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Biofouling Management: Challenges and Opportunities

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Table of Contents

List of Figures

List of Tables

Glossary, acronyms and abbreviations

AF coating – Anti Fouling coating

AFS – Anti Fouling System

CDP – Controlled depletion polymer

CII – Carbon Intensity Index

EEDI – Energy Efficiency Design Index

EEXI – Energy Efficiency Existing Ship Index

FR – Fouling Rating

FRC – Fouling release coating

GEF – Global Environment Facility

GIA – Global Industry Alliance for Marine Biosafety

IAS – Invasive Aquatic Species

IMO – International Maritime Organization

IWC – In-Water Cleaning

MGPS – Marine Growth Prevention System

NSTM – US Navy Naval Ships' Technical Manual

SEEMP – Ship Energy Efficiency Management Plan

SPC – Self-polishing copolymer

TBT – Tributyltin, a highly toxic paint that widely used as antifouling paint until it was banned by the IMO with the AFS Convention

For the sake of completeness, I shall clarify that there is a difference between paint and coating. Paints have the sole purpose of decoration, instead coatings are used for protection (e.g. from rust or biofouling) and performance (e.g. low-friction). Although they have a different meaning and serve different purposes, the two terms often get used interchangeably, even from experts and manufacturers, the same will happen in this thesis.

I. Introduction to biofouling

Biofouling has been defined by the IMO1 in the 2011 Biofouling guidelines2 as "the accumulation of aquatic organisms such as micro-organisms, plants, and animals on surfaces and structures immersed in or exposed to the aquatic environment." Although biofouling is a problem for many actors in the shipping cluster, as we can understand from the IMO definition, this work will be focused mainly on commercial shipping. The increased levels of biofouling accumulations on the ships' hull produce an increase int the resistance to motion of the ships sailing through the water. The increased resistance leads to worse performance of the ships, higher costs, and reduced energy efficiency. Maritime trade has always been critical for the development of economies, cities, and nations, thanks to its characteristics of ensuring the movement of high volumes of goods and people around the globe at the lowest costs. Currently about 90% of the total transports fall into seaborne transport, and shipping accounts roughly for 3% of the world's GHG emissions; these metrics make the shipping sector stand out as the most economical and environmentally friendly mean of transport available, and from 2008 to 2014 we experienced a rapid carbon intensity reduction by shipping thanks to the increased size of the newbuilds ships that could exploit economies of scales and offered better efficiency. Unfortunately, this trend stopped and from 2014 to 2021 total emissions increased. Total emissions are expected to increase also in the future, due to an increase in sea transport demand, despite an intensifying regulatory landscape, degrowth and deglobalization scenarios.[3] As ships sail through the water their underwater parts and their superstructures experience resistance to motion (drag). The correlation between the accumulation of micro-organisms on the ships' hulls and the increase in resistance is as old as the shipping itself. Throughout the years, the biofouling problem has been tackled by different sea-going populations (Arabs, Greeks, Romans, Vikings), and each of them came up with different solutions to defend their ships from these hitchhiking agents. In the list below some quick examples of how

[1] The International Maritime Organization is the United Nations agency that promotes conventions and best standards for maritime safety and security issues. It was established in 1948 via an international convention. It was previously known as Inter-Governmental Maritime Consultative (IMCO).

[2] IMO Resolution MEPC-207(62) adopted on 15 July 2011, "2011 Guidelines for the control and management of ships' biofouling to minimize the transfer of invasive aquatic species".

[3] For further information see Fourth IMO Greenhouse Gas Study 2020 and Simpson Spence Young outlook 2022.

different anti-fouling methods have evolved over the years[4]:

- By the 2nd century BC, the Phoenicians were known to use a mixture of arsenic, sulphur and chian oil as the first treatment used for ship efficiency.
- By the 3rd century AC, tar and wax were used to coat ship's bottoms.
- Between 8-11th centuries pitch, oil, resin, and tallow were used for hull treatments.
- Between 13th and 15th centuries, lime, and poisonous oil.
- With the industrial revolutions and the beginning of the modern shipping sector, and the use steel in shipbuilding, metallic compounds were used as antifouling paints.
- After the second world war, Tributyltin-based paints (TBT) were the market leader, thanks to their antifouling capabilities. After a phase-out period, TBT paints were eventually banned by the IMO in 2008 due to their high toxicity.
- Development of new antifouling paints. Today the most used are Self-Polishing (SP) and Fouling Release (FR) paints.

As in many other fields, most of the early research on biofouling was conducted by governmental organizations, both the British Admiralty and the US Navy started to publish their findings, with rules of thumbs[5] and technical manuals around the second half of the 20th century. With the development of commercial shipping, where cost controlling and cost reduction play a major role in determining the success of shipping companies[6], more detailed and precise research was needed. Although it was a problem known by most of the player, due to its low visibility and measurability, the problem was largely underestimated or not considered, until recently when we have seen a combination of conditions (increased competition, regulatory requirements, technological breakthroughs) that drew attention to the topic and sparked innovation in the field but, there's still a lot to be done. In fact, according to a recent survey conducted by Safinah in 2020[7], around 80% of the surveyed fleet presented biofouling levels at alarming levels. It's estimated that the biofouling problem is responsible for

[4] Woods Hole Oceanographic Institution (1952), Marine Fouling and Its Prevention, Chapter 11, The History of the prevention of Fouling pp.211-212 and Doran S., 2022, Evolving Inspection and Cleaning Technology presented at 3rd Port In-Water Cleaning Conference Hamburg,9-11 September 2022.

[5] The British Admiralty accounted for an increase of frictional resistance of around 50% after a 6-month deployment, where the US Navy proposed a 3% increase in bunker consumption per month. For further information on the early works please see "Marine Fouling and its prevention, U.S. Naval Institute.

[6]Considering the limited possibilities of product differentiation between competitors, the "same but cheaper" approach is often the preferred one by shipping companies (Jadranka et al, 2015).

[7] Biofouling in Commercial Shipping: The Importance of Ship-Specific Functional Specifications Safinah, 2020,

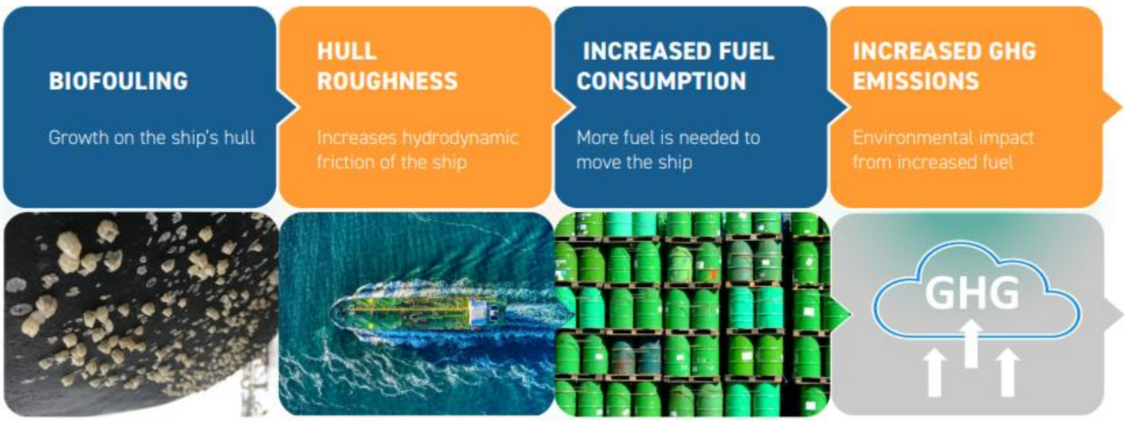
198 million tons of CO_2 emitted, about a 20% of the total emissions. (Swain et al, 2022), and converted into monetary value, depending on the cost of bunker, shipowners and ship operators are paying between 30 and 70 billion of USD every year.[8]

[8] The monetary figure is a rough estimate based on emission factor and average cost of bunker. The emission factors of the bunker oils used by vessels are around 3 (t of CO_2 emitted per t of fuel burnt), and the average cost of bunker of around 500 USD/t

I.1 What is the biofouling problem

Without delving too much into the technicalities, to have a better understating of the biofouling problem, I think it’s important to first set the theoretical framework and explain which figures are influenced by the accumulation of these micro-organisms. When biofouling is experienced on a ship’s hull and propeller, it leads to an increase in hull roughness[9], this increases the hydrodynamic friction and drag of a ship. This increase in drag leads to: (i) an increase in engine output to maintain constant speed (ii) reduced speed at a constant engine output; (iii) worse manoeuvrability; (iv) increased maintenance costs; (v) increased corrosion and shorter dry-docking intervals; (vi) potential introduction of AIS[10]. The main economic aspects, the one of most interest for this thesis, are well summarised in Figure I.1.

Figure I.1 The ship hull biofouling penalty



Source: GEF-UNDP-IMO, 2022 a.

When trying to predict the biofouling penalty[11], there are two main variables to consider, the type of biofouling and their size and fouling coverage rate.

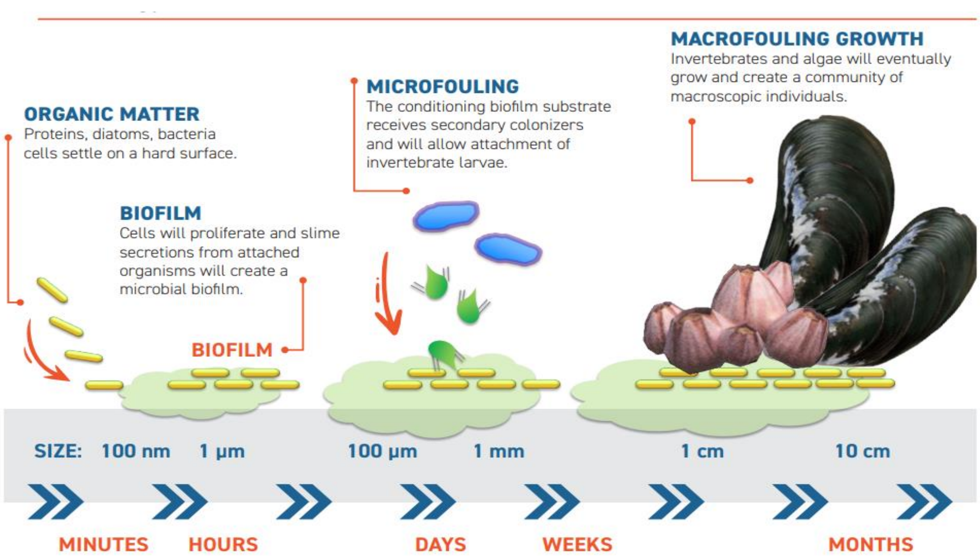
[9] Hull Roughness is the vertical distance between peak to through on a vessel’s hull. There are many ways to measure the hull roughness, and Rt50 and k_s measures are the most used.
[10] Alien invasive species are animals and plants introduced accidentally or deliberately into a natural environment where they are not normally found. They can be a major threat to native organisms and cause biodiversity loss. The impact in the EU is estimated at around EUR 12 billion Per year https://environment.ec.europa.eu/topics/nature-and-biodiversity/invasive-alien-species_en.
[11] Biofouling penalty means the percentage increase in engine power needed to maintain the same speed.

The purpose of the first variable is to determine the stage, size, and complexity of the experienced biofouling, in fact the studies show that the biofouling process follows a regular pattern illustrated in Figure I.2. Following the IMO 2011 Guidelines, for ease of comprehension, the type of biofouling can be divided into two main groups:

- Microfouling means microscopic organisms including bacteria and diatoms and the slimy substances that they produce. Biofouling comprised of only microfouling is commonly referred to as a slime layer.
- Macrofouling means large, distinct multicellular organisms visible to the human eye such as barnacles, tubeworms, or fronds of algae. They are typically more complex calcareous organisms, and they are experienced after that microfouling has already contaminated the ship. It may take months before macrofouling is experienced.[12]

Instead, the biofilm was not properly addressed by the Guidelines, and it represents a substrate that contains nutrients and gives the opportunity for biofouling organism to anchor and settle on the vessel (Cioanta & McGhin, 2017)

Figure I.2 The evolution of the biofouling process



Source: GEF-UNDP-IMO, 2022 a.

