that the visible output may look similar to the buyer. A propeller is polished, a hull section is cleaned, or an underwater inspection is completed. However, the underlying safety architecture may be materially different. In other words, the lowest price is only meaningful if the underlying safety standard is comparable.

3. From Transactional Maintenance to Safety Governance

Underwater ship husbandry is often arranged as a transactional maintenance activity: a vessel requires cleaning, polishing or inspection, a local contractor is selected, and the work is executed based on price, availability and timing. Some leading operators and technical managers already apply contractor screening, HSE review and approved-supplier processes. However, these practices are not yet consistently applied across the wider underwater ship husbandry market, especially for routine work purchased port by port. The issue is therefore not that safety governance is absent everywhere, but that the level of documentation, consistency and transparency varies significantly.

Depending on the contractual structure, charterers, ship owners and technical managers may all influence when underwater maintenance is performed, which contractor is selected and what standard is required. The diving contractor remains responsible for executing the work safely, but the wider shipping chain should be able to demonstrate that contractor selection was not based on price alone. ISO 45001 provides a useful framework for this discussion because it focuses on occupational health and safety and includes requirements related to procurement, contractors and outsourced functions (ISO, 2018). For high-risk activities such as commercial diving, contractor selection should therefore not be treated as a simple administrative or commercial decision.

A practical response is to introduce a minimum safety baseline for underwater maintenance. This baseline should not prescribe one specific contractor or restrict local competition unnecessarily. Instead, it should define the minimum conditions under which the work may be performed. At a minimum, buyers should require evidence of contractor competence, appropriate diving method, minimum team composition, documented risk assessment, emergency response capability, insurance coverage, work records and compliance with recognised industry standards, *IMO (2025)*. These requirements allow price competition to continue, but only above a defined safety threshold.

The challenge is not only performing the work safely, but demonstrating afterwards that it was performed safely and according to procedure. For underwater maintenance, evidence should become part of the service itself: risk assessments, dive logs, completion reports, photographs, video records, equipment records and, where applicable, digital inspection or robotic data. This shifts underwater maintenance from a service that is merely executed locally to an activity that can be reviewed, audited and compared across vessels, ports and contractors.

This does not mean that charterers, ship owners or technical managers must directly manage every aspect of the diving operation. They are not expected to supervise the diver underwater or prescribe every operational detail. However, they can require that high-risk outsourced maintenance is selected, documented and verified in a consistent way. Vessel assurance should therefore not only look at the condition of the vessel itself, but also at how critical outsourced maintenance activities are procured and controlled. In other words, the question should no longer be only who can perform the work at the lowest price, but who can perform it at the required safety standard and prove it.

4. Implications for Robotics

If the safety standard for diving operations increases, the cost base of diver-based services will increase as well. Larger dive teams, standby capability, surface-supplied diving equipment, qualified supervision, documented procedures, emergency readiness and compliance requirements all add cost. These measures improve the safety profile of underwater maintenance, but they also raise the market price for performing the work safely and verifiably.

This changes the commercial comparison between divers and robotic alternatives. Today, robotic systems often compete against the lowest-cost diving option available in a port or anchorage. If that option is based on a lower safety-cost structure, the comparison is not fully like-for-like. Once underwater maintenance must meet a consistent minimum safety baseline, the benchmark changes: the robot is no longer compared against the cheapest available diver, but against a compliant diving operation with appropriate personnel, equipment, procedures, emergency readiness and documentation.

In that environment, robotics becomes more commercially relevant. Robotic and semi-robotic systems can reduce human exposure underwater, standardise execution and create digital evidence of the work performed through video records, inspection data, digital reports and repeatable procedures. For technology providers, the opportunity is therefore not only to automate underwater work, but to make underwater maintenance safer, more standardised and more verifiable. A stronger safety-baseline model does not remove the need for divers in every situation, but it does create a more balanced commercial environment in which robotic solutions can scale.

5. Conclusion

Underwater ship husbandry remains a competitive and cost-driven market. Propeller polishing, hull cleaning and underwater inspections are often purchased as commodities, while the underlying safety standard can differ materially between contractors, ports and regulatory environments. The visible result may look the same, but the safety architecture behind the work may be very different.

The industry should therefore move towards a minimum safety-baseline model. Price competition should continue, but only above an agreed safety threshold. This would reduce the risk that safety becomes part of the commercial discount and create a fairer comparison between compliant diving operations and robotic alternatives. The long-term opportunity is not simply to replace divers with robots, but to redefine underwater maintenance as a safer, more standardised and more verifiable part of vessel assurance.

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System Architecture and Hull-Referenced Localization for Robotic Ship Hull Cleaning

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Abstract

This paper presents a novel multi-platform system architecture for robotic-aided ship hull cleaning. The system combines an Uncrewed Surface Vehicle (USV) used as a flexible deployment platform for a Remotely Operated Vehicle (ROV) for in-water hull cleaning, both integrated within a common tandem control law and linked through an adaptive Launch And Recovery System (LARS). For over-water relative positioning, the USV uses short baseline (SBL) acoustic positioning, specifically aimed for shallow waters. For the underwater localization, a hull-referenced pose estimator is fused with a landmark detection and map matching algorithm. Due to hull geometry and multipath effects, hydroacoustic communication between ROV and USV cannot be guaranteed. Therefore, robust self-localization relies on visual referencing against a photogrammetric hull model as ground truth, supported by a factor graph-based multi-sensor fusion backend and a list of known features, that are charted on the hull-referenced map. A custom feature detector, trained on both real-world and simulated data, enables reliable visual detection and tracking under challenging underwater conditions. This paper presents the system design, describes the USV-ROV tandem and localization approach, and reports results from field trials on representative hull geometries. In a first sea trial on a 50m vessel, the SBL coverage only available during ROV's free sail mode, while the hull-reference estimate remained continuously available and consistent with the ship hull model to within 1m on a track along the whole length of the vessel inspected, while building a map of 10 semantic landmarks, of which 4 were verified as anodes.

1. Introduction

Biofouling on ship hulls poses a persistent operational and environmental challenge for the maritime industry. Accumulation of marine organisms increases hydrodynamic drag, raises fuel consumption, and facilitates the transfer of invasive species across marine ecosystems, *Korslund and Johansen (2025), Barrère (2025)*. As biofouling increases hull roughness and frictional resistance, even light slime films can raise the fuel consumptions significantly, with reported increase of ~10-20 % for slime deposition and even higher for calcareous fouling, *Schultz et al. (2010), Schultz (2007)*. IMO estimates that a 0.5 mm slime layer covering half of the wetted surface can increase GHG emissions by roughly 20–25 %, *IMO (2023)*. Conventional hull maintenance, typically performed in dry dock, is costly, time-consuming, and increasingly subject to tightening environmental regulations. Proactive, in-water cleaning by robotic systems has therefore emerged as a promising alternative, *Bertram (2022), Lander (2022,2023), Loefler et al. (2025)*. Proactive grooming at short intervals keeps fouling in the slime stage and preserves coating integrity, *Tribou and Swain (2010),* which suggest short and repetitive ship hull cleaning operations, that favor automation.

In order to automate the process of ship hull cleaning, underwater vehicles with adequate equipment can be used. The process would generally involve two human operators, one handling robot navigation and the other managing the tether cable. By deploying the ROV from an USV, the tether management task is offloaded onto the latter. Provided that the USV can autonomously navigate and adjust the tether length, the operation can be conducted with a single operator. However, increasing the autonomy level to deliver fully autonomous underwater hull maintenance remains technically demanding, even when using a fully autonomous USV. Reliable self-localization beneath a vessel is hindered by several factors. Global positioning coupled with acoustic positioning systems requires seafloor deployment of acoustic receivers for accurate localization, while vessel-mounted receivers are affected by hull curvature and appendages that break line-of-sight to the ROV. Mapping the global position to a hull-referenced position further requires computationally demanding algorithms and a flawless 3D model of the ship hull. In addition, magnetic distortions from the steel hull structure invalidate magnetometer readings, and acoustic propagation is degraded by multipath effects in shallow, confined water environments, *Paull et al. (2014), Tan et al. (2011).*

This paper presents a multi-platform robotic system developed to address these challenges. The system integrates three complementary robotic platforms as shown in Fig.1 and consists of: (1) a magnetic inspection crawler for above-waterline and near-surface hull inspection, (2) an USV providing above-water situational awareness and communication relay, and (3) a ROV dedicated to submerged hull cleaning and damage assessment. All platforms are coordinated via a Remote Operation Center (ROC) and visualized (4).

The architecture builds directly on the work of *Zantopp et al. (2022),* who introduced the in-house built SeaML:SeaLion USV, *Zantopp et al. (2024), Müller et al. (2024),* with an integrated Launch and Recovery System (LARS) for deploying a small-size commercial ROV, using Short Baseline (SBL) acoustic positioning fused with IMU, DVL, and depth sensor in a generalized Extended Kalman Filter (EKF). Field trials in Hamburg confirmed that hull occlusion and acoustic multipath cause SBL dropouts, requiring dead-reckoning fallback. The present work extends this platform, retaining the same USV infrastructure in upgraded form called SeaML:SeaDragon, *Werner et al. (2025), Delea et al. (2025)*, and replaces the generic ROV with the Greensea Hull Service Robot (HSR), *Lander (2022, 2023)*, which achieves hull-relative "hullographic" positioning through fusing fiber-optic gyroscope (FOG), DVL, tracks encoders, and forward-looking multibeam sonar with feature-based loop closure, achieving ±15 cm accuracy.

Further related work addresses complementary aspects of hull-relative localization. *Paranhos (2020)* demonstrates self-referenced laser scanning that estimates sensor pose relative to the hull without any acoustic reference. *Vonach and Carrera Viñas (2024)* present the Relative Object Navigation algorithm for AUV localization via rotating sonar without global reference, validated at 10 cm accuracy in the ports of Rotterdam and Antwerp. *Guéré and Gambini (2021)* demonstrate AI-based fouling classification achieving 97% accuracy for niche area identification, motivating the custom feature detector described in Section III.

Building on these findings, the present paper advances the state of the art through three contributions: (i) a three-layer, three-platform architecture in which all localization outputs are expressed in a single persistent ship-referenced frame shared with planning, coverage and digital-twin logging; (ii) hull-manifold-constrained estimation scheme that decouples the geometric hull representation (offline-sampled photogrammetric hull model) from the estimation backend (GTSAM/iSAM2), yielding constant-time surface projection and reuse of the same representation for path and coverage planning; visual self-localization referenced against a photogrammetric hull model as ground truth, following the reverse-engineering approach surveyed by *Bertram and Harries (2022)*, rather than acoustic-only localization; and (iii) a custom feature detector, trained jointly on real-world and simulated underwater imagery, with semantic hull-feature front-end (anodes, sea-chest gratings, propellers, thrusters), having impact-angle-weighted false-positive suppression, providing landmark candidates for loop closure in challenging visual conditions; (iv) an empirical characterization of SBL availability under a real hull, quantifying why acoustic-only localization is insufficient.

2. System Architecture

Fig.1 illustrates the overall system architecture. It is organised into four functional layers: (i) the Operation Service Layer; (ii) the Information Model Layer; (iii) the Inspection & Cleaning Layer; and (iv) the Remote Operation Centre. Several robotic assets for hull inspection and cleaning are integrated into the system, including a magnetic crawler, an USV and a ROV. Although these platforms differ in terms of actuation, sensing and operational envelopes, their localisation outputs are represented in a common, hull-referenced coordinate system, enabling unified monitoring, planning and documentation. At the platform level, a tandem composed of an USV and an ROV simplifies the tether management problem, thereby not stretched over the ship hull and thus significantly lowering the chances for entanglement. The USV can either hold its position or maintain a constant relative distance to the pose of the ROV. In either case, the tether length can be geometrically calculated and set by the USV. However, because the relative positioning relies on the triangulation of the acoustic signals received from the SBL transponder onboard the ROV, whose signal can be obstructed when operating underneath the vessel or on the opposite side, the relative positioning is prone to acoustic jitter. To overcome this limitation, the underwater localization uses the hull-referenced estimation scheme that fuses on-board sensor data.

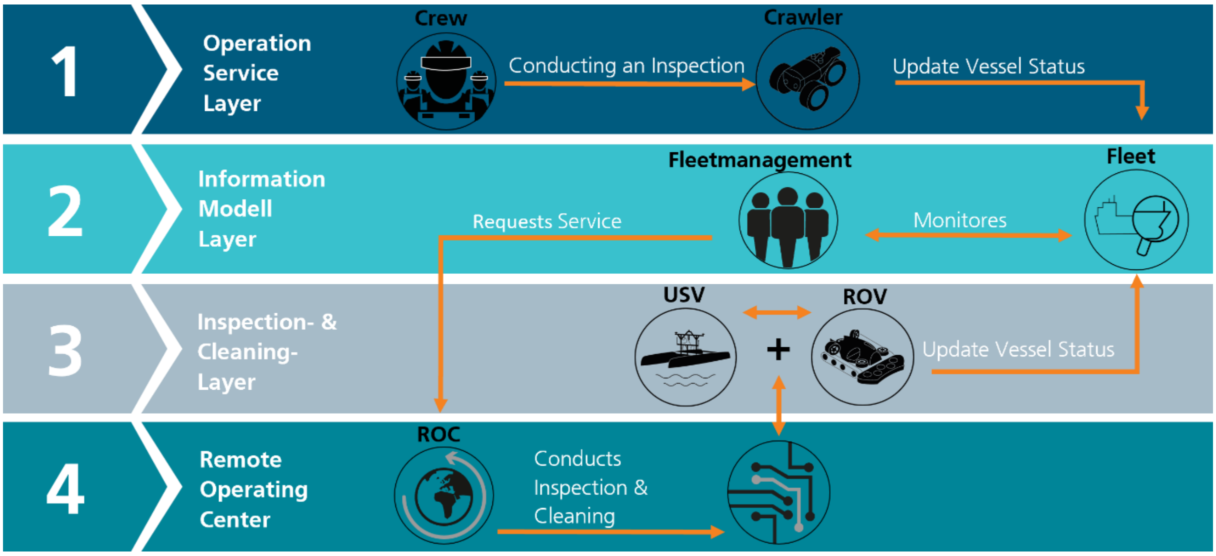

Fig.1: The layers of multi-platform robotic system, consisting in four layers: (1) a magnetic inspection crawler for above-waterline and near-surface hull inspection, (2) an USV providing above-water situational awareness and communication relay, and (3) a ROV dedicated to submerged hull cleaning and damage assessment. All platforms are coordinated via a Remote Operation Center (ROC) and visualized (4).

In the current implementation, the localization subsystem is centered on a surface-constrained, model-based estimation pipeline. Rather than building a map, the robot is localized with respect to a predefined origin, located in the mass center of ship hull mesh model derived from a CAD or photogrammetric reconstruction. Because the vessel geometry is known a priori, the system is deliberately not a general-purpose SLAM stack but a persistent, model-based localization framework on a known manifold - a choice that trades map-building generality for repeatability across deployments. The ROV telemetry provides the primary navigation input. These measurements are transformed into the global ship model frame using a configurable map-frame origin and axis mapping. The resulting coarse pose estimate is then projected onto a precomputed hull surface graph derived offline from the ship mesh. The surface-consistent pose is finally inserted into a GTSAM/iSAM2, *Dellaert & GTSAM Contributors (2022),* backend, which estimates and publishes a stable robot pose in the common map frame.

A key architectural decision is the explicit separation between geometric hull representation and state estimation. The mesh itself is not directly inserted into the factor graph. Instead, it is sampled offline and converted into a discrete surface graph representation. This graph is used online for nearest-neighbor surface projection, path planning, and coverage planning. The advantage of this design is twofold: first, it keeps the estimation backend lightweight and robust; second, it provides a common geometric abstraction for both localization and surface-bound mission planning. The same hull representation therefore supports localization, visualization, point-to-point routing, and cleaning coverage generation.