[12] In the review of the 2011 Guidelines, a quantitative definition of micro- and macro-fouling in terms of thickness is expected. (GEF-UNDP-IMO, 2022 b.)

Although it’s an easy-to-understand classification, it’s not very effective in describing the severity of the different possible levels of biofouling. The industry and academia have worked and are continuing to work to categorize standard levels to define the type and level of biofouling of ships. In Figure I.3 are listed some well-accepted types of categorizations. Instead, the definition of fouling coverage is yet to be satisfactorily addressed, but it is usually defined as the percentage of the ship hull covered by most complex type of biofouling experienced. In Table 1, the combination of both biofouling type and coverage rate.

Figure I.3 Commonly used classifications for hull roughness levels.

Description of condition	NSTM rating*	k_s (μm)	Rt_{50} (μm)
Hydraulically smooth surface	0	0	0
Typical as applied AF coating	0	30	150
Deteriorated coating or light slime	10 – 20	100	300
Heavy slime	30	300	600
Small calcareous fouling or weed	40 – 60	1000	1000
Medium calcareous fouling	70 – 80	3000	3000
Heavy calcareous fouling	90 – 100	10,000	10,000

Source: Schultz, 2007

Table I.1 Visualization of different levels of biofouling[13]

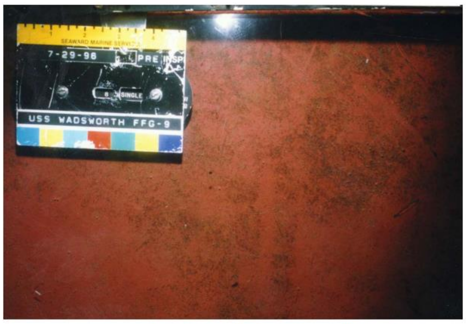


Figure 081-1-1 (SH1) FR-10, Over 30 Percent Of Area (Sheet 1 of 22).

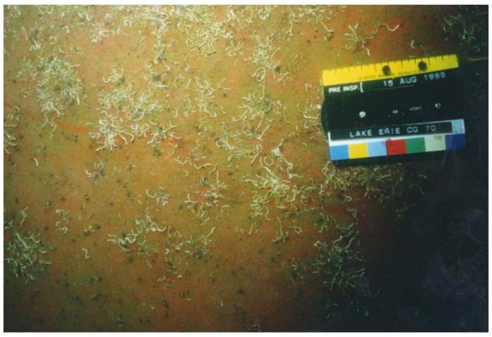


Figure 081-1-1 (SH5) FR-40, Over 20 Percent Of Area (Sheet 5 of 22).

Figure 081-1-1 (SH22) FR-100, Over 100 Percent Of Area (Sheet 22 of 22).

Source: Naval Ships’ Technical Manual Chapter 081 – Waterborne underwater hull cleaning of navy ships, 2006

[13] The FR (Fouling Rate) value inside Table 1 is equal to the NSTM rating of Figure 3

From a naval architecture perspective, the total resistance R_{Tm} (drag) of a ship sailing through the water can be conveniently decomposed into the frictional resistance component R_{Fm}, and the residuary resistance component R_{Rm}, as shown in Equation 1

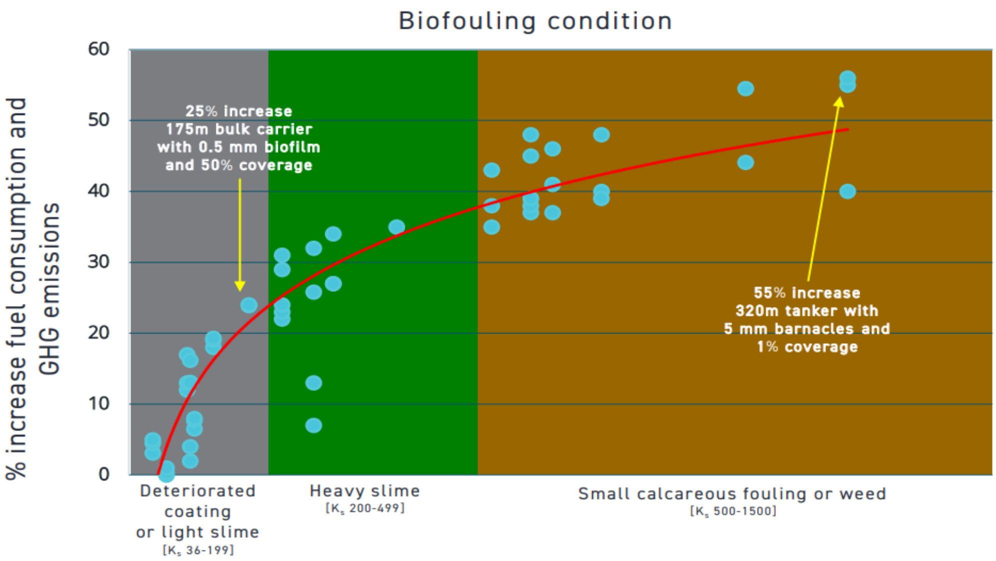
Equation I.1 – Total resistance formula

$$R_{Tm} = R_{Rm} + R_{Fm}$$

Source: Schultz, 2007 on Gillmer & Johnson 1982

The distribution of the total resistance between the two components varies depending on ship design and operational speed, but as a reference we can consider that for new ships frictional resistance accounts for 80-85% of the total resistance in slow-speed vessels, and around 50% in high-speed vessels (Bressy & Lejars, 2014). Biofouling has most of its effect on the frictional resistance cited in Equation 1, and it has been demonstrated that an "increase in biofouling level leads to a significant increase in frictional drag, although the level of the increase depends on the fouling type and coverage" (Schultz, 2007). Both academic literature and industry reports, as shown in Graph 1, confirm that an increased level of biofouling condition leads to an increase in bunker consumption and GHG emissions.

Figure I.4 Impact of biofouling on GHG emissions



Source: GEF-UNDP-IMO, 2022 a.

As said, the effects of the biofouling problem are vast, and the often most overlooked one is the introduction of Alien Invasive species. Alien species (also known as non-indigenous) are species that have established beyond their natural geographic range. Not all alien species are necessarily "invasive", but if the environmental conditions are suitable for reproduction, and there are no "natural enemies", they can rapidly spread and become invasive. Also, indigenous species can become invasive if the native environment is altered (GEF-UNDP-IMO, 2022 c). Most of the recent efforts in defending the local ecosystems from biofouling organisms have been focused on ballast water management, which ultimately led to the adoption of the Convention for the Control and Management of Ships' Ballast Water and Sediments (Moser et al, 2017). The Ballast Waters Convention (BWC), in short, was adopted in 2004 and entered into force in 2017; on the other hand, we only have voluntary guidelines in our international legal framework for the biofouling problem. This is a huge gap in our capabilities of reducing the introduction of Invasive Aquatic Species. Several studies show that the effect of biofouling in introducing non-native species is at least as relevant, if not more, compared to ballasts waters, according to studies that suggest that in some parts of the world, biofouling is responsible for 70-80% of IAS introduction[14]. The introduction of IAS has dire consequences, not only for environmental protection reasons, but also for direct economic impacts such as (i) loss of native species in fishing, and aquaculture; (ii) loss of tourism attraction, (iii) damage to coastal infrastructure, and property value. Some examples of the damages caused by IAS can be found in the Great Lakes where Zebra mussels were introduced in the 80s' probably via ballast waters in the first stage, and then further expanded through biofouling. Studies tried to estimate the economic damages caused by this introduction, but the discrepancies are extremely high, between USD 100 million and USD 6.5 billion[15]. This component of the damages caused by the biofouling problem is probably one of the most difficult to evaluate, and this may be one of the reasons that caused it to be often overlooked, falling into the McNamara fallacy.[16]

[14] The relative contribution of vectors to the introduction and translocation of invasive marine species, Marine Pest Sectoral Committee, 2010.

[15] Further information is available at: https://www.glofouling.imo.org/the-issue

[16] The fallacy occurs where there is an over-reliace on quantitative data and metrics, and not considering qualitative factors. The fallacy is usually summarized as "If something can't be easily measured it's not important, or it doesn't exist.

Observing “successful invaders” in the past, they all share some traits, such as broad environmental tolerance, rapid growth rates, production of large numbers of offspring, opportunism, early maturity, and the ability of reproduce both sexually and asexually (GEF-UNDP-IMO, 2022 c.). Understating the mechanisms affecting the successful establishment, dominance and spread (“Invasion success”) of IAS is central to developing effective management (Blackburn et al. 2011). Instead, “eradication successes”[17] are seldom, and often rely on early detection, low densities, and a contained geographical area (e.g. only in local marinas). Once IAS enters a local ecosystem, it is hard and expensive to remove them, making prevention the most cost-effective measure. (Green & Grosholz, 2020).

Factors that influence biofouling growth

Once we have established the correlation between biofouling and an increase in drag, it’s important to see the different factors that influence biofouling growth rate. One of the many components that make the biofouling problem so complex to tackle is that it’s not experienced the same in different parts of the world, because different species require different environmental conditions (e.g. seawater and fresh water creatures, warm and cold water creatures etc.). To predict Biofouling Growth (BG) the Woods Hole Oceanographic Institute (1952) proposed the following formula (Equation 2). However, some variables have more impact on biofouling growth compared to others and will be further analysed after (Uzun et al., 2019). We can identify three main areas that plays a major role in affecting (Report CEBRA, 2021).

Equation I.2

$$BG = f_1(SST, psu, pH, \upsilon, \mathrm{I}, \mathrm{S}, \mathrm{t}, m_t, \sigma, \theta_c, R_t, \eta_c$$ [18]

Source: Woods Hole Oceanographic Institute (1952)

[17] The effectiveness of Australia’s response to the Black Striped Mussel Incursion in Darwin Australia, 2000.

[18] BG is biofouling growth, SST is Seawater Surface Temperature, psu is water salinity, pH is acidity, υ is speed of the water flow, I is light intensity, S is concentration of nutrients, t is time of the exposure to water, m_t is microtexture of surface, σ is surface potential, , θ_c is the contact angle, R_t, is a roughness parameter and η_c is the value for the antifouling coating performance.

Environmental conditions,

- Water surface temperature (SST), it’s the parameter that most influence BG. Temperature influence the velocity of accumulation and its attachment capabilities. Studies have shown that biofilm accumulation is faster at higher water temperatures, but it’s also easier to clean, compared to slow growing and strong biofilm recorded at lower temperatures. (Farhat et al, 2016).
- Salinity and nutrient abundance and, biofouling is positively influenced by salinity and nutrient abundance in the water environment.
- Velocity of water flow (v), the velocity of water flow negatively influences BG. Currents with higher speeds decrease the possibilities that micro-organisms have enough time to foul the vessel. The differences can be seen both at different geographical points and within different areas of the same port (e.g., basins more exposed to water flow, and basins with stagnant water).
- Environmental conditions during sea passage, the presence of currents, weather conditions experienced and possible transitions between sea areas with different temperature and salinity levels influence the BG.