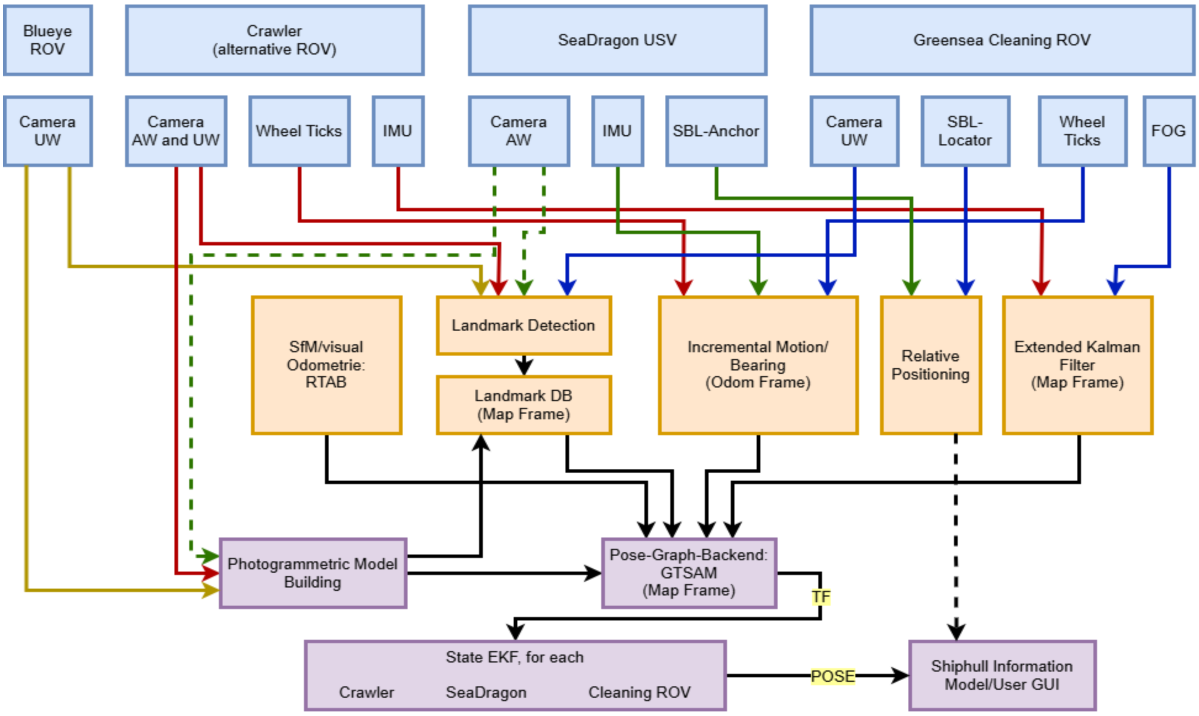

Fig.2: System architecture for self-localization and pose estimation of robotic platforms. The data processing pipeline fuses navigation and sensor signals (camera, IMU, wheel/tire ticks, SBL) through visual odometry (RTAB-SLAM), particle filter, and pose graph optimization (GTSAM) within a common map frame. The estimated vehicle poses enable robust, drift-minimal navigation independent of GNSS and magnetic disturbances, as well as georeferencing of inspection and cleaning survey data. Dashed lines indicate future extensible functionalities.

The software architecture is implemented in ROS 2, *Macenski et al. (2022),* and follows a modular node-based structure. A telemetry parsing component receives ROV's navigation data and publishes map-framed pose estimation. In the current surface-constrained configuration, this frontend applies a configurable coordinate mapping, latches the map-frame zero after reset, projects the resulting position onto the hull surface graph, and publishes the resulting pose as an absolute localization fix. A dedicated GTSAM backend node consumes these fixes, and optionally relative motion increments, to generate optimized pose estimates, paths, and TF transforms. The coordinate-frame convention, initialization procedure, and work-to-map transformation are described in Section III.

From a systems perspective, this architecture provides a significant practical benefit for hull cleaning and inspection missions: localization, path planning and inspection all operate within the same persistent ship-referenced frame. This allows for a repeatable return to relevant hull areas, tracking of mission progress across deployments. For this reason, it is more accurate to understand the system as a persistent, model-based localization framework for operations on a known hull surface than as a generic map-building SLAM stack.

3. Localization Approach

Reliable localization during underwater hull operations is challenging because the vehicle operates in a GNSS-denied environment, often in close proximity to large metallic structures and in areas with poor acoustic and visual observability. In particular, acoustic positioning based on SBL or related methods can provide useful global information in open water or near the waterline, but it cannot guarantee uninterrupted coverage beneath the hull. Line-of-sight occlusion by the vessel body and strong multipath propagation can lead to temporary or extended signal loss, especially in keel and underbody regions, Fig.3. For this reason, SBL is treated in the present architecture as a supportive navigation source rather than the sole localization solution.

The implemented localization strategy therefore uses the known hull geometry itself as the principal global reference. Instead of estimating the robot pose in an unconstrained free-space volume, the method assumes that the vehicle moves on or very near the ship hull surface. This assumption is physically well justified for a hull cleaning crawler or hull-contact inspection platform and allows the estimation problem to be reduced from unconstrained 6-DOF motion in 3D to motion that is strongly constrained by the hull manifold. The resulting formulation is better suited to the operational scenario than a generic map-building SLAM pipeline.

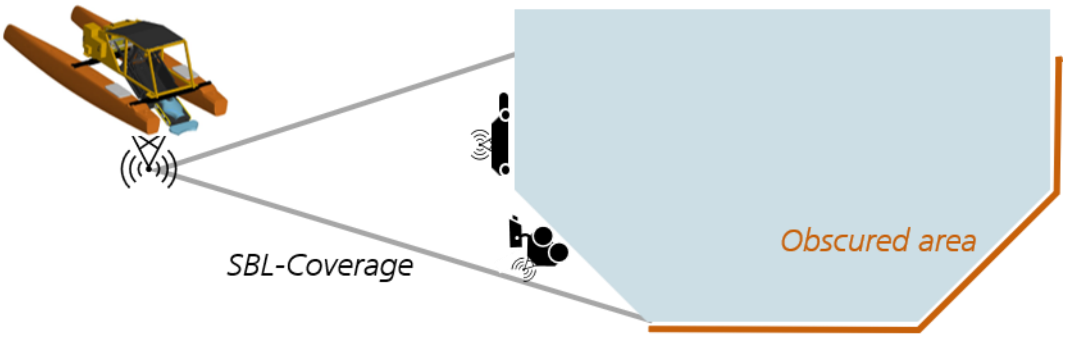

Fig.3: Example of the localization of the Crawler and Cleaning ROV using SBL showing the missing coverage. The USV on the left uses four SBL anchors, while the ROV uses a receiver.

The localization architecture uses three principal reference frames: *map*, *odom*, and *base_link*. In the present implementation, the map frame coincides with the ship or CAD model frame and is therefore the persistent reference for localization, visualization, and planning. The *odom* frame represents a local dead-reckoning frame generated from relative motion integration, while *base_link* denotes the robot body frame. The optimized transform map → *base_link* is published by the GTSAM backend, whereas *odom* → *base_link* is generated by the odometry integrator. This separation allows direct comparison between local dead reckoning and globally constrained estimation.

The current pipeline begins with ROV map-frame telemetry, which provides the quantities *work_x*, *work_y*, depth, and heading. The initialization procedure is based on a single configurable parameter, *work_origin_in_map*, which defines the map-frame initialization position. When the reset service is triggered, the backend is re-initialized at this position and the parser latches the current map-frame telemetry sample as the local zero. All subsequent ROV map-frame motion is then interpreted relative to this reset point. This mechanism provides a reproducible alignment between vehicle telemetry and the digital hull model and simplifies repeated deployment at known hull locations. The reset-relative telemetry increments are mapped to the ship-model coordinate convention through a configurable linear axis mapping. Let $(\Delta x_w, \Delta y_w, \Delta d_w)$ denote the motion in the ROV map-frame relative to the latched zero. The coarse map-frame position is then computed by

$$\mathbf{p}_{map} = \mathbf{p}_0 + \Delta x_w\, \mathbf{a}_x + \Delta y_w\, \mathbf{a}_y + \Delta d_w\, \mathbf{a}_d$$

where p_0 is the configured map-frame initialization position specified by *work_origin_in_map*, and a_x, a_y and a_d are configurable direction vectors describing how the ROV telemetry axes are aligned with the ship model frame. In the current setup, these parameters are chosen such that motion along the map-frame axes is mapped consistently onto the longitudinal and vertical directions of the hull model. This configurable formulation proved useful in practice because the exact correspondence between vehicle telemetry conventions and CAD model orientation depends on installation, mesh alignment, and mission setup.

A crucial step of the method is the projection of this coarse pose estimate onto the hull surface. The CAD mesh is not used directly during online estimation. Instead, it is sampled offline to generate a discrete surface graph, stored as a dictionary object. During runtime, the transformed map-frame position is projected to the nearest valid node of this graph. In the current configuration, nearest-neighbor lookup is performed in a selected 2D coordinate subspace, for example the $x - z$ plane, while the full 3D coordinates of the corresponding graph node define the final surface-consistent position. In addition, a surface normal filter is applied to ensure that projection occurs onto the correct side of the hull. This prevents ambiguities between port and starboard or between interior and exterior surface candidates when the geometry is locally similar.

The use of offline mesh sampling followed by online surface snapping offers several practical advantages. First, it enforces geometric consistency with the known hull surface and prevents the robot from drifting away from the hull in the global estimate. Second, it avoids the computational complexity of direct point-to-mesh optimization inside the state estimator. Third, it allows the same representation to be reused for graph-based path planning and cleaning coverage generation. The surface graph therefore acts as a shared geometric substrate for estimation, planning, and mission execution.

After surface projection, the resulting pose is published as an absolute localization fix and inserted into a GTSAM/iSAM2 backend. The backend maintains pose states and supports incremental optimization. In the current default configuration, the backend operates in a surface-only tracking mode: relative motion increments are ignored, each incoming snapped surface pose is inserted as a new state, and the optimized result is published as the robot pose in the map frame. This operating mode is defined by the parameter combination *publish_deltas*: false, *ignore_deltas*: true, and *fix_creates_new_state*: true. Consequently, the current implementation should be interpreted as a graph-based smoothing and consistency framework for surface-constrained absolute fixes rather than as a fully coupled odometry-plus-landmark SLAM solution.

Orientation is handled separately from the position. While the position estimate is dominated by map-frame coordinates and surface projection, the robot heading is derived from ROV heading telemetry and converted into the *base_link* orientation through a configurable heading model. Additional parameters such as yaw offset and vehicle mode are used to account for crawler- or ROV-specific orientation conventions. This separation between positional surface consistency and heading calibration proved beneficial in practice: positional misalignment is corrected through map-frame axis mapping and surface projection, while directional misalignment is corrected through heading conversion rather than by rotating the hull mesh itself.

Fig.4: View from the front camera showing a marking (black circle) and an anode (green circle) on the hull (left). Same features, as well as the driven path (green line), on the ship's hull (right). This is a projection onto a 3D model of the ship's hull. The left end of the path represents the ROV's coordinate system with its three axes. This is located in the center of the ROV.

Although the present implementation already provides a core localization capability, it also defines a clear development path toward richer multi-sensor fusion. The repository already contains delta builders for DVL-based, track-based, and pose-difference-based motion increments. These can be fused with the surface-constrained fixes to improve short-term motion consistency.

Beyond these motion-based extensions, a further key direction for improving robustness and drift correction lies in the exploitation of semantically meaningful visual features on the hull surface, which is addressed by the landmark-based semantic mapping component described in the following.

The landmark-based semantic mapper (based on *Werner (2026)*) builds a map of different objects (landmarks) with class labels (semantics), which represents the environment around the crawler. Traditional maps are geometry points/lines/occupancy without categories while semantic maps are more compact with object encodings and their positions. Furthermore, it can also improve loop closure in texture-poor, turbulent environments with varying lighting conditions because semantic distinct features remain recognizable. The semantic mapping layer of the system architecture is comprised of instance segmentation, projection onto the hull plane, and data association.

Firstly, the detector segments structural features hull parts, like anodes, sea chest grating, propellers and thrusters using a YOLOv8s-seg model. Then, each detection is projected onto the hull plane by fisheye undistortion and inverse perspective mapping through the calibrated monocular camera. Each projected object is filtered in a false-positive suppression stage by detection score, impact-angle weighting, association radius and a minimum hit count. The output is a confirmed list of hull features and visualized on an occupancy grid map with class, distance and mean score, Fig.4. These landmarks can be integrated in GTSAM factor graph, to correct drift and refine both trajectory and landmark positions.

In the next step, visual landmark detections can be integrated either as pose fixes or as explicit landmark factors in the factor graph. A further extension would replace the current hard snapping strategy by a GTSAM-native distance-to-surface factor, allowing the estimator to penalize deviations from the hull continuously rather than through discrete nearest-neighbor projection. In this sense, the implemented method should be viewed as the stable model-based localization core of a broader future ship-hull state estimation architecture.

4. Field Trials & Results

The results of this work are derived from the data gathered between 18-19.8.2026 on a vessel located in a protected harbor in the city of Eckernförde, Germany. The inspected vessel was docked onto a pier and the inspection was conducted on its port side and underneath its keel. Starting with a 50m ship to be inspected it was accompanied by USV SeaDragon with its LARS, carrying the HSR. The forementioned crawler was not in use.

Due to being in the early stages of integration, the underwater localization and the landmark detector have not been fused together into a common Simultaneous Localization and Mapping (SLAM) pipeline. In addition, no map matching between the identified semantic landmarks and the actual position on the ship hull on the photogrammetric ship model has been conducted to obtain loop closure.

The 2D projected track of the ROV on the ship's hull is augmented with the detected and identified landmarks (i.e. anodes), Fig.5. The hull-reference estimate remained continuously available and consistent with the ship hull model to within 1 m on a track along the whole length of the inspected vessel, while a map of 10 semantic landmarks was built, of which four were verified as anodes and six were false positives. As the hull-referenced localization is not yet integrated with the landmark detector, the pose estimation onto the 3D ship hull does not yet include the detected landmarks.

Although the current results are surface-constrained and, hence, needing adaptation for scaling the solution for different vessels to be inspected, the architecture is intentionally designed with the prerequisite of having a known vessel model. The current results cannot quantify the performance of the localization methods with the augmentation of the landmark detection. The current implementation already contains motion-increment builders for pose differences, DVL data, and starboard/port track telemetry. The components have been individually tested and are currently being integrated for a full SLAM approach, but they provide the basis for future fusion of hull-constrained absolute fixes with short-term odometry, which will be published in a separate work. In the longer term, the same backend will be extended with visual landmark detections, semantic hull features, loop closures, and CAD landmark anchors.

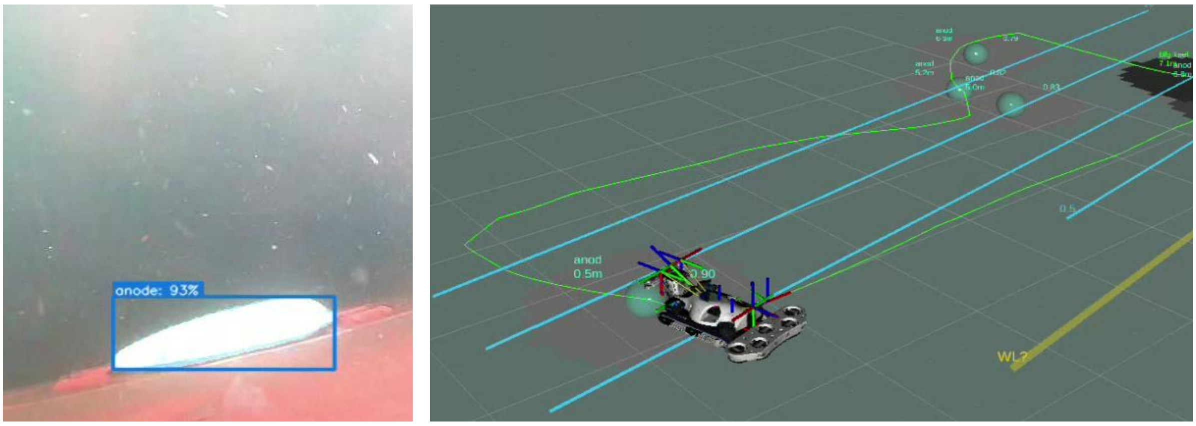

Fig.5: The left side shows an anode detected by the rear camera with a certainty of 93%. The right side shows the ROV with its position relating to detected features. The yellow line shows the waterline, while the light blue lines represent depth readings of 0.5 m and the fine green line the driven path. Behind the ROV is the detected anode shown on the left. A feature is mapped by sphere, labeled with name and certainty and a distance to the ROV is given.

5. Conclusion & Outlook

The field trials have demonstrated that the proposed GTSAM-based localization approach is viable and provides a stable, hull-referenced pose estimate under real-world operating conditions, even though further parameter tuning and validation across additional hull geometries are required. A factor-graph formulation is chosen because the problem is one of fusing heterogeneous, intermittently available and partly outlier-prone measurements into a single consistent trajectory. This model-based formulation proved to be well suited to the constrained, GNSS-denied, and acoustically challenging environment beneath a ship hull. Building on the current implementation, the target system architecture combines several complementary components into a unified estimation framework:

- local odometry and short-term smoothing to bridge gaps between absolute fixes,
- model-based surface constraints derived from the ship hull mesh to ensure geometric consistency, with additional utility nodes publishing the technical and visual hull meshes, generating the surface graph from mesh data, and providing A*-based routing and coverage planning on the hull surface,
- semantic landmark detections to support drift correction and re-localization,
- optional local SLAM and loop closures to improve robustness in visually degraded conditions,
- registration to the ship model to maintain a persistent, globally consistent reference, and
- persistent tracking in ship coordinates to enable repeatable navigation and mission documentation across deployments.

Future work will focus on integrating the underwater localization and semantic landmark detections into the SLAM pipeline, landmark anchoring or map matching of the detected landmarks with the vessel’s own database. These extensions are expected to further improve robustness, accuracy, and long-term consistency of the localization framework, moving it closer to a fully integrated, persistent ship-hull state estimation system for autonomous robotic hull cleaning.

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Digital Fouling Reports and the OpenHull Sync App Standardizing In-Water Inspection Data for Cleaning Operations and Port Compliance

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Abstract

This paper presents how standardized digital fouling reports can streamline the workflow between underwater service providers, shipowners, and port authorities, and create value for all parties. Guide 21517 is a published AMPP framework that defines an open, interoperable fouling report format, enabling consistent documentation of hull and niche area conditions across inspections. OpenHull Sync is an application built around this standard, allowing dive contractors to generate and share compliant reports directly from the field. The system ingests inspection reports from multiple sources and converts them into structured, comparable biofouling data. It supports cleaning decision-making, coating performance assessment, and compliance with increasingly stringent port biofouling requirements. As ports and flag states move toward mandatory reporting, standardized digital records offer a practical foundation for demonstrating due diligence and managing biosecurity risk. This paper describes the lessons learned in the first months of rolling out the standard. It compares various biofouling data-handling strategies, and presents the opportunity offered by an industry-wide, anonymized database of digital fouling reports.

1. Introduction

As described in *Guere et al. (2026)*, the Digital Fouling Report (DFR) is a published AMPP framework that enables the creation of structured, interoperable reports for underwater biofouling inspections and cleanings. It defines hull zones, Fig.1, and a fouling scale that is compatible with service providers' constraints and aligned with IMO guidelines.

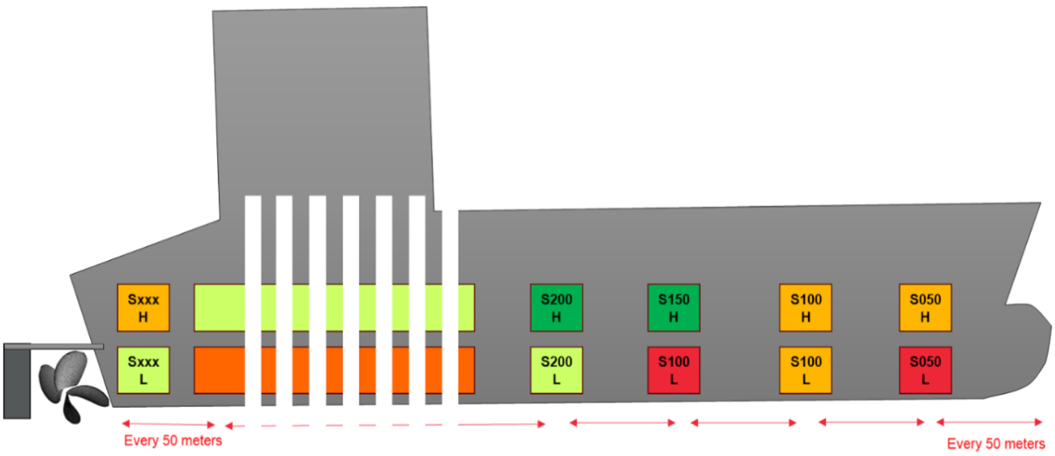

Fig.1: Vertical sides zones on AMPP Guide 21517-number of sections varies depending on vessel length

In this paper, we compare various reporting and data handling strategies found in the industry. Interviews were conducted among shipping companies, to understand how they handle biofouling data, and potential savings were estimated qualitatively compared to a baseline strategy. A quantitative case study was then conducted, comparing speed loss calculations with the biofouling score extracted from digital fouling reports, to highlight how a digital report platform can perform compared with manual PDF investigation.

2. The Hull Biofouling Data Dilemma

2.1. Description of 5 biofouling data handling strategies

Interviews were conducted with 15 commercial shipping companies to understand their methods for report handling and how they track their biofouling data. We grouped these methods into five categories.

- In Strategy 1, reports are used on the spot to decide if an inspection must lead to a cleaning, and then stored as a PDF, with accompanying images, for archiving purposes. As the baseline strategy, Strategy 1 requires no change in behaviour, which saves time in the short term. However, this strategy frequently leads to data loss (some reports are not stored properly after the service), and creates uncertainty about whether cleanings were effectively carried out. Biofouling data is mostly used on the spot, to decide if a cleaning is necessary and if it has been performed thoroughly. When a more detailed review is needed — for example in the event of a coating performance concern — data retrieval and analysis can be time-consuming and incomplete. These companies rely solely on a calendar-based schedule and/or fuel performance analyses to determine the right timing for inspections and cleanings. The state of the hull at dry dock is the main factor used to assess coating performance. No further coating or cleaning optimization is done.

- Strategy 2 consists of logging the key findings of each inspection in a spreadsheet, to maintain a logbook of hull condition after each inspection and cleaning. Each hull event — cleaning and inspection — is generally logged with an overall fouling score and a one-line description. The resulting table shows, at a glance, how hull biofouling has developed and been controlled during the vessel's dry-dock cycle. This strategy requires little time: a superintendent or ship manager, when reading a service report, also logs the one-line summary in the dedicated table. This table helps communication between ship management and fleet performance teams. However, it does not enable further cleaning schedule optimisation, and the time needed for claims investigation is still high: source reports are sometimes lost or difficult to retrieve.

- In Strategy 3, the shipping company relies on a single, digital-ready service provider (SP) to generate regular hull reports and associated dashboards. All biofouling information is stored in the SP's digital environment and can be accessed easily by the shipping company. Analysis and insights are provided by the SP based on the available data. In practice, this strategy requires either a SP with global presence and integrated systems, or a vessel that regularly calls the same port. It is better suited for operators on fixed routes, such as ferry lines.

- Strategy 4 occurs when the shipping company creates a custom reporting format and requests it from all their SPs. This generates consistency across all their reports. This custom format can then be integrated into the company's fleet management tools, generating highly comparable and informative insights. However, only large shipping companies with significant bargaining power can expect all their SPs to comply with a custom format. Furthermore, the initial rollout requires significant investment that not all companies are willing to make. This strategy also increases the reporting burden for service providers and is not practical at industry scale.

- Strategy 5 involves requesting digital reports following the AMPP Digital Fouling Reports Guide 21517, and using the consistency of these reports to unlock additional value. Unlike Strategy 4, this approach is unique in using an internationally available standard, spreading the change across all shipping companies and all SPs simultaneously. It enables detailed analysis by fouling zone, and assessment of coating integrity. This approach also allows the entire history of the vessel to be tracked in one place, from dry docks to inspections and cleanings, which creates traceability.

	Description	Pros	Cons	Comments
Strategy 1	Looking at reports only when needed (claims or concerns)	No behavioral change needed	Time consuming when further analysis is needed, some data is lost, no optimization done	Most shipping companies
Strategy 2	Logging key findings in an Excel file	Short time needed to log information	Loss of data richness, low level of tech optimization	A first step toward hull condition tracking
Strategy 3	Relying on one digital-ready service provider	Access to a platform with track record	Rarely possible in practice, locked to a single vendor	For predictable routes (ferries…)
Strategy 4	Requesting a specific format from the service providers	Tailor made, enabling deep analyses	Necessitate a substantial bargaining power, and change management for service providers	Only larger shipping companies
Strategy 5	Requesting AMPP Digital Fouling Reports	Interoperable, open, flexible, can be used in all platforms	Change of practice for service providers	The future of hull reports?

Fig.2: Summary of five report handling strategies

2.2. Optimization opportunities for the various strategies

These strategies were compared across six dimensions: initial investment needed, manpower for report handling, compliance on port entry, claim management, cleaning schedule optimisation, and technology choice optimisation. For each dimension, a qualitative estimate of the time and cost implications was made, compared to Strategy 1 as the baseline. Estimations are presented in the table of Fig.3.

	Initial investment	Report Handling manpower	Compliance Port Entry	Traceability and claim management	Cleaning schedule Optimization	Technology Choice optimization
Strategy 1 Baseline	None	Basic data storage	Compliance manually checked	Tedious PDF reports retrieval and analysis	Through fuel performance softwares only	Based on fuel consumption and dry dock state
Strategy 2 Spreadsheet	None	Ship manager logging data (10 minutes)	Compliance manually checked	Tedious PDF reports retrieval and analysis	Identify patterns faster	Qualitative tracking of new tech efficiency
Strategy 3 Single SP	None	None	Compliance manually checked	Easy analysis through SP's online tool	Predictive tools may be available, but not independent	Limited choice for cleaning tech; insights based on coating tech
Strategy 4 Custom	High - negotiating with each SP	Low if report template allows	Facilitated if report template allows	Easy through internal tool	Linking fouling with fuel performance	Optimized within the internal fleet data
Strategy 5 DFR	Medium - using a common framework	Low through OpenHull Sync	Automatic check through niche area tracking	Easy analysis through OpenHull Sync	Linking fouling with fuel performance	Optimized internally and/or with other companies

Fig.3: Comparing the impact of each strategy on hull management operations

Strategy 5, relying on an open and interoperable format, appears to be the most efficient option: with a manageable initial investment, report handling is streamlined, compliance risk is under control, and analyses are efficient, whether for claim investigation, cleaning schedule, or technology choice optimization. The entire hull history can be tracked and transparently shared across stakeholders. In the following section, we look more closely at this strategy and explore how it can gain traction across the industry.

3. A deep dive in the practicality of Strategy 5

3.1. Status of Digital Fouling Reports

The Digital Fouling Report template is available on the AMPP store. It is a spreadsheet that can be completed by any SP willing to provide it as a report to their customers, and then analysed by shipping companies using an internal tool. However, the DFR was only recently published, and no such tools yet existed. What's more, the DFR spreadsheet itself can be time-consuming to complete for a service provider; this has led to low demand from shipowners and limited uptake among service providers. To overcome this major obstacle to digital report adoption, OpenHull developed the Sync app, a solution to simplify this process.

3.1.1. Simplified Generation

As described in *Guere et al. (2026)*, OpenHull Sync allows service providers to generate compliant digital fouling reports straightforwardly, with clickable zones, images and comments, and custom niche area configuration, Fig.4.

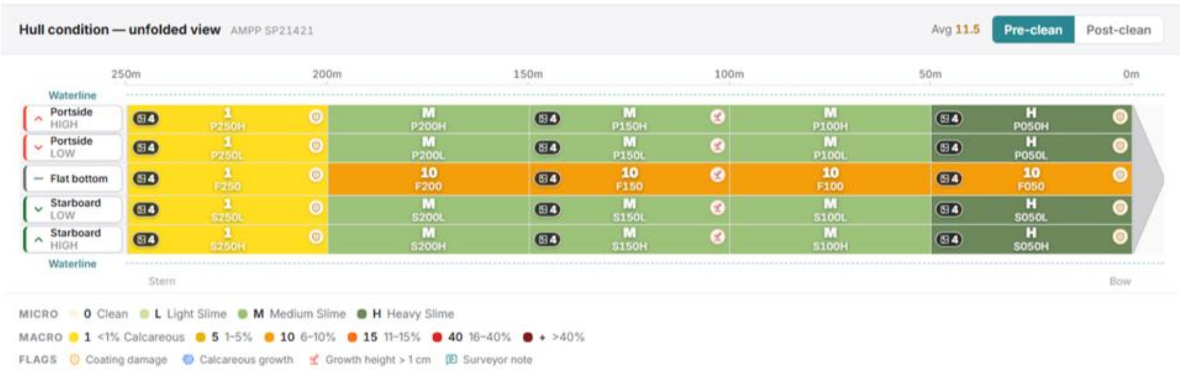

Fig.4: Online DFR viewed on OpenHull Sync

3.1.2. Simplified Requests

Additionally, OpenHull Sync streamlines communication between shipping companies and service providers: a shipping company can request a service (cleaning, partial or full inspection, propeller polishing) with a detailed scope of work, Fig.5. After acceptance from the service provider, the latter creates the report on their own OpenHull Sync interface and shares it with the customer.

3.1.3. Advantages for Service Providers

For service providers, the benefits are equally direct.

Early users among service provider organisations have reported significantly shorter report generation times compared to their traditional PDF-only process, alongside a higher perceived value of the service delivered to their customers. The inspected and cleaned areas on the hull are well described and traced. The system also allows paint damage and images of the inspection to be attached to respective areas with visual representation of the rated area.

When scope of work, fouling scores, zone coverage, and niche area conditions are documented with images in a consistent format, post-service claims are easier to resolve and the quality of the work is easier to demonstrate. For dive contractors, this is a direct commercial argument in favour of adopting the DFR format. OpenHull also allows shipping companies to find service providers willing to generate digital fouling reports as an output of their service. This, in turn, creates new commercial opportunities for vendors.

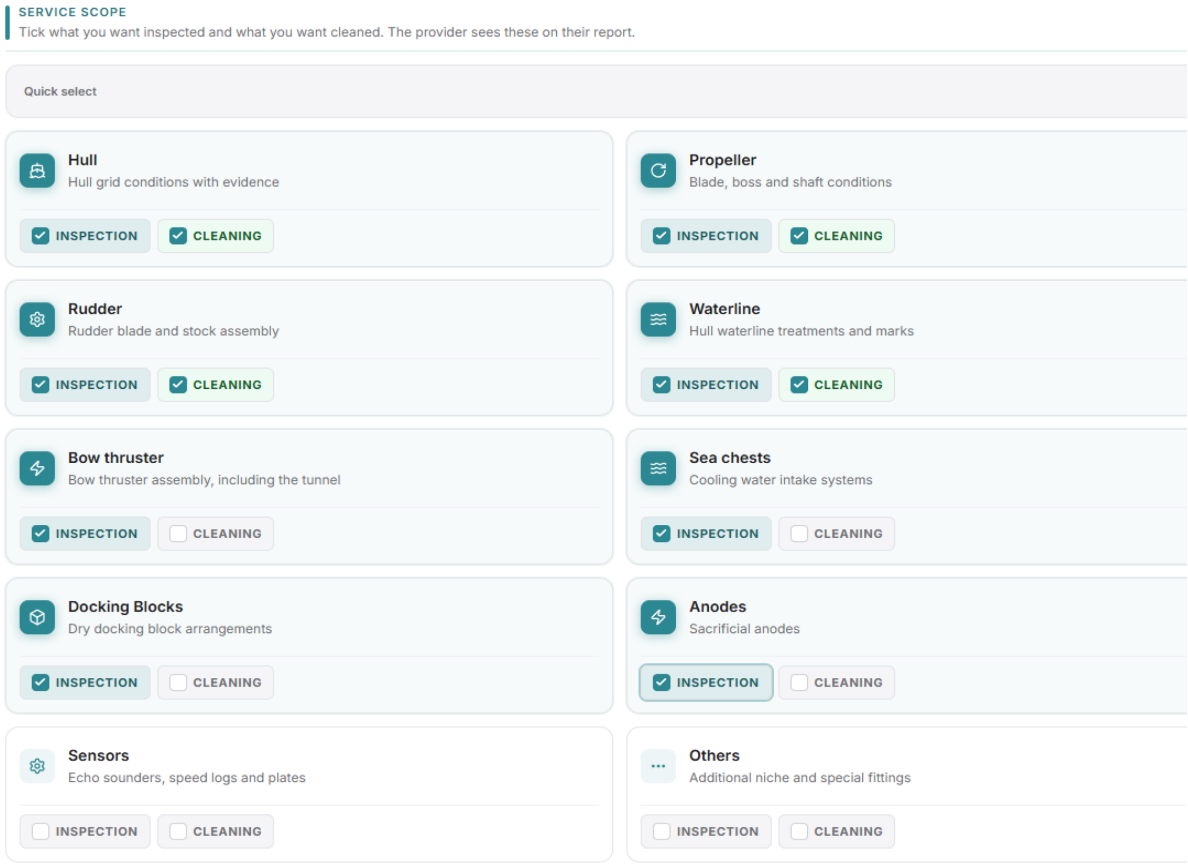

Fig.5: Sample of a service scope definition when sending a request to a service providers on OpenHull Sync

3.2. Integrating multiple data sources

Every SP has its own process, and not everyone will use OpenHull Sync to create DFRs, or be willing to create DFRs at all. For this reason, OpenHull Sync accepts data from multiple sources, Fig.6:

- DFRs generated directly on OpenHull Sync by service providers
- DFRs generated externally by SPs with their own digital tools, uploaded manually or automatically via API
- Traditional PDF reports, uploaded and digitised into a DFR

For robotic service providers with their own reporting systems, the integration path is via API or direct file upload: the DFR schema is open, and existing automated outputs can be mapped to it without changing the inspection workflow itself.