Vessel characteristics and operational profile,

- Vessel type, different vessel designs present experience BG in different forms. As said above water flow decrease biofouling accumulations, so vessels with high hydrodynamic capabilities are less exposed to this problem.
- Number, size and complexity of niche areas, niche area, which will be better explained in the next subsection, are areas on a vessel that for their design features are more exposed to biofouling accumulations. They may require a different approach compared to the hull, and they are often called biofouling “hot spots” (Moser et al, 2017).
- Static time, when vessels spend long periods berthed, in anchorage or idling, they will experience higher biofouling growth. Of course, the position of where the vessel has idled plays a huge effect. An early study (Woods Hole Oceanographic 1952) showed that the vessels that spent more time in port had a

higher change of not only developing biofouling, but also more complex types of it.

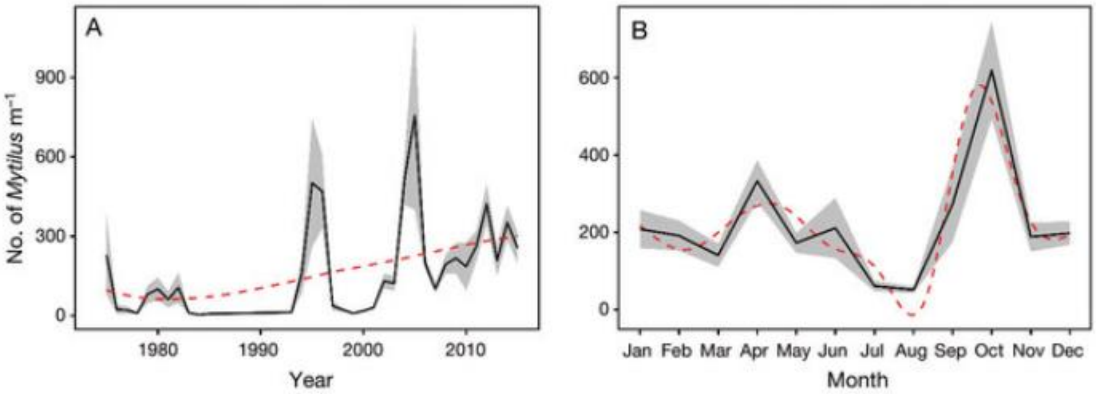
- Vessel speed, while a vessel is moving through the water, it generates a water flow that can clean its surfaces from attached organisms, so faster vessels usually contain fewer biofouling organism, because hydrodynamic drag forces remove them.

Vessel biofouling management activities

- Adoption of a biofouling management plan, having a strategy to manage biofouling (type of coating, regular inspection, cleaning if required) can drastically reduce the BG.
- Anti-fouling coating age, condition and suitability, coating are design to prevent biofouling. During their service life, coatings can be damaged or reach their limits (biocidal depletion), and so enable the attachment of water organisms. When choosing the coating shipowner must consider the expected trading profile of the ship, because a coating that is not suitable to the operations will be less or not effective.
- Presence of Marine Growth Prevention System (MGPS) are equipment designed to prevent the accumulation of organisms on the surfaces of the vessel.
- Hull Husbandry, regular inspections and cleaning can prevent the formation of macrofouling, which is the type of biofouling that creates the most serious consequences and it is harder to remove.

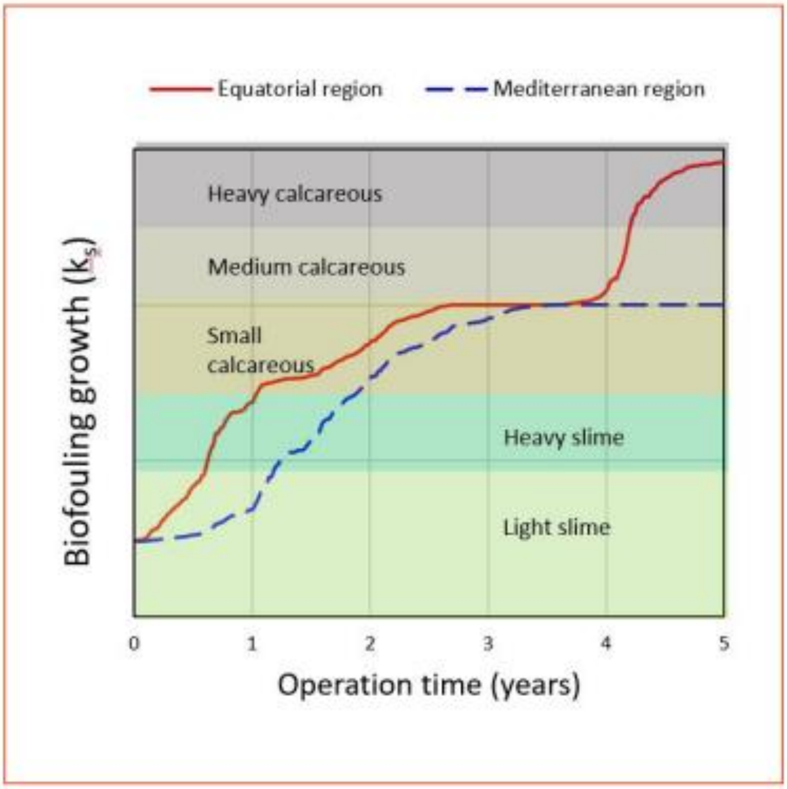
Moreover, as noted by (Atalah et al 2017) studying the recruitment trend of Mytilus, biofouling recruitment and formation is hard to predict, because it presents the elements of seasonality and volatility (Figure I.5). Combining these factor together one can identify which seas presents higher biofouling risks. For example, as shown in Figure I.6 biofouling in the equatorial regions is not only experienced faster but also reaches more complex forms compared to the Mediterranean region. This is mainly due to higher sea surface temperatures, salinity, and calmer waters. Taking all of these into account, one can really see how difficult it can be to find the perfect solution not only for different type of vessel, but even for a single vessel and makes the the implementation of biofouling management strategies extremely difficult.

Figure I.5 Modelling long-term recruitment patterns of blue mussels



Source: Atalah et al., 2017

Figure I.6 Comparison of biofouling growth in two different regions



Source: GEF-UNDP-IMO, 2022 a.

Niche areas

Niche areas refer to specific locations, that due to their design characteristics are particularly vulnerable to biofouling. Niche areas are often characterized by specific environmental and design conditions that promote fouling, such as being less exposed to water flows, absence of antifouling coatings or being more susceptible to damages, difficult to reach and to clean, higher temperatures. Given these assumptions, niche areas require a totally different approach to biofouling management compared to the hull. As most of the research on biofouling and hull cleaning deals with hydrodynamic drag reduction, and in turn fuel consumption, the effect of niche areas has been historically underestimated, as for their nature they don't have as big as of an impact on the biofouling penalty as other hull surfaces. But recent studies, not only focused on drag reduction, have exposed the real threat that unmanaged niche areas can pose on shipping. Niche areas are considered hot-spots for biofouling accumulation, where the foul can start and later spread to other areas of the vessel, and also be used as a vector for IAS, therefore, it is important to identify and prioritize these niche areas when developing a biofouling management strategy. Although, the selection of niche areas may vary among the selected literature, with some (Davidson et al., 2014) even extending to identify sub-niche areas[19], here are some of the most common:

Thruster tunnels

Nowadays, ships might have to manoeuvre in tight spaces, this is not always possible only with propeller and rudder equipment. So, modern ships are often equipped with thrusters that generates a later thrust to improve manoeuvrability capabilities of the ship, especially at low speeds, when the efficacy of the rudder is reduced.

Dry dock support strips (DDSS)

When a ship enters a dry dock, it is supported using blocks. Once the ship has entered the drydock, and the water is drained. The point of contact between the ship and the support blocks are called dry dock support strips. As these strips have to support the weight of the ship, they are inaccessible during drydocks and the application of

[19] Sub-niche areas are components of larger niche areas that present different characteristics, such surface orientation, exposure to currents and significant differences in biofouling coverage.

antifouling coatings is difficult or even not possible.

Bilge keels or fin stabiliser

Mounted on the turn of the bilge, they are narrow keels that provide hydrodynamic stability and protect the vessel from rolling (Saunders 1957). Bilge keels are static, while fin stabiliser can be deployed when high roll movement is experienced and retracted in calm waters.

Rudders

Rudders are the mechanical equipment responsible for steering the vessel. There are many rudder configurations on merchant ships, but the most common in merchant shipping is a single rudder mounted in the centre line on the aft section, behind the propeller. Rudder can steer the vessel via redirecting water flow and thus creating a rotating force, to do so, rudders must have a satisfactory control surface to provide an appropriate range of manoeuvrability (IMO, 1993)

Propellers

The equipment responsible to move the vessel forward, via torrotation received by the engine shaft. Ship propulsion devices come in many forms, fixed or variable pitch propellers, Azipod, and others, with fixed pitch propellers being the most common (Moser et al, 2017). Propellers vary in size, material used and number of propeller blades (Carlton 2012). Antifouling coatings are rarely used in propellers because the operating conditions of the propellers would quickly create wear and damage them. (Karabay 2011). Propellers have also a dedicated biofouling management practice called *propellers polishing.*

Propeller shaft casings

Strictly connected to the propeller, the shaft casing is the element that covers the engine shaft to prevent entanglements with lines, ropes or nets, this is also achieved with rope guard, which are blades mounted on the shaft casing to cut any entangled ropes.

Bulbous bow

The bulbous bow is at the fore section of the ship, and its purpose is to modify the hydrodynamics of the vessel and reduce the wave making, reducing drag and improving fuel efficiency. For its position at the front, it’s often one of the most damaged part of a ship, so the antifouling coating can be affected.

Sea chests and internal water systems

Sea chests are mainly used for ballast water intake, engine cooling and firefighting equipment. They are fitted which gratings which prevents large debris from entering internal pipelines.

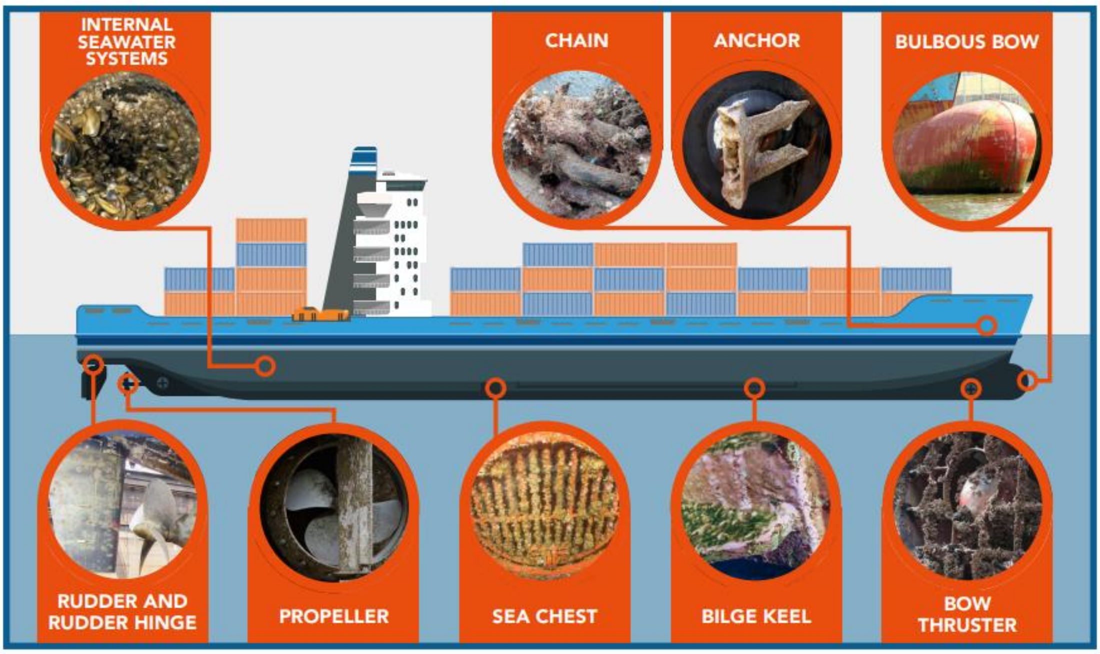
Anchor and chain

Ships are equipped with anchors located on the forecastle. When anchors and anchor chains are recovered, as they are not usually coated with antifouling paints, they can be contaminated with biofouling organisms. Although not managing to get a complete figure, a study from 2017 (Moser et al, 2017) tried to quantify the extent of niche areas in the global merchant fleet, and it resulted that from a considered fleet of 120’252 commercial ships, the total extent of niche areas was estimated to be 32’996 x 10^3 m^2, approximately 10% of the total wetted surface area. A great heterogeneity was also shown in study, with passenger ships having triple as many niche areas compared to cargo vessels.