For operators working with traditional providers, years of historical PDF reports can be uploaded and converted into structured DFRs retrospectively. This means that a vessel switching to Strategy 5 today does not start with a blank record: the inspection history can be brought into the system, giving an immediate baseline for fouling trends and coating performance assessment.

This way, shipowners and ship managers can find all their relevant reports in the same place, digitised and ready to generate insights for hull management. Fouling trends throughout the dry-dock cycle are then presented in a vessel dashboard, Fig.7, including coating integrity scores and the estimated fuel penalty due to fouling. Events (inspections, cleanings, propeller polishing, and dry docks) are documented with their overall fouling scores, regardless of the data source.

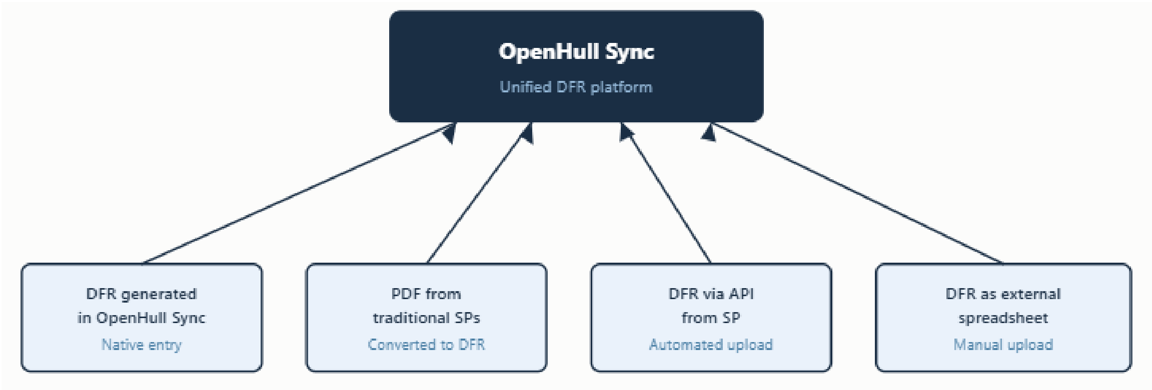

Fig 6: OpenHull Sync pools and structures all data sources for underwater surveys

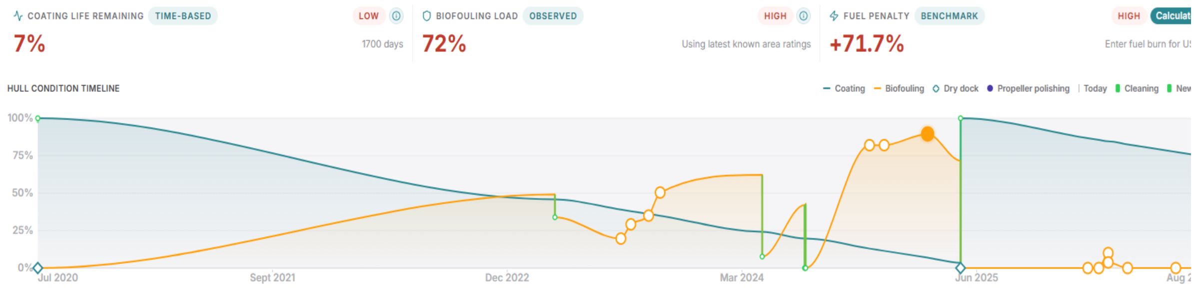

Fig.7: vessel dashboard with all events logged, fouling levels and coating integrity, and their impact on fuel penalty. This impact is calculated based on the fouling rating from the hull inspections and can be directly compared with performance software.

Data can be shared vessel by vessel to partners or vendors, such as ship owner, ship manager, coating provider, to enable transparency, shared insights and feedback from all parties.

3.3. From hull fouling reports to hull management

3.3.1. More regular, more informative inspections

The first benefit OpenHull Sync brings to hull management is a single-glance view of the fleet's status. The dashboard monitors and alerts when a vessel passes beyond a threshold for coating integrity, fouling level, or date of last inspection. Better data handling makes regular inspections more relevant and informative, and supports the trend toward more frequent in-water surveys: as data accumulates and is easily analysed, the value of each inspection increases.

3.3.2. Hull inspection as part of the Biofouling Record Book

IMO guidelines describe how inspections should be logged in a Biofouling Record Book (BRB), in line with the vessel's Biofouling Management Plan (BMP). These guidelines are expected to become legally binding in the coming years, and more local authorities (including Brazil) already require them as a mandatory document for port entry.

OpenHull Sync makes it possible to generate a BMP and update the BRB after each inspection. Niche areas are configured for each vessel individually (Fig 8), and tracked over time. The compliance module then prepares the necessary documents for port entry (starting with Brazil) in a step-by-step, guided process. The next section shows how Digital Fouling Reports facilitate port entry to Brazil.

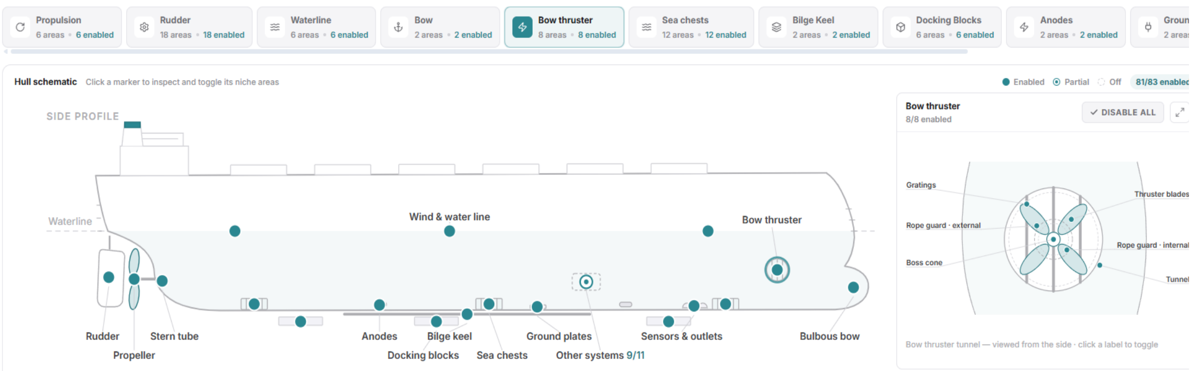

Fig.8: Niche area view. Each niche area type can be added in custom numbers, or disabled

3.4. A Concrete Compliance Workflow: Brazil Port Entry

Brazil has enacted mandatory biofouling management requirements for all vessels over 24 metres entering its waters. Under NORMAM-401/DPC Chapter 4, *DPV (2026),* vessels must carry a Biofouling Management Plan (BMP) and a Biofouling Record Book (BRB), and maintain hull fouling at level 1 (microfouling) or below. Full enforcement with sanctions begins on 10 January 2028, but the requirements are in force today. Brazil is therefore a practical test case for what structured digital fouling data can do for port compliance.

In practice, preparing for a Brazil port call has historically involved retrieving scattered PDF inspection reports, manually checking niche area coverage, and compiling a compliance package with no standardised format. For both shipowners and service providers, as well as for port authorities, this is time-consuming and error-prone, particularly when reports come from multiple providers across different ports. OpenHull Sync addresses this by connecting the inspection workflow directly to the compliance output. Fig.9 shows the five-step process from inspection to port-entry package.

In step 1, the dive contractor conducts the inspection and rates every configured niche area directly in OpenHull Sync, with photos and pre/post-cleaning scores where applicable. This structured input immediately updates the Biofouling Record Book (step 2), removing the need for any manual reformatting.

When a Brazil voyage is planned, the shipowner or fleet manager opens the Voyage Assessment module (step 3), enters the target port and expected arrival date, and OpenHull Sync automatically checks the vessel's current evidence position: is fouling at level 1 or below? Are all required niche area ratings present? Is the BMP complete and current? If any gaps are found, the system flags the specific actions needed (for example, "complete niche-area evidence for sea chest gratings" or "arrange cleaning, fouling level 2 detected") and the service provider is contacted to resolve them (the dashed loop). Once the evidence is complete, the full compliance package is assembled and exported (step 4): a vessel-specific BMP PDF, the Record Book for the relevant period, and all supporting inspection reports and images. The operator then submits this package through the appropriate channel to the Brazilian Maritime Authority (step 5).

The consequences of non-compliance are concrete. Under NORMAM-401/DPC Chapter 4, the Brazilian Maritime Authority may issue warnings, detain a vessel, or prohibit port entry. Administrative fines apply to irregularities and obstruction of inspection, and simultaneous violations can be cumulative. The current adaptation period until January 2028 is intended as a buffer. For operators calling Brazilian ports regularly, the cost of preparing a compliant evidence package well in advance is modest compared to the operational and financial impact of detention if unprepared in 2028.

This workflow reduces what was previously a multi-hours administrative exercise — retrieving reports from providers, checking niche area coverage manually, assembling PDFs — to a process that is largely automatic once inspection data is in the system. For service providers, it means that a single inspection, conducted and recorded properly, generates both the client's operational report and their compliance evidence in one step. When regulation is enforced, this kind of integrated workflow will become a practical necessity for operators calling Brazilian ports regularly.

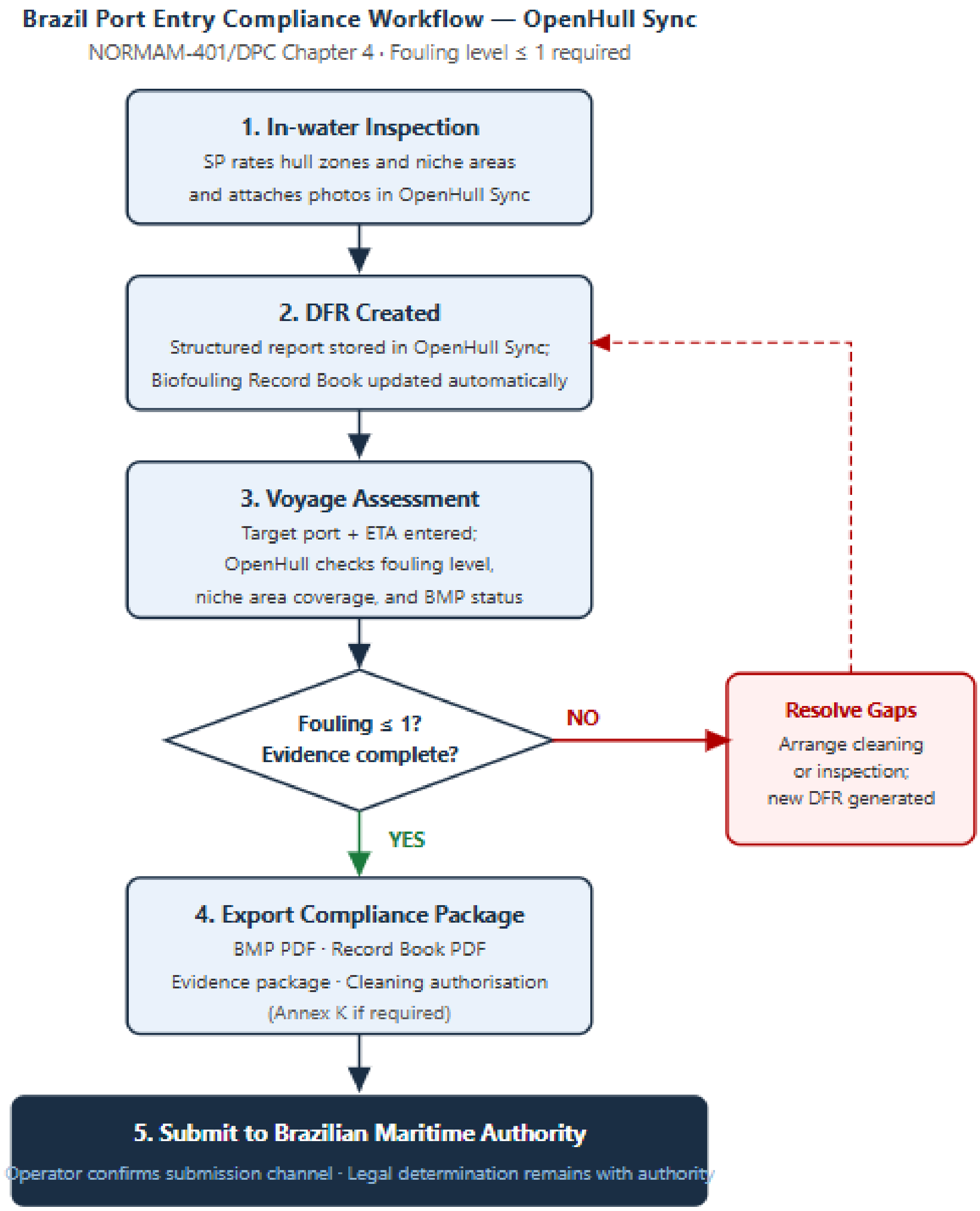

Fig. 9: Brazil port entry compliance workflow using OpenHull Sync. The dashed red loop indicates the resolution path when fouling level or evidence is insufficient. OpenHull Sync supports evidence preparation only; legal compliance determination and authority submission remain the operator's responsibility (NORMAM-401/DPC Chapter 4).

New Zealand's Craft Risk Management Standard (CRMS) presents a similar structure, with mandatory niche area inspection and photographic evidence before entry. While the documentary requirements differ from Brazil's, the underlying data (niche area fouling scores, hull condition, cleaning history) is the same and the DFR template includes all niche area types and subcategory required by the CRMS. A DFR generated for one jurisdiction can therefore serve as the evidence base for multiple port requirements, with only the output format varying.

Port compliance ultimately depends on the quality of the inspection data from the service provider. A shipowner cannot demonstrate that niche areas were inspected, that fouling was below the required threshold, or that a cleaning was performed correctly, without a structured, traceable record from the SP. For robotic service providers in particular, whose systems already generate granular zone-by-zone data automatically, the step from proprietary output to a standardised DFR is small, and the compliance value it creates for the shipowner is large. Choosing a SP capable of delivering DFR-compliant evidence is therefore a direct risk management decision for operators calling regulated ports.

Overall, OpenHull Sync simplifies both the generation and use of digital fouling reports, paving the way for broader industry adoption.

4. Case Study - Fuel consumption

The case study below illustrates under which conditions digital fouling reports can provide additional insights when cross-checking with fuel performance, for example to reveal cleaning compatibility issues.

To quantify the fuel savings that better hull data monitoring can enable, data extracted from OpenHull Sync was compared with data from the fuel performance software of the same vessel, throughout a dry-dock cycle. The analysis was performed on historical data from a chemical tanker, covering the dry-dock cycle from July 2020 to June 2025 (first five years of Fig.8).

Over this period, the vessel underwent 3 hull cleanings and regular inspections. The shipping company was following Strategy 2: a log spreadsheet listing all hull operations and inspections was available. Hull cleaning details were extracted from PDF reports and digitised. Not all data from crew-conducted hull inspections could be retrieved: some were available as pictures, others as PDFs; for some others, data was lost entirely, and the logbook entry was the only remaining source. The logbook did not always record the fouling level found, only that a partial inspection had been performed. This illustrates the risk of data loss in Strategies 1 and 2. The first cleaning was performed after 3 years, followed by regular inspections and 2 further cleanings in year 4.

4.1. Comparison with Fleet performance Speed Loss

Fouling data from OpenHull Sync was plotted alongside the fleet performance software's speed-loss data, after data cleaning. 4000 noon reports were collected; 1620 were in sailing conditions, and 1577 were considered valid by the performance software, Fig.10. Speed-loss curves generated by this software account for local conditions such as current, waves, and wind. Comparing the two data sources, Fig.11, reveals insights that neither can provide alone.