Effective biofouling management in niche areas requires a tailored approach that considers the specific conditions and risks associated with each area. This may involve implementing different prevention and control measures in different areas, depending on the types of organisms that are present and the degree of fouling. For example, in a cooling water system, an antifouling coating may be effective in preventing the growth of algae and bacteria, while physical barriers or biological control methods may be necessary to prevent the attachment of larger organisms such as barnacles or mussels. By identifying and addressing niche areas in biofouling management, stakeholders can more effectively protect infrastructure, reduce maintenance costs, and promote environmental sustainability. Considering the niche areas since the earliest time of vessels design is the best and most long-lasting solution. The design should minimize the extent of niche areas or the possibility of them to foul. The following list of recommendations are set to reduce the risk associated by niche areas (IMO 2011 Guidelines and Georgiades et al. 2018):

- Exclude small niches and sheltered areas as much as possible.
- Design round corners and gratings for better application of antifouling coatings.
- Minimise the size and number of sea chests and fit a MGPS.
- Design components that can be easily accessed for inspection, cleaning and maintenance.

Figure I.7 Typical niche areas on a merchant vessel



Source: GEF-UNDP-IMO, 2022 c

I.2 Biofouling management solutions

Vessel operators use technologies, and management practices to minimise the effects of biofouling to a level that is acceptable to the industry in terms of operational efficiency (Report CEBRA, 2021 on Davidson et al. 2016). After having described in subsection 1.1 the negative consequences caused by biofouling, in this subsection the existing solutions to the problem will be discussed. As said the biofouling problem was long acknowledged, although often misrepresented or overlooked (Woods Hole Oceanographic, 1952). Historically, the tendence of biofouling management was to rely exclusively on the effectiveness of antifouling paints, with copper sheathings before and TBT coatings later. Following reports from aquaculture companies, the awareness on the toxicity of TBT paints began to spread, which ended with the adoption of the AFS convention from the IMO in 2001 its entry into force into 2008. The alternatives to TBT coatings were biocidal and biocidal-free coatings.[20] Other than fouling prevention methods, little literature was found on available solutions to clean ships once they have already been fouled. Nowadays, biofouling on ships and other infrastructure can be managed from two main perspectives: (i) preventive solutions have the purpose of preventing, reducing, or delaying biofouling contaminations, and are often referred to as the "first line of defence" and as discussed in the introduction the solution for preventive management are already established; instead (ii) reactive solutions are used only when vessels already present biofouling at an advanced level, this segment was historically more fragmented. Thanks to the development in robotics and automation, this category recently saw a breakthrough with many new companies rising in the last 10-15 years. The individual solutions that compose the two categories will be discussed in the coming subsection, whereas in Section III the largest European companies, which offers both preventive and reactive solutions, will be analysed. The author will try to divide them into these categories to the best of his ability, but some repetitions could occur, because of an observed trend that sees historical companies offering preventive solutions also developing reactive solutions to offer their customers a full package of products & services and exploit the rising trend and awareness on biofouling management.

[20] For further information on the historical development of the antifouling strategies please see Marine Fouling and its Prevention, Chapter 11, The history of the prevention of fouling.

Preventive Solutions

Application of antifouling coatings

Anti-fouling coatings are a combination of all component coatings surface treatments, used on a ship to control or prevent attachment of unwanted aquatic organisms. (IMO, 2011). The Industry is primarily concerned about the effects of biofouling on hydrodynamics, added resistance and associated costs. Modern coatings need to maintain a sufficient level of protection for extended periods of time irrespective of the exposure condition (Sánchez & Yebra 2009). The current AF coatings market can be divided into two main categories: (i) biocidal antifouling coatings, which inhibits or limits the settlement of organisms using chemically active compounds; (ii) biocide-free coatings uses other properties to prevent or limit biofouling growth. (Bressy & Lejars, 2014; Report CEBRA, 2021).

Biocidal antifouling coatings

Biocidal anti-fouling coatings contain toxic agents (usually 35-50% of dicopper oxide[21]) and booster biocides (0.1-10%) to broaden the protection from species resistant to the main biocide (Bressy & Lejars, 2014). The biocides contained in the paint are released gradually over time to prevent the adhesion of organisms. The factors that influence on the effectiveness and the longevity of the biocidal coatings are: (i) leaching rate and efficacy of the biocide life of the coating (Floerl et al. 2010) , (ii) concentration of biocide within the paint, (iii) amount of paint applied, (iv) its correct application and (v) the match between paint type and vessel operational profile (Georgiades et. 2018). Biocidal coatings come in a variety of ways, and each of them have their own characteristics which are best suited for a range of vessel types and their intended activities. The longevity of biocidal coatings varies considerably, and vessels owners and managers should seek advice from coating manufacturers to determine which type of coating best suits their needs. Their longevity range lasts between 12 months and 90 months. In 2014, biocidal coating accounted for 90% of the market share (Ciriminna &

[21] Dicopper Oxide (Cu_2O), according to the European Union, this substance is very toxic to aquatic life with long lasting effects. Its use it’s permitted only for selected cases for example as biocide for preventing fouling. (https://echa.europa.eu/substance-information/-/substanceinfo/100.013.883).

Pagliaro. 2015), but they could experience a decline due to the advent of foul release coatings. In general, the performance of CDP is considered poor but, due to its low cost, they are still preferred for vessels which have short dry-dock intervals and those operating in low biofouling regions (GEF-UNDP-IMO, 2022 a.).

Table I.2 Types of biocidal anti-fouling coatings

Type	Target	Expected longevity
Insoluble matrix, contact leaching paint	Recreational boating	12-24 months
Soluble matrix conventional	All types but not suitable for high-speed crafts	12-36 months
Soluble matrix, controlled depletion polymer (CDP) / Ablative paints	All types but less suitable for high-speed vessels or tropical waters	Around 36 months
Self-polishing copolymer (SPC)	Mainly commercial vessels	60-90 months
CDP/SPC hybrid coating	All types of vessels	36-60 months

Source: Adapted from Report CEBRA Project, 2021 Factors that influence vessel biofouling and its prevention and management

Biocide free antifouling coatings

To address the environmental concern of the release of biocide in the sea due to the use of biocide coatings, in the 1970s non-biocidal coatings started to be developed (GEF-UNDP-IMO, 2022 a). Today the main alternative to biocidal coatings is Foul-Release Coatings (FRC). They prevent biofouling thanks to their surface properties that create a “slippery” layer on the vessel’s surfaces that minimise adhesion of biofouling organisms and facilitate their removal when a sufficient water flow is experienced (CEBRA report, 2021). The surface smoothness of FRCs is not only useful in biofouling management, but also in reducing drag and fuel consumption before biofouling even occurs (approx. 10% reduction in fuel consumption). As FRCs do not use biocide they are not subjected to biocidal legislation. (Bressy & Lejars, 2014). FRCs are mainly composed of fluoropolymers and silicone elastomers, hence the commonly used name of Silicone paints. FRCs technology is more expensive compared to biocide coatings due to higher initial cost of paint and application. Silicone-based coatings are difficult to apply, and they require the use of specialised application equipment, which increases costs and time (Yamashita, 2022). Due to their functioning, FRC are most suitable for vessels with high speed (>15 kts[22]) and high activity (e.g., ferries, container ships, gas carriers, cruise ships, RO-RO vessels etc.). Thanks to research and development in the field, the functioning range will expand also towards slower and less active vessels (CEBRA report, 2021). The reported lifetime is high (5-10 years) and comparable with the best performing SPC, but FRCs are more susceptible to damages caused by anchor chains or mooring operations, which would hugely decrease their efficacy. Another aspect that requires to be addressed is the real environmental sustainability of these paints. Although it’s true that they do not contain biocides, they could still release toxic additives and silicone in their surroundings, and the consequences are still unknown (Rittschof, 2009).

Table I.3 List of others non-toxic anti-fouling solutions

Name	**Description**
Hybrid silicon-based FRCs	Improving FRCs properties by adding other materials to the silicone matrix

[22] Knots (Kts) is the commonly used unit of measure for the speed of ships. One knot equals to one nautical mile (Nm) travelled in one hour. One knot equals to 1,852 km/h.

Ultra-hard coatings	Non-toxic, inert and long lasting coatings. Requires regular in-water cleaning.
Fouling resistant surfaces	Chemically engineer surface properties to prevent biofouling (Hydrophobicity or hydrophilicity)
Engineered surface texture, nanotechnology	Modifying a surface on a micrometre scale to create antifouling properties

Source: CEBRA, report 2021

Installation of Marine Growth Prevention Systems (MGPS)

Marine Growth Prevention Systems are designed to prevent or delay biofouling occurrence in ships, and they are especially used for niche areas such as sea chests, and the internal piping network (ballast waters, water for fire suppression, engine cooling etc.) MGPS are needed for niche areas because they typically experience higher levels of biofouling due to their design characteristics, and they are harder to reach for reactive maintenance (CEBRA report, 2021). Heavy levels of biofouling in the internal piping can block the regular flow regimes of water and thus affect the operability of the vessel, or far worse lead to corrosion and degradation of their structural integrity. (Grandison et al., 2011). As noted by Grandinson MGPS can be used for two functions, prevention of fouling which is the most desirable outcome but rarely achieved; and remediation of existing fouling, which may create additional problems with the removal of organisms and clogging of pipelines. [23] The recent report by CEBRA (2021) still describes three main technologies used in MGPS that are:

- **Sacrificial anodes** are placed on the vessel hull near the sea chest gratings or inside the pipework and they are linked to a power supply that directs an electrical

[23] Depending on the area that has been fouled, the removal could be done by hand either by the vessel's crew or specialized divers.

current to the anodes. The current leads to corrosion of the anode and the release of metals (e.g., copper, aluminium or iron), at a desired rate, into the water to create an antifouling and anticorrosion layer on the surface. The use of sacrificial anode is a relatively inexpensive and established technology, but there are concerns about its effectiveness and on the use of copper, which is increasingly under scrutiny as a toxic agent (Lewis, 2016 & Grandinson, 2011).

- **Electrochlorination** is used to convert chlorine, present in seawater, into sodium hypochlorite using the principle of electrolysis. Sodium hypochlorite is an effective anti-fouling agent. Onboard generation is achieved with the uptake of seawater to an electrolyser cell where a low voltage DC current ensure the transformation process. The treated water is then run into the internal seawater system. This technology is established and relatively inexpensive, but an overdose with sodium hypochlorite could induce corrosion and should then be avoided.

- **Direct chemical dosing** uses the injection of liquid antifouling directly into the internal pipes, but this system loses its effectiveness when the distance from the injection increases (Lewis, 2016).

In the lasts years we experienced the development of new technologies that could fall under the definition of MGPS, of which the most promising ones are [24]:

- **Ultrasound / Ultrasonic systems**, ultrasound transducers are attached to the vessels inside walls and emit low-powered ultrasonic[25] pulses that create movement of water molecules on the underwater profile of the hull and prevents/delay the growth of biofouling. The results seem promising, at least in delaying the formation of macro-fouling (Alvarez, 2022), but this technology is often cost-prohibitive for mosts shipowners (Grandinson, 2011).

- **Ultravioletviolet-C light systems** use UVC[26] LEDs[27] tiles create a sterile zone to prevent biofouling adhesion. This technology seems to prevent all forms of fouling.

[24] With promising the author means either the most referred in literature or that companies are trying to scale these technologies up with large adoption and promotion campaigns.
[25] Ultrasounds means outside of the human audible range, above 20kHz.
[26] Ultraviolet – C (UVC) light is also known as Germicidal UV and is commonly used to sterilize water and surfaces. Its wavelength is shorter than visible light (180-280 nanometers).
[27] Light-Emitting Diode is an electronic device that emits light when a voltage is applied to it.

At this stage, only small scale experiments are conducted, and the limiting factor is the lifetime of the LEDs that do not cover the commonly used dry-docking intervals of ships.

In conclusion, literature on MGPS is scarce and mostly dedicated to power station cooling systems and not for shipping, but it appears that a single MGPS strategy is unlikely to be able to control all fouling pressures, and a combination of treatments may be necessary (Grandinson, 2011), and when assessing the biofouling and biosecurity risks we need to approach the subject from an “entire vessel perspective” rather than different mechanisms (Coutts & Dodgshun, 2007)

Adoption of Biofouling management plans and record books

The implementation of a ship specific biofouling management plan and record book is suggested by the voluntary IMO 2011 Biofouling Guidelines. These two could be developped as stand-alone documents or be integrated in any existing ship’s plan. The management plan should contain the recommended management measures usually undertaken by the vessel and must be updated as necessary. The plan should include:

- Details of the AFS, management practice or treatment used, with additional information regarding niche areas.
- Identification of hull locations susceptible to biofouling, schedule of planned inspections, repairs, maintenance, and renewal of AFS.
- Details for the safety and training of the crew.

Instead, the biofouling record book should contain details of all inspections and management measures undertaken on the ship and shall always be updated and kept on board. This record keeping method should allow owners and operators evaluate and judge the effect of any measure and operational practice used on the ship. The record book could also assist the port of call authorities to assess the biosecurity risk of any ship entering their water and minimizing delays to ship operations. The information recorded in the record book should include:

- Details of AFS and management practices used.
- Dates and location of entry and re-floating from dry-docking/slipping, and any measures taken to remove biofouling, renewal or repair of AFS.
- Dates and location of In-water inspection, their results, and if any corrective action taken or necessary.
- Dates and details of inspection of internal seawater systems, their results, and if any corrective action taken or necessary.
- Details of when the ship has been operating outside its normal operating profile, or has been inactive for extended periods (hot / cold laid ups[28])

As the Guidelines are voluntary there are no mandatory rules on how the management plan and the record book should be developed, however templates are provided as Annexes of the Guidelines or can be easily found online[29].

Proactive cleaning

The idea of light, and regularly performed hull cleanings (grooming) has developed in the last 20 years, but only the recent developments in robotics and remotely operated vehicles enabled the idea to be a practical solution for biofouling management. The goal of this technology is to clean the vessel when only biofilm or microfouling is experienced, and thus preventing harder to clean macrofouling, which is also associated with a higher biofouling penalty (CEBRA report, 2021). The cleanings are frequent and scheduled (weekly, or monthly cleaning) usually done via a ROV or other equipment. This management practice is effective, and non-damaging for both biocidal and biocide-free coatings and its application has the potential to reduce GHG emissions and prolong the service life of coatings, but it’s especially important vessels FRCs that are experiencing long idle times (Swain et al, 2022). If a traditional reactive

[28] Lay-up means that the vessel has been temporarily taken out of service, and it’s a tool used by vessels operators to control and reduce costs during economic downturns. With a warm lay-up a ship can be brought back into service at short notice, instead cold lay ups are more drastic and the ship is usually at anchor, or in a secure harbour with no crew on board. As sawn in the previous subsection idle times and lay-ups leads to an increase in biofouling accumulation.

[29] https://www.imarest.org/special-interest-groups/biofouling-management/3505-template-for-biofouling-management-plan

cleaning (e.g. dry-dock or with divers) is expensive time consuming and there's a risk of damaging the expensive coating, proactive cleaning could be done in more gentle ways with ROV or other equipment without disrupting the vessel's schedule. Technologies for proactive cleaning is experiencing a continuous evolvement (CEBRA, report 2021) and although one of the premises of this technology was that it created only a small discharge that didn't require biofouling capture and treatment, the academic community is still doubtful about it (IMO, 2019).

Reactive Solutions

If the goal of proactive solutions is to prevent and delay the occurrence of biofouling (*resetting and slowing the clock*), reactive solutions are employed only once the first line of defence has been breached and the vessel is already fouled. The objective of reactive solutions is to clean the vessel and restore its operational efficiency (*moves the hands back*).

Out-of-water maintenance

As per SOLAS Regulation 10 and Classification Societies requirements commercial vessels must be dry-docked at least once every 5 years provided that a minimum of two inspections of the ship's bottom are performed, except where the risk profile of the vessel requires different measures, these measures are required to emit the Safety Construction Certificate[30]. Drydocks are used to inspect all the hard to access areas of a ship, perform maintenance, cleaning the underwater parts, conduct repairs and applying anti-fouling coating if required. During drydocks the most used cleaning methods are high pressure freshwater flushing and mechanical removal, whereas desiccation is not economically feasible neither for large vessels nor small boats (CEBRA report, 2021). The biofouling removed in dry-docks can be collected, treated

[30] Different measures can be found for bulk carriers or tankers older than 15 years, where the bottom inspection should be done in dry-dock, or the Extended Dry Dock (EDD) scheme that allows to extend the regular 5 years interval to 7.5 years provided that two In-Water Surveys are conducted. For further information SOLAS 74/88 or https://euroflag.lu/operations/extended-dry-dock-edd/.

and disposed of more easily compared to In-Water cleaning. Dry-docking cleaning has been shown to be the most effective and the most environmentally-sound solution (Woods et al. 2007) compared to In-water cleaning, but as its disadvantages has that it's extremely costly and time consuming and that it requires an extensive planning activity, especially if the cleaning falls outside of the regular dry-docking schedule, and this is the main cause the led to the development of In-water cleanings, having access to benefits of sailing with a clean hull but without the associated costs.

In-water cleaning

The objective of in-water cleaning is to remove all visible and macroscopic biofouling on the hull, for example, according to the NSTM, in the US navy a FR40 over 20% of the hull is the trigger to a full hull clean. The removal doesn't kill all the organisms, so the capture and treatment of biofouling is a critical step. As illustrated by Song and Cui (2020), there are three main categories of devices and methods to perform underwater cleaning operations.

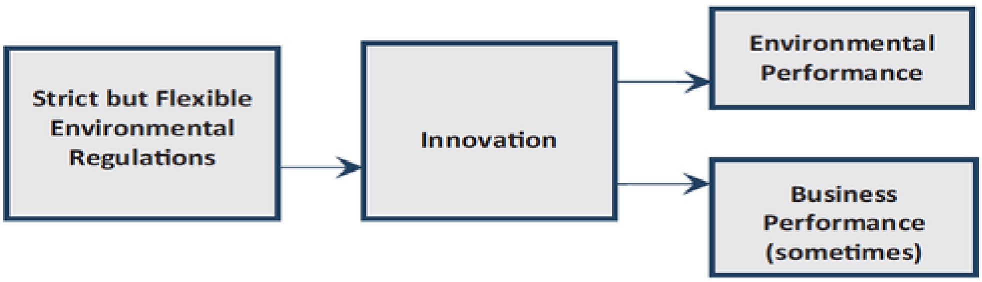
- Manual cleaning, divers use sponges, brushes, and scraping devices to manually remove biofouling from the hull. It's typically done on small boats and yachts and has low effectiveness. (Davidson et al. 2018)
- Powered rotary brush cleaning, as manual cleaning soon showed its limits, the industry started to develop equipment to increase cleaning effectiveness and efficiency. Different types of brushes can be used depending on the surfaces that needs to be cleaned and the severity of biofouling (nylon brushes suitable to remove slime and microfouling and steel brushes for hard calcareous fouling).. With this type of mechanical cleaning, the possibility of damaging the coatings is higher compared to other methods, and it's typically not effective against biofilm (Cioanta & McGhin, 2017).
- Noncontact cleaning, by avoiding contact with the vessel's hull the probably of damaging the antifouling coatings is reduced and the removal effectiveness is increased. Noncontact cleaning technologies include high-pressure water jet, cavitation water jet, ultrasonic, laser and others, with the first two being the most used.

As seen in proactive cleaning, also the reactive cleaning saw recent development thanks to the development in robotics. Rotary brushes and noncontact cleaning can both be used in handheld equipment, diver operated karts or remotely operated vehicles. When In-water cleaning is performed using divers, this is usually associated with high labour intensity, low efficiency, limited working time and potential personal injury, instead regarding ROVs the combination of different technologies for both cleaning (rotating brush and cavitation jets) and adhesion (permanent magnetic, electromagnetic, and bio-inspired adhesion) is recommended (Song & Cui, 2020). Although very effective in cleaning flat, or semi-flat surfaces, at the moment ROVs are not designed for cleaning curved areas, like the propeller. When talking about propeller cleaning the preferred term is *propeller polishing*. If the literature about biofouling on the hull and its effect on energy efficiency is extensive, the impact of biofouling on the propeller is frequently neglected. The overall effect of hull cleaning on energy efficiency is higher due to larger area of the hull but, if analyzed per unit area, the influence of propeller condition on ship performance is significantly more important (Farkas et al., 2020). Moreover, the associated costs with a propeller polishing are also lower making it an interesting alternative (Ballegooijen & Muntean, 2016). Since removal of biofouling organisms does not necessarily means that the organisms are made inoffensive, there is a potential risk of diffusion of invasive alien species, and that is the reason many countries and regions are prohibiting in-water cleaning. Ensuring biofouling capture is one of the main areas that needs to be addressed.

I.3 Current legal framework and future developments[31]

Regulations, especially environmental regulations (ER), are negatively perceived by companies as they increase costs and reduce their competitiveness, as if there was a trade-off between economic growth and environmental protection. However, in 1991, Michael Porter hypothesised that well-designed and strict environmental regulations can benefit both the environment and the polluting firms. Porter claims that the companies will be encouraged to increase efficiency and invest in technologies to comply with the regulations, which in turn increase productivity or the value for end users. Ideally, the costs for complying with regulations will be covered partially or fully by the benefits achieved. The hypothesis is often considered in two versions: (i) the "weak" version states that ER stimulate innovation, and numerous studies corroborate this version; (ii) the "strong" version states that by stimulating innovation companies will increase their productivity and so increase economic performance but has fewer real-life applications.

Figure I.8 Porter hypothesis (PH)



Source: Porter 1991

As introduced in the previous subsections, even though the biofouling problem has been long known by all the stakeholders of the maritime cluster, regulations on how to properly address it are lagging. In fact, they are missing, incomplete or only voluntary. However, we can identify regulations at different levels:

- International, conventions, guidelines, and recommendations both from policy makers and industry organizations [Table 4].
- Regional, national, and subnational policies [Table 5].

[31] This subsection uses as a reference the following document (GEF-UNDP-IMO, 2022 b.), which compares the relevant regulations on biofouling management and IWC updated to 28 January 2022

The IMO 2011 Guidelines objective is to reduce the likelihood of IAS diffusion by implementing biofouling management, but they are only voluntary, so currently there are no mandatory international requirements directly related to biofouling management. The rationale behind the mandatory AFS convention was to ban TBT from coatings, instead the London Convention and protocol ban the discharge of wastes in the sea, so it's clear that they have no power in enforcing best practices in biofouling management to reduce the risks of IAS diffusion or reducing the drag cause by biofouling[32]. It's in this legal vacuum that both industry-backed organizations and environmental conscious nations proposed their own guidelines to ensure operational efficiency for the fleets of their members, and national regulations respectively. The lists of the most relevant regulations, policies and standards are proposed below. It appears obvious as the biofouling problem should be better addressed at international level to minimize further variations and discrepancies in the policies.