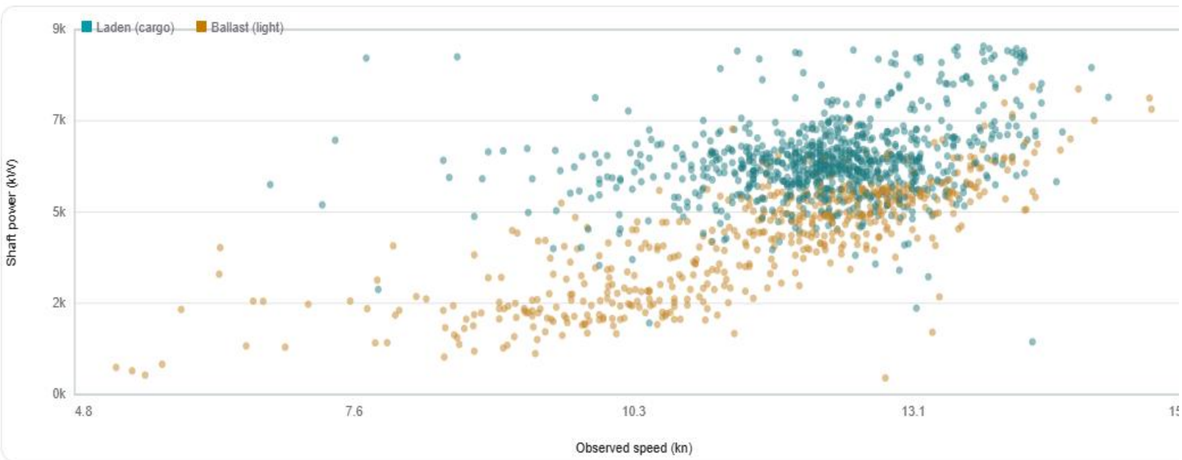

Fig 10: Noon reports show a correlation between shaft power and observed speed, with a data scatter as expected from this type of data

Fig.11: Fuel performance loss compared with OpenHull biofouling level. Blue-green line: speed loss (left axis). Red points: OpenHull biofouling observations (right axis). Yellow points: inspections logged in the spreadsheet, but for which no fouling degree descriptions were found. Dotted lines: in-water cleanings; solid green bands: dry-docks. Cleaning points show the recorded score immediately before and after the work. The dark bottom lane shows every period of at least 24 h reported as anchored, drifting, idle, stopped, or in dry-dock; gray background bands highlight those lasting at least 14 days. These periods indicate non-sailing or waiting activity.

In [1], we see a case where speed-loss calculations could have prompted a hull inspection. After an idle period, speed loss rises suddenly from 0–1% to 4%. Unfortunately, the hull cleaning was not performed until 18 months later. Many shipping companies tend to delay inspections, because they expect a full coating efficiency after dry dock and these inspections are tedious to arrange within some vessel operational constraints. With help in the inspection request process, regular informative inspections can become a baseline.

In [2], a full cleaning was performed just before an idle period. Macrofouling was clearly formed on the hull since the 2020 docking and a more aggressive than necessary cleaning method had to be used. Either because of the idle period's impact on a freshly polished coating, or because some areas were not cleaned thoroughly, fouling built again quickly in the following three months. Even where speed loss is not clearly visible in noon report data, a smoother hull always improves hydrodynamics. This highlights how well-documented inspections and cleanings can help identify and reduce fouling faster than performance software only. In addition, recording the technology used to clean fouling, can help discern if the proper cleaning set up was used, considering the level of fouling and the type of coating.

In [3], between the last cleanings and dry dock, a series of regular idle periods occurred over 9 months. Partial inspections in the logbook described a polished-through coating and growing fouling. However, the data from these inspections could not be retrieved, and no cleaning was performed. A better tool to record inspection would have been beneficial to extract the full value from them. Over the long term, more detailed records of cleaning methods will make it possible to distinguish between cleanings that accelerate coating polish-through or refouling, and those that do not affect long-term coating performance.

4.2. Correlation between Speed Loss and OpenHull Biofouling Score

Looking more closely at the correlation between the OpenHull Biofouling Score and speed loss, Fig.12, voyages in laden and ballast conditions were plotted separately. In laden conditions, a pattern emerges: power demand is higher when the biofouling score is higher. In ballast condition, the data is more scattered and the correlation is not significant. This is consistent with the fact that biofouling impacts hull resistance most when the vessel is fully loaded and deeper in the water. Fouling is generally more severe near the waterline.

This also reflects the fact that much of the power demand calculation (and biofouling impact) falls within the error range of speed-loss calculations, especially for vessels relying on noon reports only.

These findings show that OpenHull Sync, with well-structured data, can generate meaningful results for hull smoothness, even where speed loss is within the error range of fuel performance software. In turn, better data on hull condition can justify more frequent inspections, to track fouling and address it promptly with the most suitable technology.

Insights from hull inspections then become real data sources to explain the coating performance and wear, anticipating maintenance and confirming results before overconsumption can be seen in the data.

4.3. From fouling to saving potential

To compare the projected impact of biofouling on fuel consumption, three methods were used: the calculated overconsumption from the fuel performance software (based on noon reports); the impact of fouling severity as described in the IMO guide, Fig.13; and the OpenHull calculation derived from fouling location and published literature, *Demirel et al. (2019)*.

All three saving potentials were plotted in the same graph, Fig.14. The IMO-based and OpenHull calculations align closely, both suggesting a daily saving potential of USD 3000–5000 due to fouling alone. The fuel performance software gives a more conservative estimate, with less than USD 3000/day of savings from all sources combined, including fouling.

The first two curves probably overestimate fouling impact to some degree. But the gap may also reflect an underestimate from the noon report data, given its scatter and error range. It would be valuable to repeat this comparison on a vessel using high-frequency sensor data, to test whether the fouling signal becomes clearer in that context.

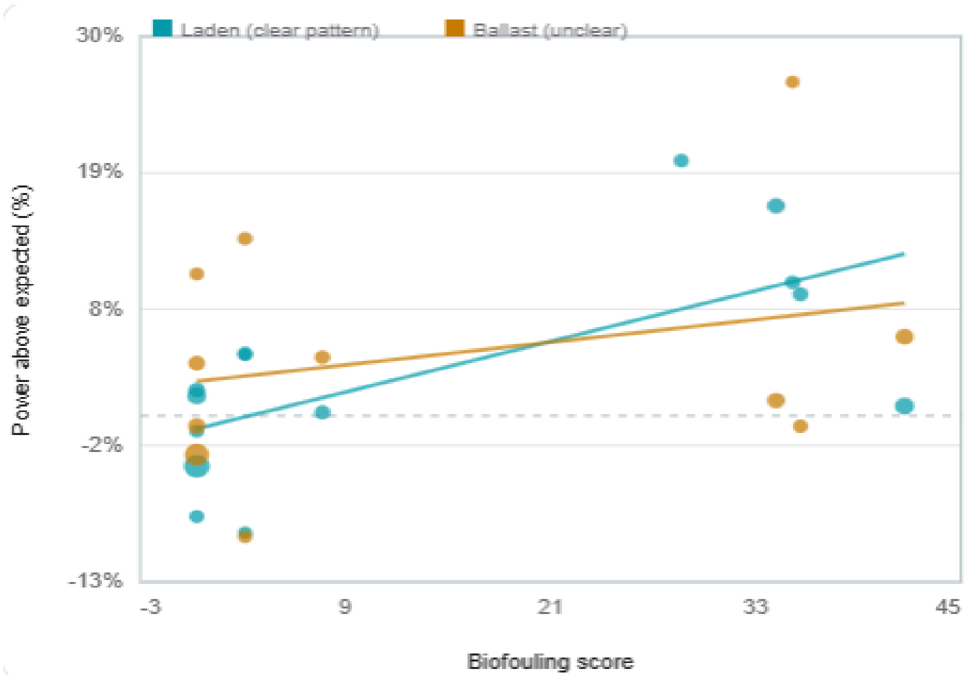

Fig.12: A correlation between the biofouling score and the additional power demand exists in laden condition (blue), but not in ballast condition (orange). Data stemming from 724 laden noon reports, and 482 ballast reports, cleaned and processed by the fleet performance software.

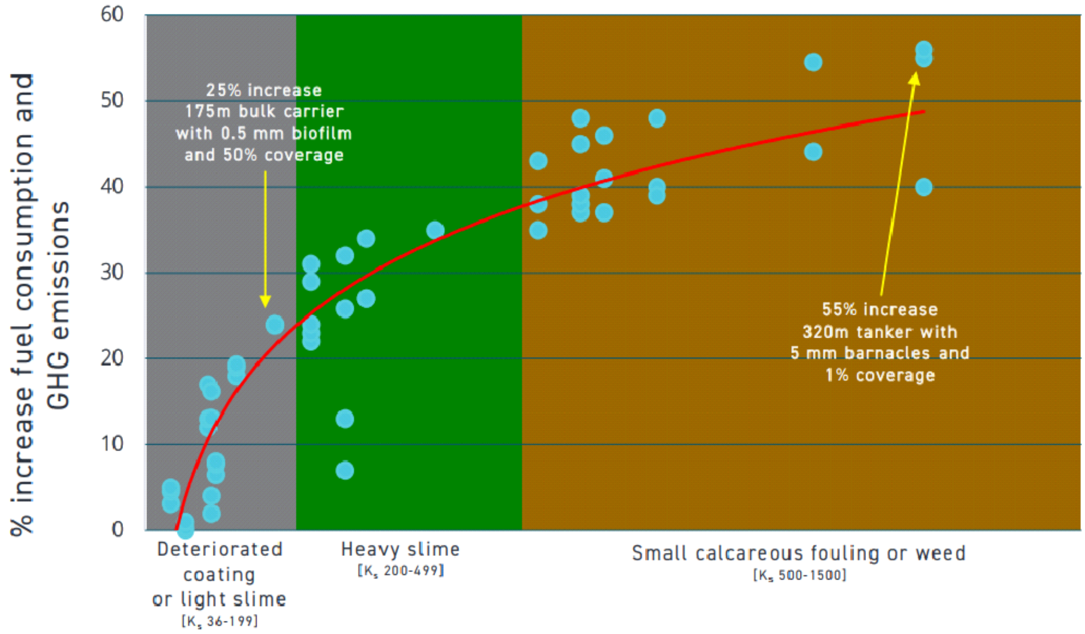

Fig.13: Increased fuel consumption estimations based on fouling level, *GEF-UNDP-IMO (2022)*

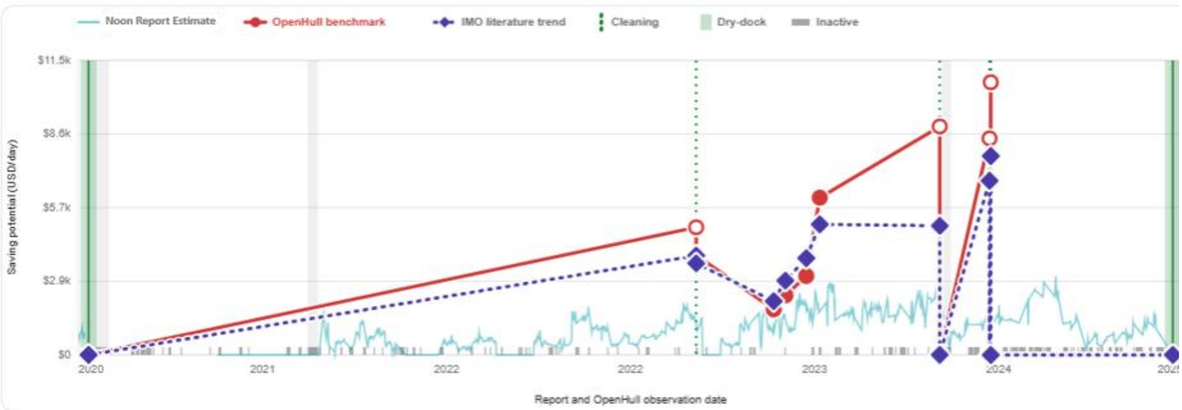

Fig.14: The thin blue-green line is the performance software's daily estimate. The solid red OpenHull line and dotted purple IMO GloFouling line are calculated only at inspection, cleaning, and dry-dock dates and use the same fixed reference fuel consumption of 26.4 t/day. At cleaning dates, both benchmark curves show the pre- and post-cleaning conditions. Connecting segments are visual guides; they do not estimate conditions between observations. The IMO series is an approximate digitization of the literature-summary trend in *GEF-UNDP-IMO (2022),* mapped through the roughness categories in its Table 1. It is not an IMO regulatory formula or measured vessel result. The three series therefore compare relative magnitude, not accuracy against ground truth. The 2020-2023 segment spans a period with no OpenHull hull-condition evidence.

5. Toward an industry-wide, anonymized database for hull technologies

The coating-cleaning-operation triangle is still poorly understood at industry level. A coating that performs well for one operator can fail quickly on another vessel with a different route, idle pattern, or cleaning technology. These interactions are difficult to study from individual fleet data alone — the sample sizes are too small and the variables too many. A shared, anonymised database is the only realistic path to building robust knowledge on these compatibility questions.

More specifically, regular inspections will provide insights into cleaning and coating compatibility, and their suitability for a given vessel's operating profile. Many questions still need to be answered:

- Is there a cleaning technology that never damages any coating?
- Is there a fouling prevention system that thoroughly protects sea chests and other niche areas?
- Does silicone foul faster after a waterjet cleaning? Under which pre-fouling conditions and operating profiles?

Without zone-by-zone records of fouling before and after each intervention, many patterns are invisible, absorbed into the general noise of fuel performance data. With structured inspection records, the hypothesis becomes testable. This is the kind of question that an industry-wide database, with many vessels and many cleaning events, could begin to answer systematically.

When protecting a hull, shipowners weigh three main criteria that must work well together: the coating technology, the cleaning method, and the operational profile of the vessel. Historically, innovation in coatings has penetrated the market slowly, relying on the experience of individual fleet managers, small-scale tests, and the relationships between coating manufacturers and shipping companies. Returns of experience have largely been confined to individual companies.

There is now a growing awareness that no single shipping company can test all coating solutions, and that problems arising from poor cleaning-coating-operational compatibility can be avoided through better data sharing. Conferences and scientific papers based on real vessel data have helped spread this knowledge.

Given the many variables that can affect coating performance on a given vessel (unforeseen idle time, dry-dock weather conditions, a cleaning with an overly abrasive brush...), only large-scale data can reveal meaningful patterns.

This is the vision behind OpenHull Sync. While offering a private, company-specific environment to monitor fouling, OpenHull is also building an industry-wide, anonymised, technology-agnostic database for hull technologies. Shipping companies that agree to share their digital fouling reports and experience will have access to anonymised data from other participants.

For service providers, offering participation in this database to their customers also creates value: recommendations informed by real, comparable data across hundreds of vessels are far more credible than those based on proprietary case studies alone.

6. Conclusion

Now that digital fouling reports are available and easy to generate, a better strategy with significant savings potential becomes feasible: requesting a single, standardised reporting format from all service providers. The industry can now act collectively and make this a reality, benefiting service providers, shipping companies, and innovative technologies alike.

Already joined by 51 organisations, the OpenHull Sync app is a practical solution to make the transition to DFR smooth and informative, and to unlock opportunities for better hull care, lower fuel consumption, and reduced greenhouse gas emissions.

The practical steps are straightforward:

- For service providers, and particularly those already generating structured data through robotic inspection systems, the next step is to map their output to the DFR format and make it available to their customers as a standard deliverable.
- For shipowners and operators, the next step is to request DFR-compliant reports from their providers and begin building the inspection record that port compliance will require.

- For the industry as a whole, the next step is to explore under which conditions DFR could be shared in a joint database, with vessel owners controlling what is shared, and everyone benefiting from the patterns that only large-scale data can reveal.

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Beyond the Berth: Autonomous In-Transit Hull Grooming and Inspection

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Abstract

A hull fouls between cleanings, so the fuel penalty is set less by how well the hull is cleaned than by how often. Calibrated to the full-scale measurements, added fuel consumption averages 12.9% across a five-year docking cycle under annual in-water cleaning, against 0.4% under grooming every 10-14 days. Only the days a ship spends at sea can support that frequency, and only autonomously. This paper presents the CRABI magnetically attached platform grooming the full wetted surface with waterjets underway, quantifies the economics for a 4000 TEU container ship, and proposes a collaborative validation program.

1. Introduction

Biofouling raises the frictional resistance of a ship's hull, and the fuel penalty has been measured repeatedly over almost a century of trials. What has not changed in that time is the constraint on doing anything about it: divers, quayside robotic systems and drydocking all require the vessel stationary, in port, and inside a permitted window, which caps in-water cleaning at roughly once a year on most commercial vessels and guarantees that the hull fouls in between. The result is a sawtooth condition profile, and the fuel penalty that matters is not the peak but the average across the interval. Reducing that average requires either a lower peak or a shorter interval, and only the interval is genuinely available: coatings are close to their practical limit, whereas cleaning frequency is limited by access rather than by physics.