Table I.4 Regulations and Guidance at International level

Regulation	**Nature**	**Purpose**	**Effective Mechanism**
IMO 2011 BIOFOULING GUIDELINES	Voluntary	Reduce biosecurity risks associated with the transfer IAS via shipping	Biofouling Management Plan (BFMP) & Biofouling Record Books (BFRB)
AFS CONVENTION	Mandatory	Restrict and control the pollutant used in AFS	Ban the use of unsafe substance (mainly TBT)
LONDON CONVENTION AND PROTOCOL	Mandatory	Prevention of marine pollution by dumping of wastes.	Prohibits wastes release (including biofouling, AFS debris and residue)

[32] Reducing the drag caused by biofouling should be in the owners/operators' best interest, so the 2011 guidelines mainly deal with the environmental risk of IAS.

INTERTANKO[33] Guide to Modern Anti-fouling Systems and Biofouling Management	Voluntary	Provides recommendation and advice for all aspects of hull management	Addresses common issues following a 10-day idle period
BIMCO[34] Industry Standard on IWC	Voluntary	Set cleaning, capture, and filtering standards for IWC	Clean 90 % of biofouling; 90% of captured material and passed through a 10-micron filter

Source: GEF-UNDP-IMO, 2022 b.

Moreover, there are also relevant ISO STANDARDS in biofouling and hull management such as ISO 13073-1 (Risk assessment on anti-fouling systems on ships) and ISO 19030 (Measurement of changes in hull and propeller performance). The biofouling problem is also significant for the recently introduced IMO energy efficiency indicators EEXI[35], CII[36], or the European Trading Scheme in which shipping was introduced in 2022. Having a common framework and guidelines on biofouling is important, but considering how differently biofouling is experienced in different part of the globe, there's also a need to have specific regulations that can tackle this problem in the most effective and efficient way, and that is the duty of Regional and national regulations. As of January 2022, there are 19 regulations (regional, national, and sub-

[33] The International Association of Independent Tanker Owners is the trade association of independent tanker owners, representing the interest of its member. The organization works on technical, operational, legal and commercial issues affecting its associates. About Us - INTERTANKO

[34] The International and Baltic Maritime Council is one the most important association of the maritime industry. It mainly represents the shipowners but also charterers, shipbrokers, agents and managers. Its main goal is to promote and facilitate trades, and protect the interests of the shipping community. BIMCO is also famous for publishing some of the most used standard forms used in maritime contracts About us and our members - BIMCO

[35] Energy Efficiency Existing ship Index, is a measure on technical efficiency of a vessel, modelled after EEDI (Energy Efficiency Design Index). Vessels that do not meet the EEXI requirements will not be issued the International Energy Efficiency Certificate (IEEC) effectively preventing them to participate in international trade.

[36] Carbon Intensity Indicator is a short-term measure that focuses on operational efficiency. CII calculates the carbon intensity of vessels based on actual operations metrics and rates vessels from A to E on an annual basis. The corresponding CII scores will get progressively stricter year after year, requiring a constant improvement from shipowners. Vessels that achieve a D rating for three consecutive years, or an E rating in any single year, will be required to take a corrective action plan. The score will take into consideration the fuel consumption, the CO_2 emission factor, the distance travelled and the cargo carrying capacity.

national) already in place, and 27 intended to be developed in the next five years. As Figure I.9 shows, most of the policies on the topic is coming from countries in the Pacific-Rim. Instead, Table 5 lists some of the most relevant policies. To support the implementation of the 2011 Guidelines the GEF-UNDP-IMO GloFouling Partnerships Project (GFP) was launched in 2018. The GFP aim is to spread awareness about the topic, build capacity and help nations publish their biofouling management regulations. To improve consistency with the 2011 Guidelines and reduce variations in the policies, the GFP has already published many materials on the topic, including 3 guides[37].

Table I.5 Regional, National, and sub-national Policies

Regulation	Nature	Effective Mechanism
SRIMP-PAC (2006) Shipping related introduced marine pests in the **Pacific Islands**	**Voluntary guidance** Create a regional strategy to address both ballast water and biofouling. With technical training, capacity building and ensuring best practices in the region	Recommends hulls and niche areas to be cleaned before leaving the Pacific-Rim countries, scrutinizes ships before allowing entry to port at the first port of call, and raises awareness on biofouling prevention and control in Pacific Island Countries.
Australia Biosecurity Amendment regulations (2021)	**Mandatory** for all vessel to manage unacceptable risks and **voluntarily** ensuring sector specific best practice	Comply with one of the following: • Implementation of an effective BFMP • Last hull cleaning within 30 days prior to arriving in Australian territory. • Implementation of an alternative biofouling management method pre-approved by the department.

[37] Guide 1 – Guide to Developing National Status Assessments, Guide 2 – Guide to Developing National Rapid Economic Assessments, Guide 3 – Guide to Developing National Biofouling strategies

New Zealand The New Zealand Craft Risk Management Standard (2018)	**Mandatory** Different measures differentiating short stay ships (less than 3 weeks) and long stay ships (more than 3 weeks	Clean within 30 days before visiting NZ or within 24 hours of arrival, noting that no IWC is allowed in territorial waters. Demonstrate continual maintenance and best practice, Submit a Craft Risk Management Plan for approval
California The Californian Biofouling Regulations (2017)	**Mandatory** for all vessel above 300 GT	Vessels must submit a Reporting Form to the dedicated authority on how biofouling is managed that must include: Details of last out of water maintenance, AFS used, any MGPS installed, average speed and time spent in port over the last 4 months, details of last ten ports visited, whether any inspection or cleaning has occurred since the last out-of-water maintenance

Source: GEF-UNDP-IMO, 2022 b.

Other notable mentions for policies and guidelines that are not effective yet but expected to be are: the "COMPLETE Project's Proposal for a Regional Baltic Biofouling Management Roadmap"; the "Regional Marine Pollution Emergency Response Center for the Mediterranean Sea (REMPEC)", the private "Clean Hull Initiative" led by The Bellona Foundation to develop a standard for proactive cleaning and most importantly the revision of the "2011 Biofouling Guidelines". The final draft was finalized during PPR[38] 10 (24-28 April 2023) and will later be discussed and

[38] The Sub-Committee on Pollution Prevention and Response (PPR) deal with all matters relating to pollution prevention and response which falls within IMO's remit. The PPR is one of the sub-committees that assists the MEPC, by reviewing in advance technical documents and regulations that will be

adopted by MEPC[39] 80 (3-7 July 2023). The revision is expected to include:

- A more type-specific approach, clearer and less general
- A quantitative definition of micro and macro-fouling,
- A minimum inspection frequency of 12-18 months depending on the availability of performance monitoring system,
- A recommended outcome for IWC operations,
- Recommended handling of biological waste.

Figure I.9 Nations with current or proposed biofouling management policies

Source: GEF-UNDP-IMO, 2022 b.

discussed by the Committee. Sub-Committee on Pollution Prevention and Response (PPR) (imo.org)

[39] The Marine Environment Protection Committee (MEPC) addresses environmental issues under IMO's remit. The MEPC consists of all Member States and is particularly concerned with the adoption and amendment of conventions and other regulations that deals with the environment. Marine Environment Protection Committee (MEPC) (imo.org)

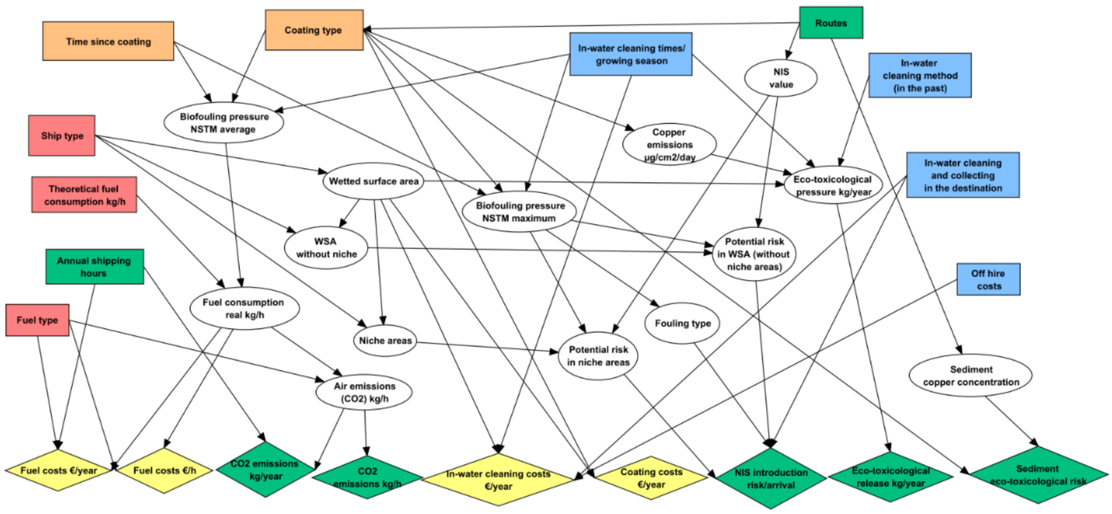
II. State of the art on biofouling management

The literature review for this subsection contains one relevant paper published on academic research websites and the relevant contributions of 3 international conferences and forums held in 2022. The conferences analysed are the 7th Hull Performance & Insight Conference (HullPIC 22, Tullamore, 9-11 May, 2022), the 3rd Port In-Water Cleaning Conference (PortPIC 22, Hamburg 9-11 September, 2022), and the 2nd GloFouling Forum (London 11-14 October 2022). At the end of this subsection there will be a summary comparison table of the literature review, containing the studies used in the first two sections of this thesis.

Emilia Luoma et al,. (2022) – "*A multi-criteria decision analysis model for ship biofouling management in the Baltic Sea"*

Considering the complexity of the biofouling problem and the variety of solutions proposed by the various companies, shipowners might have difficulties to identifying the optimal biofouling management costs, the one that minimize economic costs for the shipowners and reduce environmental impacts and risks. The authors of this paper developed a multi-criteria decision analysis model (MCDAM). A Multi-criteria decision analysis allows decision-makers to compare various alternatives based on multiple criteria or objectives. Regarding biofouling management, the MCDA can be used to assess different management strategies. The objective is to identify the most effective and efficient approaches for preventing or mitigating biofouling on ships. The MCDA supports decision-makers in taking informed decisions, considering the trade-offs among different criteria (less initial costs, higher running costs, or higher pollution levels). The model provides a structured and systematic approach to the decision-making process, that is particularly valuable in complex problems. The objective of this is paper is to create a tool to support shipowners in: 1) choosing the optimal biofouling management strategy, 2) Preventing further introduction of IAS, 3) reducing pollution to the maritime environment. To develop this tool, the authors used a Bayesian Network (BN), which is a probabilistic graphical model used in uncertain situation, The model is made of a set of variables that influence the results of the multi-criteria analysis. The study was focused on the Baltic Sea area and data was collected via interviews with representatives from shipping companies and an IWC provider, plus literature reviews and field testing. The graphical representation of the MCDAM is shown in Figure II.1, with different shapes and colours of the nodes representing different variables and arrows representing the conditional dependencies between the variables.

Figure II.1 Graphical representation of the MCDAM



Source: Louma et al., (2022)

The model was used to compare 3 different scenarios (SC1-3) with 3 sub-scenarios each (A-C) and the effectiveness of different strategies on reducing costs (yellow diamond shapes) and environmental impacts (green diamond shapes). Then the following step was to set the variables of the model and wait for the results. The results of this study are not particularly relevant to this thesis, but rather I was interested in the comprehensive and systematic approach used to find the optimal management strategy based on type specific needs. This type-pecific approach is a point made by other authors in this section.

II.1 7th Hull Performance & Insight Conference (HullPIC 22)

Table II.1 Contributions from the HullPIC conference

Authors & Title	Research topic	Geography destination / origin	Contribution
Markus Hoffmann – *"The Impact of 'Fouling Idling' on Ship Performance and Carbon Intensity Indicator (CII)"*	Impact of fouling idling on CII	World fleet (Sweden)	Industry I-tech AB
Keng Khoon Tan, Sergiu Paereli, Angelika Brink – "*Impact of hull coating on EEXI and CII"*	Hull coating on EEXI and CII	World flee (Norway)t	Industry Jotun A/S

Source: Author

Markus Hoffmann - *The Impact of 'Fouling Idling' on Ship Performance and Carbon Intensity Indicator (CII).*

As seen in the previous subsection, idling creates a great biofouling risk for commercial ships, because it gives opportunities to biofouling agents to attach to the ships' hull, and given that biofouling is not experienced the same everywhere, where the idling occurs also has a great impact on the biofouling growth. So, the author of this conference paper tries to measure the impact that idling has on the newly introduced energy efficiency regulations EEXI and CII. The author first introduces that, although the community agree that idling refers to "*a vessel being stationary in a spot without movements",* many disputes still arise between shipowners and coating manufacturers on the length of the idling guarantee[1]. Then, the author differentiates between

[1] The idle period guarantees refers to the period of time the manufacturers guarantee that the coating will protect the ship from biofouling. The idle guarantee on most coatings range from 14-21 days, while premium coatings can reach up to 30 days. More information available on [Idling: bad for business, bad for biofouling | Hellenic Shipping News Worldwide]

"commercial idling" as "idling due to commercial activities and inactivity of vessels" and fouling idling as "any idling in areas that presented high biofouling risk." The authors collected vessels' data using AIS technology and after filtering all the unnecessary or misleading data found that.

- The number of idling vessels roughly doubled over the last decade,
- Between 50-85% of idling occurs in waters above 15°C, depending on season and vessels are increasingly idling in biofouling "hotspots", where the water temperature is above 25°C.
- The number of idling vessels greatly increased during 2020 due to the impact of the CoVID-19[2] pandemic.

The author concludes that idling will have a great impact on the CII score of vessels, and that shipowners needs to ensure that their ship is protected, by being familiar with the characteristics of the antifouling coating, avoid idling in biofouling hotspots or taking appropriate action on the resume of operation. This paper seems extremely relevant with the foreshadowed decrease of freight rates, especially in the container sectors, that will require carriers to take actions to counter overcapacity.

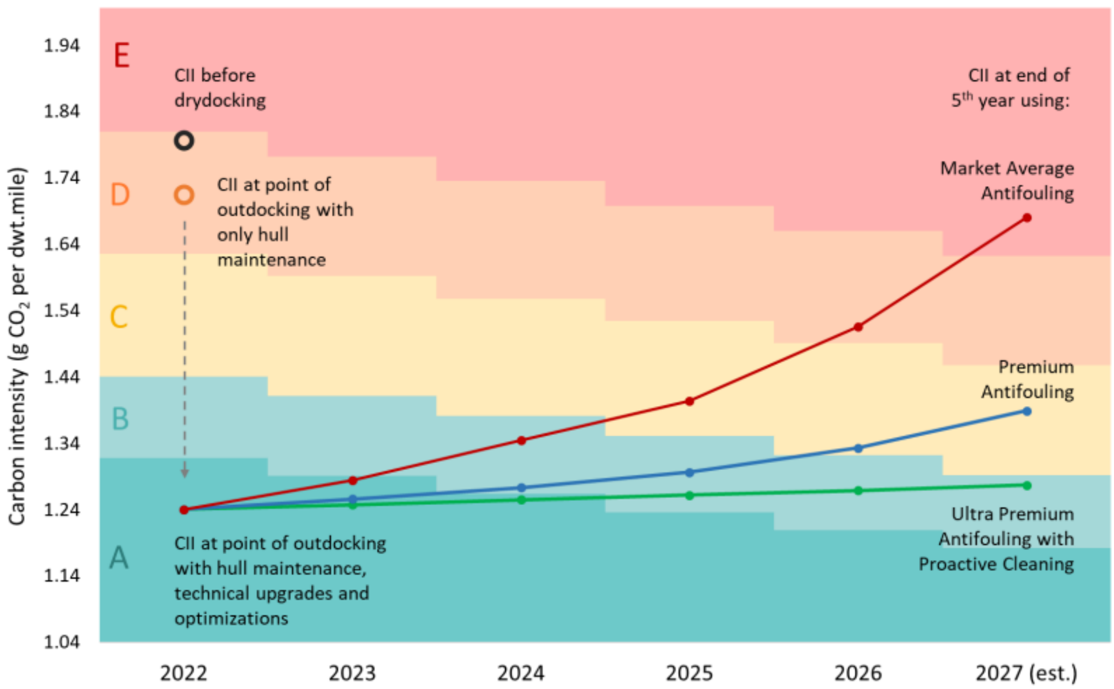
Keng Khoon Tan, Sergiu Paereli, Angelika Brink
Impact of hull coating on EEXI and CII

The author of this conference paper are all employees of the Norwegian Coating manufacturing company Jotun A/S. The paper introduces the new measures proposed by the IMO to reduce emissions the EEXI and CII and tries to correlate the performance of these two measures with the characteristics of the antifouling paint used. The purpose of EEXI regulation is to reduce carbon emissions through vessels retrofits or reduction in speed through Engine Power Limitation (EPL). The authors point out that the effect of applying a new coating on EEXI can only be considered through sea trials and are considered as a "snapshot" of the technical efficiency of the vessel. This means that on EEXI score, the results of the smooth application of a low-quality antifouling paint can be greater than the poor application of a high-quality antifouling paint, even though the

[2] Corona Virus Infectious Disease

former will degrade sooner resulting in more CO_2 emissions over time, which is instead computed by the CII. On the other hand, when considering CII scores there's a clear difference between high and low-quality coating, and the paper shows the comparison between three antifouling coating alternatives in Figure II.2. With all other variables held constant, the worst solution will receive an E rating at the end of the 5^{th} year instead, the other two alternatives will be CII complaint (C or better) throughout the dry-docking interval.

Figure II.2 CII over a 5-year drydocking period for different hull protection solutions.



Source: Keng Khoon Tan et al., 2022

The author points out that the solutions with Ultra-premium coating and proactive cleaning have almost a flat line, and the slight gradient is attributed primarily to damages caused at berthing. Nevertheless, this costly solution still won't achieve an A rating at the end of 2027 due to the rating bands becoming progressively stricter. Moreover, the authors discuss other implications of the CII ratings, for example some charterers may charter only vessels with a high score, or having a good CII rating allow accessing better financing and insurance deals[3]. In conclusion, although EEXI is the

[3] In 2021 a pool of major banks financing the shipping industry agreed and signed the Poseidon

most immediate concern, poor and short-term oriented decisions will probably result worse off in the long run, and by investing in high-quality hull coatings and regular cleaning shipowners can obtain significant benefits, such as lower fuel consumption and improved energy efficiency and positioning their vessel as a more attractive for charterers, investors, and marine underwriters. As said, this contribution comes from a coating manufacturer, and it wants to convey the message to invest in premium coatings, so although this is a valuable contribution, in my opinion we should take it cautiously.

Principles, and they will commit to assessing the average carbon intensity of their shipping portfolio on an annual basis. The same happened at the end of the year for marine insurance companies signing the Poseidon Principles for Marine Insurance.

II.2 3rd Port In-Water Cleaning Conference (PortPIC 2022)

Table II.2 Contributions from the PortPIC 2022 conference

Authors & Title	**Research topic**	**Geography destination / (origin)**	**Contribution from**
Volker Bertram - Review of Robotic In-Water Hull Cleaning	IWC and ROV	World fleet (Norway)	Classification society (DNV)
Simon Doran - *Evolving Inspection and Cleaning Technology*	Developments of IWC	World fleet (UAE)	Industry – ROV company (HullWiper)
Aron Sørensen - *Survey on Biofouling Management and Anti-fouling System*	Survey on AFS	World fleet (Denmark)	Industry association (BIMCO)
Geir Axel Oftedahl, Runa Skarbø, Morten Sten Johansen, Helle Vines Ertsås, Christer Oepstad - *A Way Forward for In-water Proactive Cleaning*	Proactive cleaning	World Fleet (Norway)	Industry (Semcon – Bellona – Jotun)
Alessio Di Fino, Maria Salta, Ko Coppoolse - *Effects of Repetitive Underwater Cleaning Operations on Two Fouling Release Coatings*	Proactive cleaning on FRC	World Fleet (The Netherdlands)	Research center (Endures)
Burkard T. Watermann, Donna L. Garrick, Katja von Bargen - *First Application and Approval Scheme for IWC on Non-toxic Hard Coatings in Ports of Bremen - Dead End or Challenge*	IWC on biocide-free from a regulatory side	Ports of Bremen (Germany)	Research centre and Port authority (LimnoMar – Bremenports)

Atsuhiro Yamashita *Biocide-Free Antifouling Paint / Possible and Effectiv*	AFS biocide free paints	World Fleet (Japan)	Coating industry (Nippon Paint Marine)
Jasper Cornelis, Luc Van Espen, Jean-Pierre Maas - *Underwater Cleaning in the Flemish Ports: Lessons Learned and Challenges for the Future*	IWC regulatory side	Belgian ports (Belgium)	Port Authority (Port of Antwerp-Bruges & North Sea Port)
Michael Lehmann, Tone Knudsen Fiskeseth - *Independent Testing of In-water Cleaning Companies*	Independent testing of IWC providers	IWC providers world-wide (Norway)	Classification Society (DNV)
Karl Lander Frequent and Habitual: How Autonomous Robots Can Make Routine Grooming and Inspection Accessible	IWC proactive	World Fleet (USA)	Industry – ROV company (Armach Robotics)
Yusik Kim Joint Efforts among a Ship Builder, an AFC Maker, Maritime Research Institutes and an IWC Company for GHG Emission and Biofouling Reduction	Comprehensive approach to Biofouling Management	World Fleet (Japan)	Industry -ROV company (TAS Global)
Ole Christian Troland Taking Biofouling Not Seriously Today Will Have Serious Effects Later	Effects of biofouling	World Fleet (Norway)	Industry – ROV company (ECOsubsea)
Runa Skarbø The Clean Hull Initiative One Year Later: Towards an ISO Standard on Proactive Hull Cleaning	Setting a ISO standard for proactive cleaning	World-Wide Proactive cleaning providers (Norway)	NGO (The Bellona foundation)

Source: Author

Volker Bertram - “*Review of Robotic In-Water Hull Cleaning”*

This contribution comes from a senior manager of the Norwegian classification society DNV. The paper describes the development of ROV hull cleaning from its early stage of academic research to the currently proposed solutions. Nowadays, the market is highly segmented with several local cleaning providers competing on a global market (Noordstrand, 2020). Each cleaning company developed its own design, so there is a lack of standardization, typical of young industries. This diversity in the approach can be explained by various factor.