This paper makes the case for shortening the interval by an order of magnitude, grooming every 10 to 14 days rather than cleaning once a year, and for doing it while the vessel is underway, which is the only way that frequency becomes achievable. Grooming is used here in the sense of MEPC.378(80): proactive, frequent, low-force removal of microfouling before macrofouling attaches, as distinct from reactive cleaning of established fouling after the drag penalty has been paid.

2. The Measured Fouling Penalty and the Cost of Infrequent Access

Full-scale measurements of the fouling penalty span almost a century and the reported range is wide. Davis recorded 32% and 37% resistance increases on naval hulls after 240 and 300 days (IMO, 2022); *Hundley and Tsai (1992)* reported fuel penalties of 23-114% on three frigates after 167 to 795 days; *Haslbeck and Bohlander (1992)* measured an 8-18% shaft power recovery after cleaning a fourth. Fig.1 plots these against exposure time. Most of the spread is explained by era rather than physics: the highest values come from pre-modern or now-banned coatings, and averaging those together with modern systems produces a number that describes no vessel in service today.

The most methodologically robust evidence concerns commercial vessels with modern coatings. *Adland et al. (2018)* followed eight sister Aframax tankers over five years of noon-report data, controlling statistically for speed, wind and draft across 20 in-water cleanings and 16 drydockings, and found a 9% reduction in fuel consumption following in-water cleaning and 17% following drydocking. *Ballegooijen (2016)*, 9.2% on a 13000 TEU container ship at 550 days, and *Murrant et al. (2019)*, 9% on an offshore patrol vessel over two years, converge on the same order. The 9-17% band is shaded in Fig.1 and is the calibration used throughout this paper, in preference to laboratory-scaled or naval predictions, because it is full-scale, commercial, statistically controlled and independently published.

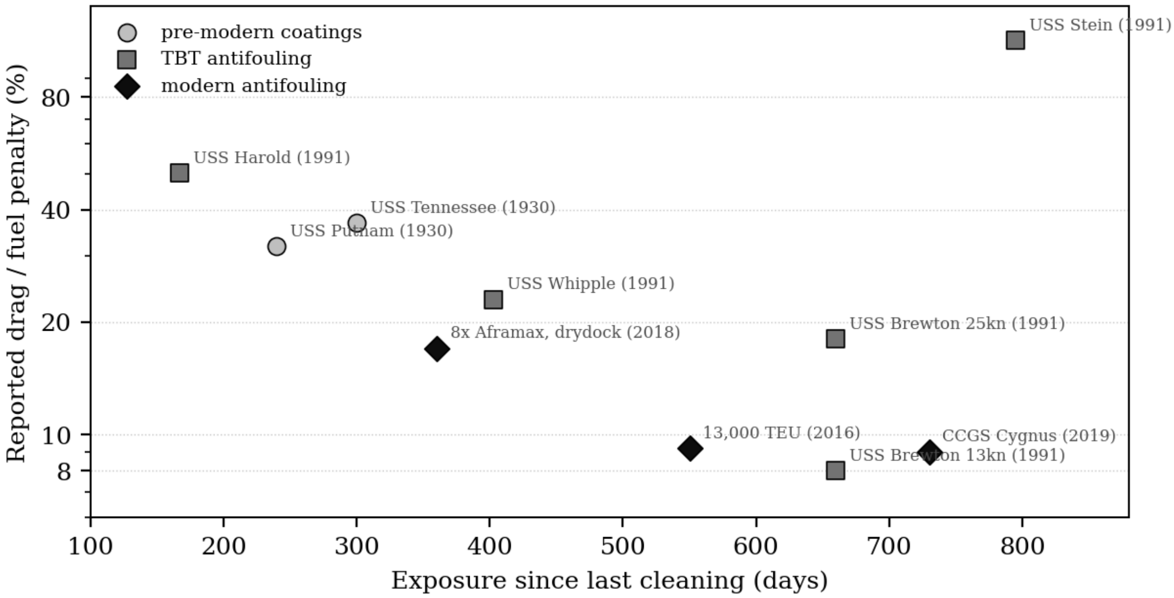

Fig.1: Reported full-scale fouling penalties against exposure time since last cleaning. Marker shading indicates coating era. The shaded band shows the 9-17% range supported by studies on modern antifouling coatings in commercial service.

The ceiling on frequency is administrative and logistical, not technical, and the quantity governing fuel consumed over a maintenance interval of length T is the time-average of the added consumption P(t), not the brief post-cleaning minimum:

$$\text{mean penalty} = (1/T) \int_0^T P(t)\, dt$$

Fig.2 constructs the profile this implies for the *Adland et al. (2018)* endpoints. Their estimator is log-linear, so each recovery acts multiplicatively on fuel consumption: an in-water cleaning removes 9% of prevailing consumption, and the 17% drydock recovery fixes the penalty immediately before docking at 1/0.83 − 1 = 20.5%. With cleanings at months 12, 24, 36 and 48, the growth between events is then solved rather than assumed: 12.4 percentage points per annual cycle, or 1.04 points per month, within the 0.3-1.5% per month measured across monitored fleets, *Gundermann and Dirksen (2016)*. The saturating curve shape and its 4.5-month time constant are the remaining assumptions; the measured endpoints are not.

Integrating the two profiles across the 60-month cycle gives the headline result: a mean added fuel consumption of 12.9% under annual in-water cleaning against 0.4% under grooming every 10 to 14 days, a difference of 12.5 percentage points sustained for the whole docking cycle. Two uncertainty ranges attach to the 12.9% figure, and they answer different questions. The first is measurement: *Adland et al. (2018)* report how their recoveries shift with the choice of event window, and re-solving the calibration across that range moves the mean between 11.1% and 13.5%, the shaded band in Fig.2. The second is curve shape: the saturating form is an assumption, but both endpoints are measured, so any monotone concave growth law through them gives a mean between 10.4% (the linear limit) and 16.6% (instant regrowth). On the groomed side, 0.4% counts biofilm regrowth only. If residual coating ageing is retained as well, the groomed mean rises to roughly 2.5% and the difference narrows to 10.4 points; Section 5 carries that lower, conservative figure. No individual grooming pass removes much material, because by design there is little material to remove. The benefit is that the hull never departs far from the condition it was painted to have.

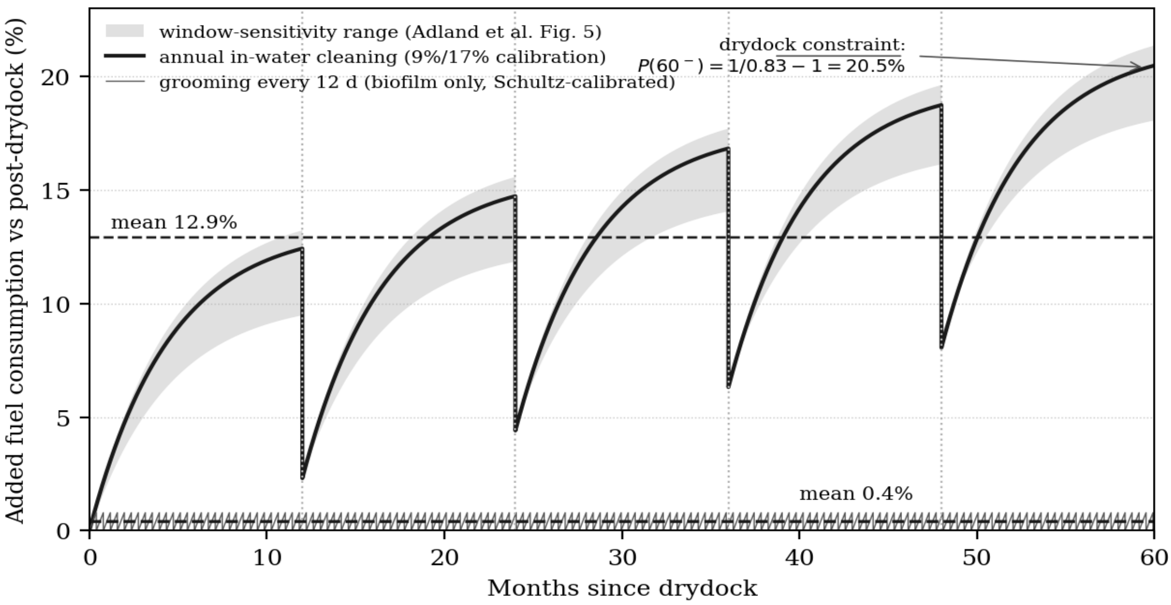

Fig.2: Added fuel consumption over a 60-month docking cycle. Upper curve: annual in-water cleaning, calibrated so each cleaning recovers the 9% and drydocking the 17% measured by *Adland et al. (2018)*; the grey band re-solves the calibration across their reported cleaning-window sensitivity. Lower trace: grooming every 12 days, biofilm regrowth only, on the *Schultz et al. (2015)* calibration of Fig.3. Dashed lines are the cycle means, 12.9% and 0.4%; the gap between them is the fuel penalty avoided.

3. Grooming Interval, Biofilm and Coating Wear

The case for a two-week cycle rests on how quickly biofilm alone imposes a penalty and on what removal costs the coating. *Schultz et al. (2015)* grew diatomaceous biofilms on fouling-release coatings under cyclic dynamic exposure; scaled to a mid-sized hull, required shaft power rose 4.2% after three months and 5.9% after six, below the in-service figures of Section 2, as it should be, because macrofouling is excluded. Fig.3 shows the two-parameter first-order fit through those points that generates the groomed profile in Fig.2.

Hunsucker (2016) measured biofilm roughness of 900-2000 μm at 35 days, a 20-34% full-scale drag increase under the *Schultz (2007)* scaling, and found that biofilms grown under dynamic conditions were markedly more tenacious than those grown static, which largely sloughed off at speed. The implication is uncomfortable for any strategy that relies on hydrodynamic self-cleaning: the biofilm that forms while a vessel is underway is precisely the biofilm that does not release at speed, and slow-steaming weakens the assumption further. Removal has to be mechanical, and if it is to be low-force, it has to be frequent.

Tribou and Swain (2010) supply both the sufficient frequency and its coating cost. In static tropical seawater over 120 days, approximately a worst case for fouling pressure, only grooming intervals of six days or shorter kept coated surfaces free of fouling, and the force required to remove what had accumulated tripled once the interval exceeded roughly twelve days, Fig.4. Removal force is what damages coatings, so grooming frequency and coating life are the same variable seen from two sides. *Utama et al. (2021)* measured the reactive alternative: the abrasive methods used in a drydock cleaning and repainting cycle had themselves increased hull resistance by 7%, of the same order as the 9% penalty from fouling itself. *Oliveira and Granhag (2020)*, by contrast, groomed with gentle waterjets at bimonthly intervals and observed no measurable coating damage. An interval short enough that adhesion never matures keeps removal in a regime where the coating is not the limiting component, and it is what makes non-contact waterjet removal sufficient: no bristle load on the coating, and no hard fouling debris carried through a rotating contact against it.

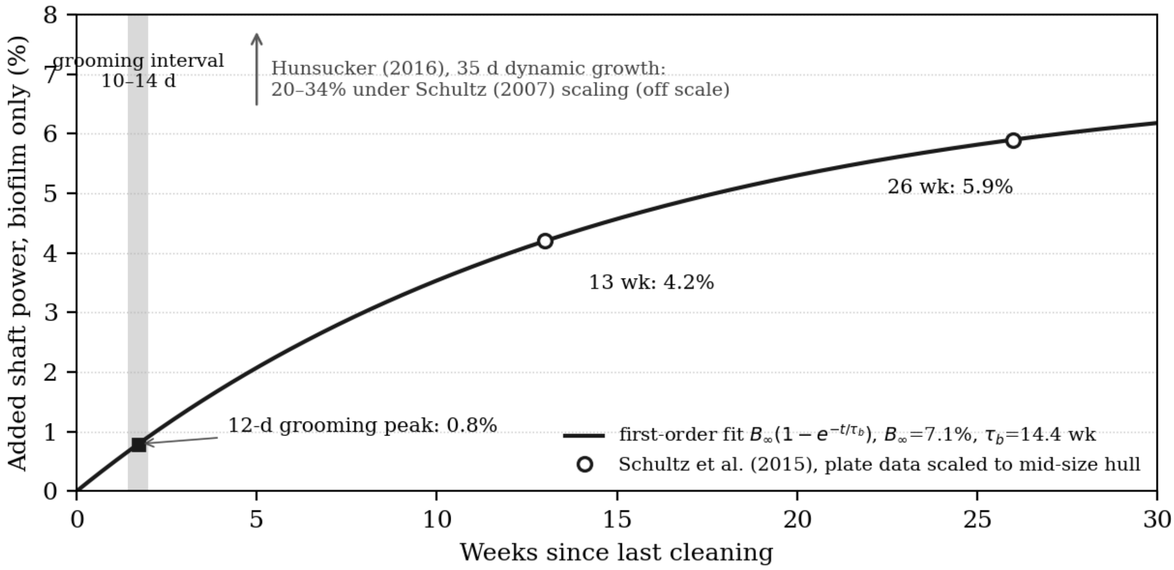

Fig.3: Biofilm-only added shaft power against exposure since last cleaning. Points are the *Schultz et al. (2015)* plate measurements scaled to a mid-size hull; the curve is the two-parameter first-order fit through them (saturation 7.1%, time constant 14.4 weeks). The *Hunsucker (2016)* 35-day dynamic-growth range, 20-34% under *Schultz (2007)* scaling, lies off scale. The shaded band is the proposed grooming interval, at which the biofilm penalty peaks at 0.8%.

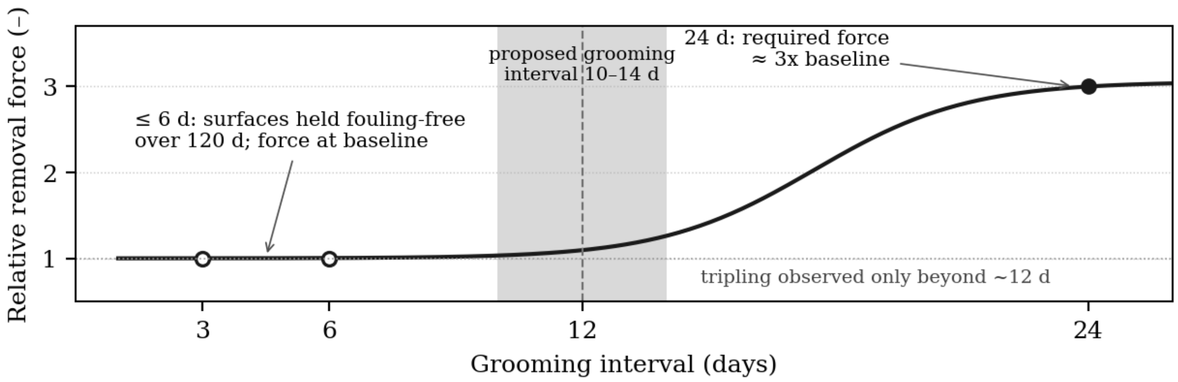

Fig.4: Relative maximum removal force against grooming interval, schematic of the *Tribou and Swain (2010)* findings (120 days static immersion, Florida; intervals of 3, 6, 12 and 24 days tested). Anchored observations: intervals of six days or shorter maintained fouling-free coated surfaces at baseline force; required force reached roughly three times baseline at 24 days, with the increase observed only beyond approximately twelve days. The transition curve is indicative.

4. In-Transit Autonomous Grooming

The requirement that emerges from Sections 2 and 3 is a grooming interval of roughly two weeks, applied at low removal force, over the full wetted surface of a hull the operator cannot take out of service to reach. CRABI is an autonomous platform built to that requirement. It attaches to the hull and operates at vessel speeds up to 24 knots and in conditions up to Beaufort 4, manoeuvring across the full wetted surface, vertical sides, bilge radius and flat bottom, grooming approximately 400 m^2 per hour with an 870 mm swath and non-contact waterjets, and returning to an onboard docking station to recharge between passes. Mission planning, hull navigation, swath-by-swath coverage, obstacle recognition around sea chests, anodes and bilge keels, return to dock, recharging and data upload occur without a pilot, a tether, or crew involvement.

Fig.5: Grooming platform: hydrodynamic body with inverted main wing and forward canards providing the speed-dependent downforce of Section 4. Hull-facing equipment is not shown.

Operating on a hull moving at up to 24 knots requires the platform to hold and manoeuvre against hydrodynamic forces that grow with the square of vessel speed. Two principles are combined: controlled magnetic attachment to the steel hull, with the magnetic circuit sized for coating-safe contact pressure rather than brute force, and a hydrodynamic profile that converts boundary-layer flow into stabilising downforce in the manner of an inverted aerofoil, so that the faster the vessel moves, the more the flow contributes to holding the platform on, Fig.6. The vessel's own motion becomes an operational asset: the platform grooms and inspects during precisely the period when the hull is otherwise inaccessible and biofilm is actively growing. And because attachment derives from the hull itself rather than from tow tension or way-speed, the same platform grooms with the vessel stationary in port or at anchor, which is when fouling pressure is highest.

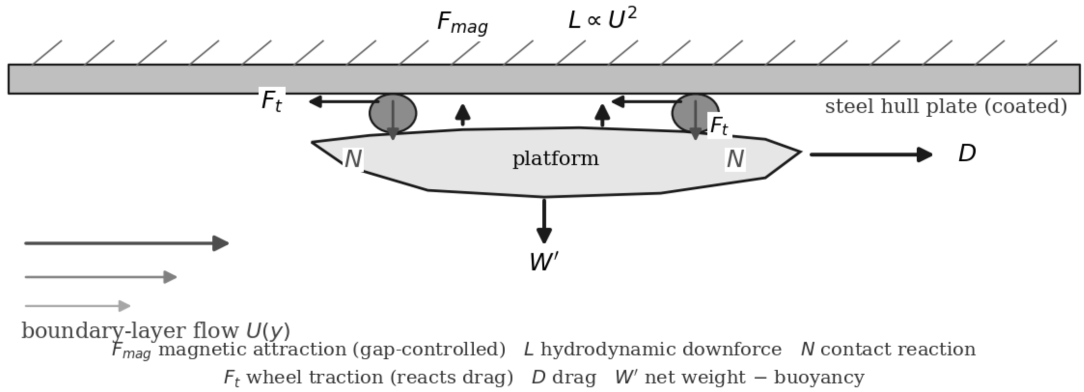

Fig.6: Force balance on the platform at transit speed: magnetic attraction and hydrodynamic downforce react contact forces and net weight normal to the hull; wheel traction reacts drag along it. Vector directions are indicative; magnitudes are not disclosed.

The primary operating mode is proactive grooming every 10-14 days, holding the hull at FR-0 to FR-1, the regime MEPC.378(80) defines as proactive cleaning; capture is not applied because only early-stage biofilm is removed, dispersed along the open-ocean route rather than concentrated in port receiving waters. A corrective in-port mode, with or without capture as fouling rating and local rules require, handles vessels entering a grooming programme with established fouling. Every grooming pass is also a sensing pass: cameras document coating condition, fouling rating and mechanical damage by hull zone on every cycle, and positioning telemetry logs what was groomed, where and when. The result is an auditable record aligned with MEPC.378(80) documentation expectations and ISO 6319:2026 reporting, generated automatically rather than assembled from event video, and a hull condition that becomes a continuously monitored parameter, comparable to main engine performance, rather than a quantity sampled annually by divers.

The operational case is best stated as a comparison of access modes rather than of removal mechanisms, and Table I sets out the constraints applying to each, including crew-deployed tethered devices towed along the hull while underway. Tethered in-transit tools share the central advantage of operating outside port limits and represent a real advance over purely reactive cleaning. Their constraints are geometric and operational rather than regulatory: a body towed on a line from the deck sweeps the bands the line geometry allows, leaving the flat bottom, roughly half the wetted surface on a full-form hull, and the stern hard to reach; the working force derives from way-speed, so nothing can be done at anchor or in port, where fouling accumulates fastest; each deployment consumes crew time and a weather window, so the achieved interval is set by operations rather than by fouling biology; and removal is by rotating brush contact, whose required force grows with whatever has been allowed to accumulate. An adhered, autonomous, non-contact platform is unconstrained on each of these axes. The distinguishing feature of in-transit autonomous grooming is not that it removes fouling more effectively; it is that it is the only access mode that can sustain the required interval over the whole hull without being rationed by port access, crew availability or line geometry.

Table I: Hull-grooming access modes and the constraints applying to each. Achievable intervals are typical commercial practice rather than technical limits.

Constraint	**Diver**	**Quayside / support-vessel ROV**	**Crew-deployed tethered device (in-transit)**	**CRABI autonomous grooming**
Vessel state required	Stationary, in port	Stationary, in port or at anchor	Underway, within speed band	Underway or stationary
Hull coverage	Full, by dive plan	Sides and bottom, in port	Vertical sides; bottom and stern constrained by line geometry	Full wetted surface incl. flat bottom and bilge radius
Achievable interval	Annual or less	Monthly at best	Crew- and voyage-dependent	10-14 days, deterministic
Removal mechanism	Brush or jet; high force on mature fouling	Brush or jet; moderate to high force	Rotating brush contact	Non-contact waterjet, low force
Operator dependency	Dive team per event	Pilot and comms link	Crew deployment and recovery each pass	None during operation
Grooms while idle (port / anchor)	Yes, where permitted	Yes, where permitted	No; requires way-speed	Yes
Coverage verification	Event video	Video and telemetry	Event video	Logged position and imagery, every pass

5. Economics

Whether a two-week interval is worth sustaining is answered with a deterministic per-vessel model that accepts operator-specific inputs (fuel consumption, sea days, bunker price, docking schedule, trade profile) and resolves annual benefit into bunker savings, dry-dock interval extension, carbon and CII value, and coating preservation.

Table II: Model structure and default inputs. All formulas are stated so results can be reproduced with operator-specific values.

Variable	**Calculation**	**Default / Range**
Fouling penalty (P)	Direct input: % added fuel consumption vs clean hull	9% (5-12%)
Effectiveness (E)	Direct input: % of fouling penalty eliminated	80% (60-90%)
Annual fuel saved (MT)	Daily fuel (MT/day) x P x E x sea days/yr	Vessel-specific
Bunker savings ($)	Annual fuel saved x bunker price	$500/MT ($400-650)
Carbon value ($)	Fuel saved x 3.114 tCO2/MT x carbon price	$25/tCO2 (EU ETS higher)
Dry-dock extension ($)	(DD cost / old interval) - (DD cost / new interval) + off-hire and docking-preparation savings	30% extension; 1 dock day saved

Every formula is stated in Table II so that a reader who rejects an assumption can substitute their own value and recompute. Inputs are calibrated on the literature of Section 2; fleet inputs are drawn from operator-provided records covering a 61-vessel container fleet and a 55-vessel dry bulk fleet; emissions use the IMO factor of 3.114 tCO2 per MT of fuel, *IMO (2020)*.

The fouling penalty default of 9% is the in-water cleaning recovery *Adland et al. (2018)* observed, and it is conservative twice over: it excludes the further 8 points recoverable only in dock, and it is a single-event recovery whereas the quantity governing fuel is the cycle mean, which Section 2 puts at 12.9%. The 80% effectiveness default is the proportion of the penalty grooming eliminates; the Section 2 integration implies 97% if the hull is held to biofilm regrowth alone and 81% if residual coating ageing is retained, so the default matches the pessimistic case. It is not 100% because residual roughness remains and niche areas outside the groomed envelope continue to foul. Both defaults are replaced by measured ISO 19030 values as validation data accumulates (Section 7).

For a representative 4000 TEU container ship (approximately 50000 DWT, consuming 45 MT/day at service speed, 280 sea days, $500/MT bunker), Table III resolves the modelled benefit: $719200 per year gross, 63% of it from the bunker category, the only category derived directly from measured data. The dry-dock category includes one term that follows from the inspection record rather than from fouling: because every grooming pass is also a sensing pass (Section 4), the vessel arrives at the yard with hull condition, coating state and work scope already documented, removing the initial inspection-and-scoping day from the docking critical path. One off-hire day at a $25000 per day time-charter equivalent, amortised over the five-year docking interval, contributes $5000 per year. Applied across a 61-vessel container fleet spanning 1200 to 4800 TEU, the same model gives $35 million per year gross; the per-vessel average sits below the Table III ship because the fleet includes small feeders. These are model outputs on literature-calibrated inputs, not measured returns, and service pricing is commercial and vessel-specific rather than published here.

Table III: Modelled gross annual benefit for a representative 4000 TEU container ship

Benefit category	**Annual value**	**Share of gross**
1. Bunker consumption savings	$453600	63%
2. Dry-dock interval extension and docking preparation	$100000	14%
3. Carbon credits and CII recovery	$105600	15%
4. Coating preservation	$60000	8%
Gross annual benefit	**$719200**	**100%**

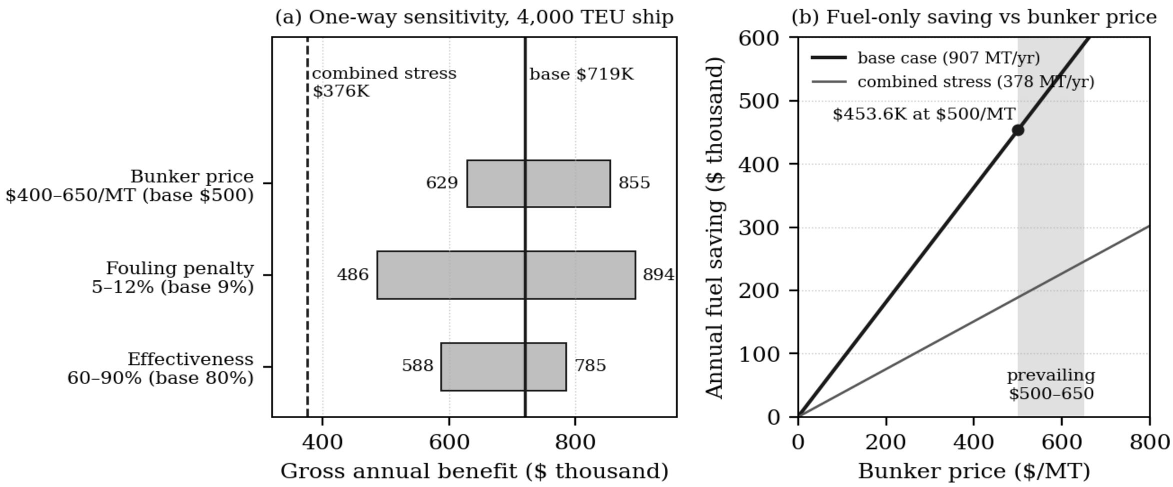

Fig.7: (a) One-way sensitivity of gross annual benefit for the 4000 TEU ship of Table III; the dashed line is the combined stress case. (b) Annual fuel-only saving against bunker price for the base and combined stress cases, with the prevailing price range shaded.

The model's principal sensitivities are bunker price, the fouling penalty and the effectiveness rate. Fig.7 varies each in turn for the ship of Table III, computed directly from the formulas of Table II with all other inputs held at base values. Bunker at \$400/MT reduces the gross benefit by 13%, to \$628500; a 5% fouling penalty by 32%, to \$486200; 60% effectiveness by 18%, to \$588200. Applying all three at once still leaves \$375600, just over half the base case, of which \$151200 is the bunker category alone. Whether that clears the cost of any given service arrangement is a commercial question; the quantity established here is the size of the penalty currently left on the table.

6. Coating Compatibility, Environment and Regulation

The economics assume the coating survives the treatment, and that cannot be left implicit: a regime that saves fuel while shortening coating life has moved cost rather than removed it. The mechanism protecting the coating is the interval itself. Adhesion never matures, so jet forces remain far below damage thresholds, and the supporting evidence is that of Section 3: no measurable damage from gentle jetting at bimonthly intervals, *Oliveira and Granhag (2020),* against a 7% resistance penalty from abrasive cleaning, *Utama et al. (2021)*. Qualification against specific biocidal self-polishing, foul-release and hard non-biocidal products is in progress and no product-specific result is claimed here; the measurement set is dry film thickness, surface energy, roughness and microscopic surface condition with re-fouling follow-up, and acceptance criteria are better settled with coating manufacturers and independent test houses than declared unilaterally (Section 7).

The same interval carries the regulatory case. Fuel saved is emissions avoided at 3.114 tCO_2/MT, and the saving propagates directly into the CII Annual Efficiency Ratio; for vessels near a C/D or D/E boundary, hull condition can determine whether corrective action plans are required. On biosecurity, the concern with reactive cleaning is that established macrofouling communities are viable, reproductively mature organisms, removed and released into precisely the receiving waters regulators are trying to protect, which is why Australia, New Zealand and a growing number of ports require capture. A hull held at FR-0 to FR-1 carries no established community to translocate and sheds negligible early-stage biofilm, dispersed along the open-ocean route; it arrives at every port within even the most stringent arrival standards, with the compliance record generated automatically (Section 4).

Grooming falls within the proactive-cleaning category of MEPC.378(80) rather than the reactive cleaning that port permitting regimes are written to control. This is not a means of working around regulation, since arrival-condition standards still apply on every entry; it is a hull that satisfies them more reliably and with better documentation. In-transit grooming complements the in-port maintenance ecosystem rather than replacing it: corrective cleaning, niche-area and propeller work, inspection diving and the class and repair functions of the dock all remain, with demand shifting toward more targeted intervention.

7. Conclusion

The fouling penalty on a modern, well-coated commercial hull is a measured quantity rather than an estimate: 9% recoverable in water and 17% in dock, *Adland et al. (2018)*, a 12.9% mean over the docking cycle under annual cleaning. What the industry has lacked is not evidence that the penalty exists, but a means of acting on it more than once a year. Frequency, not force, is the variable that matters, and the two are inversely related: grooming every 10 to 14 days holds the mean to 0.4%, at removal forces low enough that the coating is not the limiting component, on the only access mode, autonomous, adhered and in-transit, that can sustain that interval over the full wetted surface. For the 4000 TEU container ship modelled, the result is roughly \$0.7 million per year of avoided fuel, emissions exposure and maintenance cost.

The assumptions behind that figure are stated and bounded in the sections above, and closing them is proposed as a shared programme rather than a proprietary claim. Deployment begins with a two-to-three-vessel, six-month pilot under ISO 19030-2 monitoring with quarterly joint review, measured data replacing the literature calibration. Three studies would advance the evidence base for proactive grooming regardless of which platform performs the work, and CRABI is seeking partners for each: a multi-supplier coating-compatibility panel programme with shared acceptance criteria and a common definition of grooming efficacy; a biofilm regrowth study resolving the twelve-day force threshold by water temperature, season, trade region and idle fraction, since the grooming interval proposed here remains to be validated across trade regions and seasons; and a longer-horizon controlled trial replicating the *Adland et al. (2018)* design for grooming, a groomed cohort against a conventionally cleaned control with intervals varied deliberately and independent analysis a condition rather than a concession. ISO 6319:2026 supplies the reporting structure for the cleaning event itself, what remains is an agreed method for reporting what an event achieved and how long the achievement lasted, and CRABI would rather help build that convention with coating manufacturers, class societies and test houses than publish numbers against a standard of its own devising.

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Controlling Fouling on Stationary Vessels

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Abstract

Marine biofouling can develop rapidly when vessels remain stationary. Many antifouling approaches are ineffective on stationary vessels, since they depend on water movement to prevent or remove fouling. Ultrasonic antifouling uses vibrations to continuously prevent the first stage of biological processes that lead to macrofouling. Experimental results on mussel larval settlement show that ultrasonic treatment can prevent biofilm-mediated settlement without needing water movement, hence is effective on fouling of stationary vessels. Continuous operation of ultrasonic vibration is essential, however, and all protected surfaces must be brought into sufficient vibration. For hulls, frame-structure and accessibility are thus decisive for ultrasonic protection's effectiveness.

1. Introduction

Marine structures are rapidly colonized with biofouling when exposed to seawater. Biofouling affects vessels' seawater cooling systems and hulls, offshore structures and many other submerged surfaces. The consequences of fouling range from increased maintenance and corrosion to reduced cooling performance and, in the case of fouling on hulls, increased resistance and fuel consumption.

Biofouling is often discussed in terms of the organisms that eventually become visible: barnacles, mussels, tube worms, hydroids, bryozoans and other macrofouling organisms. They are the end stage of fouling. The process begins much earlier.

As soon as some surface is submerged, organic molecules and other dissolved material adsorb onto it. Bacteria, diatoms, algae and other microorganisms subsequently attach and establish a microbial biofilm. This biofilm is the familiar slimy, mostly transparent layer that develops on submerged surfaces. It changes the physical and chemical characteristics of the surface and provides conditions that facilitate the subsequent settlement of macrofouling organisms.

This staged development is important when considering antifouling technologies. Preventing the surface from becoming biologically conditioned in the first place appears a more elegant and efficient approach than remedying mussels or barnacles after they have attached.

Many antifouling technologies use chemical biocides to interrupt the biological process or address existing macro-fouling. Others use mechanical cleaning to remove fouling after it has developed. Ultrasonic antifouling introduces high-frequency mechanical vibration into the protected structure addressing the first stages of fouling, instead of releasing chemical biocides into the surrounding water.

A recent study by Capelle et al. investigated whether ultrasonic vibration could interfere with the staged fouling process culminating in mussel larval settlement, *Capelle et al. (2026).* Steel plates were exposed to Mytilus edulis larvae in tanks with and without ultrasonic treatment. Under control conditions, without the ultrasonic vibration, the plates grew 2.5-week-old biofilm which increased mussel settlement odds by approximately 49-fold. Ultrasonic treatment at 28 kHz eliminated this biofilm-mediated enhancement, resulting in practically no fouling (one in 49 only).

The study is particularly relevant because it points towards prevention of the biological process that precedes macrofouling, rather than removal of macrofouling once it has developed.

Shipsonic's experience with ultrasonic antifouling on box coolers is consistent with this interpretation.

Vessels on which box coolers were clean when the system was installed and switched on, have experienced minimal fouling. Where box coolers were already fouled, or where ultrasonic protection was only activated after exposure to seawater, fouling could later on establish, even if the ultrasonic vibration was continuously present on the surface with biofilm.

2. The Staged Process Culminating in Macrofouling

Biofouling is not a single event. It is a succession of processes, with the early stages creating conditions in which later stages can occur.

2.1. Initial surface conditioning

The first stage starts almost immediately after immersion. Dissolved organic molecules and other material in seawater adsorb onto the surface and form a conditioning layer.

Although this layer is not itself a microbial biofilm, it changes the surface properties and provides conditions favourable for microbial attachment. The relevant question for an antifouling technology is therefore not necessarily whether every molecule can be prevented from reaching the surface, but whether subsequent biological development can be prevented.

2.2. Microbial attachment and biofilm development

Bacteria, diatoms, algae and other microorganisms begin attaching to the conditioned surface. Over time, these organisms form a structured microbial community embedded in extracellular polymeric substances (EPS).

This biofilm is not simply a layer of dirt. It is a biologically active system with its own physical structure, chemical gradients and biological interactions. The biofilm can alter surface roughness and chemistry and can produce substances that influence the behaviour of larger organisms.

This makes biofilm development a critical transition in the fouling process. From Shipsonic's field experience, biofilm can form very quickly after an object becomes submerged in seawater. The exact rate depends strongly on environmental conditions. In some locations and seasons, visible biofilm development can occur within hours, while other environments develop more slowly.

2.3. Settlement of macrofouling organisms

Once a suitable microbial community has developed, larvae of larger fouling organisms may be attracted to the surface. For many macrofouling organisms, the presence of a microbial biofilm appears to provide an important settlement cue or suitable settlement surface.

Keeping some surface free of biofilm can therefore prevent or strongly reduce subsequent macrofouling.

The recent Mytilus edulis experiment provides a clear example. Under controlled conditions, the presence of a developed microbial biofilm produced approximately 49 times higher settlement odds than the ultrasonic treated surfaces, which remained free of biofilm. Under ultrasonic treatment at 28 kHz, this biofilm-mediated enhancement disappeared and hardly any macro-fouling developed, *Capelle etal. (2026)*.

This does not mean that biofilm is the only possible route to settlement for every macrofouling organism. Different organisms respond to different physical and chemical conditions. The result does, however, demonstrate the importance of the early microbial stage for at least one important macrofouling organism.

2.4. Why the early stage matters

Once mussels, barnacles or other organisms have established themselves, the problem becomes substantially more difficult to solve.

If biofilm is the gateway to macrofouling, preventing biofilm is fundamentally different from trying to deal with macrofouling after it has developed.

This distinction is important when comparing different antifouling technologies. Technology that prevents the early biological process does not need to remove an adult mussel or barnacle because these were prevented from settling.

3. Addressing Biofouling on Seawater Cooling on Vessels

3.1. The Workings and Effectiveness of ICAF in Preventing Macrofouling on seawater cooling

Impressed Current Antifouling (ICAF) is widely used in marine cooling systems, including box coolers and seawater intake systems. Its basic principle is to release copper ions into the surrounding seawater by applying an electrical current to consumable copper anodes.

For copper-based ICAF systems, copper ions create an environment that is unfavourable to the establishment and development of marine organisms. ICAF is therefore a preventative technology rather than a method for removing mature fouling.

This distinction is important. ICAF manufacturers explain that established macrofouling, such as settled mussels, cannot be removed or even killed by the system. The purpose is to maintain conditions that inhibit biological development.

The concentration and distribution of copper ions around the protected surfaces are consequently important.

In a box cooler, ICAF copper anodes are generally installed beneath the tube bundle. The released copper ions need to reach along the length of the tube bundle and the areas that are to be protected, often more than a metre above the anodes.

When the engine is operating and the box cooler is carrying a heat load, warmer water rises and temperature-driven circulation will occur within the sea chest. This circulation contributes to the distribution of copper ions from the anodes to the length of the tube bundle. The temperature difference water circulation is called thermosiphon principle.

When the engine is shut down, the heat source disappears and the temperature difference driving thermosiphon circulation also disappears. In a stationary vessel, there is normally no external flow either. ICAF therefore has an important dependency on temperature differences of operating cooling installations.

This means that ICAF is ineffective whenever the engine is off, because the mechanism used to distribute the copper ions is linked to the thermal conditions in the cooler and sea chest.

ICAF also has several practical requirements: consumable anodes; electrical power and control equipment; electrical connections to submerged components (‘through-hull’); space for anodes and their brackets; periodic inspection and replacement; and continuous release of copper ions into the surrounding environment.
These requirements have been satisfied in large numbers of installations over decades. ICAF has been used successfully for many years. They do, however, become relevant when comparing ICAF with an antifouling method.

3.2. The Workings and Effectiveness of Ultrasonic Antifouling

Ultrasonic antifouling introduces high-frequency mechanical vibration into the object to be protected. An ultrasonic transducer converts electrical energy into mechanical vibration. When coupled to a solid structure, the vibration propagates through that structure and brings the protected surface into vibration.

Unlike ICAF, ultrasonic antifouling does not consume a biocidal material. The only consumable input is electricity.

The precise biological mechanism is still unclear. Several mechanisms have been proposed, including disruption of microbial attachment, disruption of the extracellular polymeric substance matrix, acoustic streaming, cavitation effects, changes in the near-surface environment and behavioural responses of larvae.

The work by *Capelle et al. (2026)* is particularly relevant because it investigated the biofilm-mediated settlement pathway. Their 28 kHz ultrasonic vibration treatment practically eliminated the 2.5-week mixed microbial biofilm development. On the reference plates, which were not under ultrasonic vibration treatment, biofilm developed significantly. The subsequent introduction of exactly measured 500,000 mussel larvae in each separated tank resulted in a 49 fold higher Mytilus edulis settlement on the control plates while hardly any mussel settlement occurred on the treated plates. (The difference was 49 fold, therefore a treated plate had about 2% mussel settlement of the reference plates).

The experimental findings therefore have an important practical interpretation: ultrasonic treatment can keep a surface sufficiently free of biofilm to prevent the subsequent biological conditions that lead to macrofouling.

We do not need to know every detail of the biological mechanism before recognising the practical significance of this result. If the surface remains clean of biofilm, the subsequent settlement process can be interrupted.

This means in practice means that treatment needs to start immediately, as soon as the surface to be protected becomes exposed to sea water.

At the same time, the experiment does not establish one unique mechanism. Further work is needed to determine exactly how ultrasonic vibration interferes with the biofilm–larva interaction and how broadly the observed effect applies to other organisms.

3.2.1. Continuous operation

If ultrasonic treatment prevents biofilm development rather than removing it, continuous operation becomes critical.

Shipsonic’s experience indicates that systems that are switched off can lose their protective effect. An ultrasonic system does not leave a biocidal layer behind after it is switched off. The protection is created by the physical treatment itself.

This creates a straightforward practical requirement: when a vessel is stationary, the ultrasonic system needs to remain powered if the protected surface is to remain protected. This is particularly relevant during shipyard periods. A vessel may be returned to the water before its normal electrical systems are fully operational. New-built vessels can also spend months in the water during final construction and commissioning. If the vessel does not yet have its normal power supply, continuous ultrasonic protection requires another source of power.

3.2.2. Ultrasonic effectiveness in different operating conditions

Vessels that are moving at normal speed, laying stationary or moving very slowly constitute different conditions that affect anti-fouling solutions in different ways. Similarly, whether engines are or are not operating, has implications for the effectiveness of ultrasonic and ICAF anti-fouling on cooling systems.

The objective of ultrasonic and ICAF antifouling is similar: both are preventative technologies. The crucial difference is how they achieve that prevention.

ICAF requires copper ions to reach the surfaces being protected. In box-cooler installations, thermosiphon circulation contributes to this distribution when the engine is operating and there is a temperature difference.

Ultrasonic antifouling does not depend on water circulation. It depends on the protected structure being brought into sufficient vibration and on the system remaining powered continuously.

3.2.3. Box-cooler circulation under different operating conditions

- Stationary + engine running: thermosiphon/natural-convection circulation can occur because there is a temperature difference.
- Stationary + engine off: there is no meaningful heat load, so the thermal driving force disappears.
- Moving + engine running: external flow and the thermal circulation both contribute.
- Moving + engine off: there is external water movement, but no thermosiphon/natural-convection circulation since there is no cooling heat load.

This overview demonstrates that vessels who are stationary with engine off, will not experience functioning ICAF systems and laying stationary with engine off will normally result in biofouling problems. These vessels can consider preventing the biofouling by adding or switching to ultrasonic solutions.

For vessels that are at times moving but with engines off (a situation that is increasingly common in hybrid electric-diesel vessels) the water movement may also not be sufficient for the ICAF system to work fully. Several of these vessels have decided to add or switch to ultrasonic anti-fouling, in the experience of Shipsonic.

4. Addressing Biofouling on Hulls

The same basic biological sequence of fouling applies to a ship's hull. The hull is rapidly conditioned after immersion, microorganisms attach and form biofilms, and larger organisms can subsequently settle and develop into mature macrofouling communities.

For hulls, the consequences of fouling are particularly significant because increased surface roughness increases hydrodynamic resistance and therefore fuel consumption. For various reasons, possibly including that fouling on the hull is more visible, this problem has received more attention than fouling on cooling systems, both in terms of its impact and its environmental aspects. Fouling of hulls is, like with seawater cooling systems, primarily fought with biocides and also hulls are and were traditionally kept clean with copper-based solutions (paints).

The stationary condition is as important for hulls. Several forms of hull protection are widely used, including copper-containing antifouling paint, silicone-based systems and hard coatings. Their anti-fouling mechanisms differ but all rely on water circulation for their effectiveness. As a result, all experience fouling during prolonged stationary periods in sea water. Where copper and other biocides need to reach all parts of the seawater cooling system through water circulation, for hulls the different antifouling options depend on the water circulation for the biocides to free or for the early-stage fouling to fall off due to water speed.

Ultrasonic antifouling has a different working, also on hulls. Its preventive action does not depend on the vessel moving through the water. If continuously powered and properly coupled to the hull structure, it can continue to protect the hull while the vessel is stationary. The only requirement is continuous power.

This makes ultrasonic antifouling one of the few available approaches capable of providing effective fouling prevention under both moving and stationary conditions.

For hulls there are, however, some important challenges.

Ultrasonic transducers need to be installed on the inside of the hull and normally are installed ‘dry’. The transducers (also named ‘transponders’ or ‘loudspeakers’) bring the entire hull plate into vibration and thereby protect the outside surface. While the hull is acoustically an easy shape to bring into vibration, it has some barriers for the vibration to cover all parts. Sea-going vessels have frames, usually at 600mm spacing. Frames stop the ultrasonic vibration from travelling to the next space beyond the frame. Therefore, transducers need to be placed between each set of frames, resulting in a large number of transducers.

Secondly, on many vessels it is difficult to reach all parts of the hull from the inside. Ballast tanks, piping, insulation and some types of double-hull arrangements can prevent transducers from being installed in the positions required for optimal ultrasonic vibration propagation.

As a result, on many retrofits it may currently not be possible to protect every part of a hull with ultrasonic antifouling. For these vessels, hybrid solutions, combining ultrasonic anti-fouling, robot/in-transit cleaning and/or biocidal coating on parts out of reach of ultrasonic, may be a good alternative.

When taking all factors into account, including costs of coatings (both the material, docking and applying them), the lifetime of coatings, the environmental impact and costs of cleaning, some owners may in future request for vessel design that makes it possible to install ultrasonic anti-fouling in such a way that the full hull is covered. If ultrasonic antifouling is considered during the design of the vessel rather than added afterwards, transducer access and vibration transmission could become part of the structural design process.

The experimental findings, mentioned in the introduction chapter, therefore have relevance beyond the particular steel plates used in the mussel study. A hull is a large steel structure and, apart from interruptions created by frames and other structural features, it is an acoustically favourable object for transmitting mechanical vibration.

The challenge is consequently not whether a steel hull can vibrate, but whether the vibration sources, the transducers, can be placed in such a way that the high-frequency vibration can reach all parts of the hull that need protection.

4.1. Combining ultrasonic antifouling with hard coatings

Ultrasonic antifouling does not replace the corrosion-protection function of a hull coating. With ultrasonic coating no longer needs biocides or other self-polishing options. A hard coating can be combined with ultrasonic antifouling, for an environmentally friendly corrosion protection and speed optimizer. Ideally the coating will have a long life-time, to match the expected life-time of ultrasonic anti-fouling.

Shipsonic is therefore currently considering hybrid solutions in which ultrasonic antifouling is combined with a hard coating and, where necessary, a cleaning option. The ultrasonic system would protect the parts of the hull that can be covered acoustically. The hard coating would provide corrosion protection and a smooth surface, while mechanical cleaning could be used for areas that cannot be adequately protected by ultrasound.

It is too early to claim that such a combination will maintain a hull in good condition for ten years or longer. That should be regarded as a future potential result requiring long-term full-scale experience.

If such durability can ultimately be demonstrated, however, the consequences could be significant: fewer dry-docking interventions, lower stripping and recoating requirements, lower coating costs and potentially longer periods during which a smooth hull surface is maintained. The benefits for the oceans and ports may also be substantial.

In addition, such a solution can protect vessels that are stationary for extended periods and may even prove effective on floating objects.

5. Conclusions

Marine biofouling develops through a succession of stages, beginning with surface conditioning and microbial attachment and potentially culminating in the settlement and growth of macrofouling organisms. The early microbial biofilm is particularly important because it can provide a suitable surface and/or biological cues for subsequent settlement, without which settlement does not happen. For mussels and likely other macrofouling organisms, keeping the surface free of biofilm can therefore prevent or strongly reduce subsequent fouling.

The recent experimental work on Mytilus edulis provides useful evidence for this mechanism. Under control conditions, a 2.5-week-old mixed microbial biofilm increased mussel settlement odds by approximately 49-fold. Ultrasonic treatment at 28 kHz eliminated this biofilm-mediated enhancement and remained virtually clean, or 49-fold less settled, *Capelle et al. (2026)*.

Both ICAF and ultrasonic antifouling are preventative technologies. The important difference is how they create that prevention. ICAF uses consumable copper anodes and depends on copper ions reaching the surfaces to be protected. In box-cooler installations, the thermosiphon principle contributes to the distribution of these ions when the engine is operating and a temperature difference exists.

Ultrasonic antifouling instead uses mechanical vibration of the protected structure. It does not depend on water circulation, but it does depend critically on continuous operation and sufficient vibration of all surfaces that need protection.

This difference implies that stationary vessels without engine power can be fully protected by ultrasonic anti-fouling, while ICAF is hardly effective. The effectiveness of ultrasonic anti-fouling is also higher for vessels moving with engines off, as happens with hybrid electric/diesel vessels.

For hulls, the principal advantage is similar. Ultrasonic antifouling can continue to operate while a vessel is stationary, provided that the system remains powered and the relevant hull surfaces are brought into sufficient vibration. This is an advantage of ultrasonic anti-fouling over coatings or paints. These require movement of the vessel to keep the hull clean.

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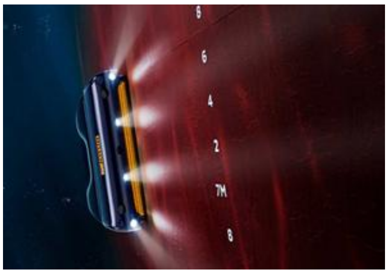

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