- The appropriate cleaning approach depends on the coating used on the hull.
- Cleaning companies are relatively small and they can be associated with start-ups or Small to Medium Enterprises (SMEs) at best.
- The ROV design is internally developed and the assembly is either done in house or outsourced at local workshops.
- There are no agreed standards design or production of ROVs

The author expects consolidation of the market and robot design with time, following the trend experienced by other industries, and even a differentiation between ROV manufacturers and cleaning services providers. The formers could adopt a modular design approach to cut production costs and ensure flexibility. Then, the author lists the current commercial in-water robotic cleaning solutions (Figure II.2) and notes that compared to a 2016 listing, there were fewer companies. The list proposed by the author is very extensive, but it should be noted that not all the companies cater the same needs (e.g. the Italian Keelcrab offers its ROV to clean yachts and pools). Then, the paper focuses on 5 the key players that have pushed the most the development of the market. According to Bertram they are HullWiper, Fleet Cleaner, ECOsubsea, SeaRobotics, Jotun. The author then proposes the areas that need to be addressed to ensure the development of this sector, and he points out at:

- Guidelines for accreditation for in-port cleaning, matching of cleaning method with type of coating, collection and disposal of removed fouling, documentation of results.
- An open approach from ports to cleaning services providers that have adequate proof of environmentally acceptable procedures, otherwise all the cleanings will

be conducted in 3rd world countries without supervision causing great damage to the underwater environment.

Figure II.3 Overview of ROV IWC companies

Company	Robot	Country	Adhesion system	Cleaning system
ECOsubsea	COLLECTOR	Norway	Magnetic	Waterjet
Daewon mechatronics	Daewon robot	Korea	Thrusters	Brush
Fleet Cleaner	Fleet Cleaner	NL	Magnetic	Waterjet
Hullbot	Hullbot	Australia	Thrusters	Brush
Searobotics	Hull BUG	USA	Magnetic/Vacuum	Brush/Waterjet
Armach Robotics	Hull Cleaner	USA	Low-pressure adhesion system	Brush/Ultrasonic
Jotun	HullSkater	Norway	Magnetic	Brush
Commercial Diving Service	Hull Surface Treatment	Australia	Magnetic	Thermal shock
HullWiper	HullWiper	UAE	Vacuum	Waterjet
KeelCrab	KeelCrab	Italy	Vacuum	Brush
VertiDrive	Vertidrive M-series	NL	Magnetic	Waterjet
Cybernetrix	Magnetic Hull Crawler	France	Magnetic	Waterjet
Proceanic	Magnetic crawler	USA	Magnetic	Ultrasonic
ECAGroup	Rovingbat	France	Vacuum	Brush/Waterjet
Scrufy	Scrufy	Greece	Magnetic	Brush
Hhcleaning	SeaBadger	Denmark	Thrusters	Waterjet
C-Leanship	ShipShiner	Singapore	Thrusters	Waterjet
Shipshave	ITCH	Norway	Ship flow field	Brush

Source: Author modified on Bertram 2022

The author concludes the paper with what it expects from this market in the future:

- Cooperative robotics, when two or more robots work together on the same task, this could reduce cleaning times, and improve cleaning effectiveness. For example, we could see one large robot focusing on flat areas and smaller robots cleaning curve areas.
- System solutions, the mismatch between coating and cleaning technology creates problems and finger-pointing between the different stakeholders. To resolve this problem, we need to ensure the exchange of clear instructions between coating manufacturers and the cleaning providers and avoid information loss. Another, more desirable solution would be an integrated solution, where one companies supplies both the coating and the cleaning (e.g. Jotun’s Hull Skating Solutions).
- Port services or on-board equipment, the cleaning market could either develop more towards the land side, with cleaning providers servicing many ships with the associated economies of scale; or towards on-board equipment, where each vessel has its own dedicated cleaning method, so shipowner can regularly and independently plan the cleaning schedule of its vessel and suffice the currently

low number of cleaning ports. The author expects port services to be the winners in the long run thanks to the economies of scales but thinks that on-board equipment could see a spread in the short-run thanks to the fragmented policies on IWC and limited capacity from IWC providers.

Simon Doran - "*Evolving Inspection and Cleaning Technology*"

This contribution comes from the Managing Director of HullWiper, one of the key players of ROV IWC highlighted by the previous author. In particular, I think it's interesting to analyse what he says are the main area the company is working on to improve its service and noting the partnerships launched with other stakeholders of the maritime industry. The company states that it's working on:

- Increasing the size of fouling that can be cleaned and captured,
- Increase cleaning efficiency obtaining faster cleaning times,
- Reducing the size of ROVs and making them easier to handle,
- Improving video image quality for inspection and cleaning operations,
- Improving the filtration systems,
- Allowing the ROVs to maintain a cleaning pattern without pilot action,
- Allowing the ROV to operate with strong currents,
- Developing cost-effective ROV without compromising quality and reliability.

HullWiper partnered with International Paint (the subsidiary of AkzoNobel specialized in marine coatings), and Seadrone a ROV specialist company to meet their objectives.

Aron Sørensen - "*Survey on Biofouling Management and Anti-fouling Systems*"

In September 2021, the Baltic and International Maritime Council (BIMCO) conducted a survey on biofouling management and AFS. The survey collected responses from 53 companies (mainly shipowners and operators) coming from 23 different countries and representing 5,668 ships, which accounted for approximately 8% of the world fleet employed in international trade. To my surprise, 21% of the sample reported no implementation of any form of biofouling management, this is possibly due to the to the voluntary nature of IMO Guidelines and the lack of in-water inspection and cleaning services in some ports. The remaining participants were asked information on how biofouling is managed on their fleets. Most of the AFSs used claimed a lifetime of 5 years (typical dry-docking intervals), and the average claimed lifetime being 4.92. However, only 66% of AFSs reached above 80% of claimed lifetime, thus creating the opportunity to biofouling growth. Currently, the most popular method used by shipowners and operators to assess biofouling growth are physical inspections (34%). Other methods included calculations using data collected from the crew (23%), online hull performance monitoring systems (14%). Some respondents utilized multiple methods to assess biofouling growth. Cleaning frequency was also examined, with the majority of cleaning conducted between the second and fourth years of a ship's service. On average, AFSs needed to be cleaned less than twice (1.84 times) during a five-year period. However, there were variations, with some AFSs requiring no cleaning while others needed multiple cleanings. The survey provided valuable insights into current biofouling management practices, however it faced challenges that didn’t allowed it to gain deeper knowledge on the performance of various AFSs systems, because the same AFSs were used in really diverse contexts (e.g. different ships, different trading areas different seasons) that effect their lifetime.

Geir Axel Oftedahl, Runa Skarbø, Morten Sten Johansen, Helle Vines Ertsås, Christer Oepstad – “*A Way Forward for In-water Proactive Cleaning”*

The paper argues that since conventional antifouling paints can’t offer fully reliable protection from fouling yet, cleanings should occur when a biofouling is detected. In particular, the authors discuss about proactive cleaning defined as “gentle, habitual and frequent mechanical maintenance of a ship’s hull in order to keep it free from fouling and particulate debris” (Tribou & Swain, 2015). The IMO notes that proactive cleaning is recommended once biofouling reached the light microfouling stage (slime layer is less than 5mm in thickness), and that the cleaning can be done without capture if it does not damage the hull coating. (IMO, 2021). Both reactive and proactive IWC methods are still at an early stage, but it’s likely that all stakeholders share an interest of the development of these technologies and their regulations to create a level playing field. However, stakeholders are likely to differ on whether IWC should be mandatory or voluntary, with shipowners hoping it would remain voluntary, but government agencies could act unilaterally making the regulations mandatory. This is what happened in New Zealand, banning IWC activities from the country. If other countries issue their regulation, there will be fewer places where reactive cleaning is allowed, making proactive cleaning the only solution to clean the ship.

Alessio Di Fino, Maria Salta, Ko Coppoolse
Effects of Repetitive Underwater Cleaning Operations on Two Fouling Release Coatings

This study, conducted by a Dutch research center on corrosion and antifouling studied the effect of proactive cleaning on Fouling Release coatings. The study measured the effect on two different types of FRC, a hard paint and a soft silicone-based paint. Several testing panels were painted with the coating and immersed into water, and held still, the worst-case situation for FR paints. The cleanings were conducted by a drone equipped with brushes, in 7 weeks of the study, 5 cleanings were conducted. Although both types of coatings benefited from the regular cleaning, they responded differently to it. The Hard paint seemed to be better at preventing biofouling growth, but the cleanings were less effective on it. In fact, the soft FR paint was practically biofouling-free after each cleaning, but that was not the case for the hard paint. In particular, the hard paint presented earlier on barnacles' growth that had to be removed manually. Another difference reported was the type of biofouling, with soft paints reporting higher slime accumulation, and the hard paints more algae. Unfortunately, the study cannot demonstrate if cleaning frequency plays an important role in maintaining biofouling free surfaces as assumed by Hearin et al. (2016). The tested surfaces were found in good condition, with no visual damages, corroborating Hearing et al,. (2015) results. In conclusion, the findings suggest that gentle cleaning methods can remove early-stage biofouling while preserving the coating system, potentially increasing its service life. Moreover, the study emphasizes the importance of matching the appropriate cleaning setup to the type of fouling pressure and fouling control coating used.

Burkard T. Watermann, Donna L. Garrick, Katja von Bargen
First Application and Approval Scheme for IWC on Non-toxic Hard Coatings in Ports of Bremen - Dead End or Challenge?

This contribution comes from a German research center, and the Authority of Bremen Ports, and it discusses the guidelines, issued in 2021, to issue permits for IWC in the ports of Bremen. IWC activities are classified as "use of water resources" and are then subject also to the Water Resources Act. The Guidelines state that IWC is allowed only if performed on abrasion-resistant, biocide-free coatings, at least 95% of capture rate, and filtration rate of <50 μm can be ensured. Each cleaning activity is also subject to the approval of the Water Authority on a case-by-case basis after review of the application documents. So, to conduct IWC operation in the Ports of Bremen, there are two important documents to obtain. The first one is a permission for IWC issued by the Ports of Bremen to the cleaning company, and then the permit issued by the Water Authority each individual cleaning. To issue the latter document the Water Authority assesses:

- Certification on the effectiveness of the cleaning, capture and treatment systems for different levels of fouling of the cleaning company. This proof of effectiveness must have been produced by an independent, qualified institute.
- Information on the biofouling management of the vessel (commonly used templates are accepted e.g. BFMP, BFRB), and its trading profile (speed, last ports of call in the last 12 months, and cleaning history).

These documents must be submitted by the cleaning company to the Water Authority at least one week prior to the day of the intended cleaning. If the reviewed documents are satisfactory, the Authority will issue the permit to the cleaning company. The cleaning company is responsible for monitoring the operations. Samples of port water at the ship and of the wastewater must be taken before, during and after the cleaning to estimate effectiveness of capture, and filtration.

Atsuhiro Yamashita - *Biocide-Free Antifouling Paint / Possible and Effective*

This paper comes from the Japanese coating manufacturer Nippon Paint Marine, and describes the development of biocide-free SPC antifouling paint, both from a theoretical and practical point of view, providing 4 interesting case studies of the new paint applied to vessel both as test patch and as full coating. The new paint was developed following three main design criteria “low-friction”, “long-term” and “biocide-free”, the result was the AQUATERRAS paint. This paint was developed using anti-thrombogenic polymers[4], that mix layers of hydrophilic domain with layers of hydrophobic domain. This mixture of layers doesn’t exist in nature so, to the author saying’s, biofouling organisms gets confused when they approach the coating, and hesitate to try to adhere there. Then, the author reported the results of the commercial application of AQUATERRAS ships, mainly cruise vessels. All the four vessels were exposed to waters with a high biofouling activity, and their operations were greatly impacted by the CoVID-19 pandemic, so they presented long idle times. However, when the ships were dry-docked, their surfaces coated with this new paint were in excellent conditions (Table II.3). Moreover, the paint was also designed to be “low-friction” and studies conducted with the Kobe University found out that AQQUATERRAS can also achieve a 10% of fuel consumption compared to conventional SPC paints, just by presenting a less rough surface.

Table II.3 Results of the application of AQUATERRAS

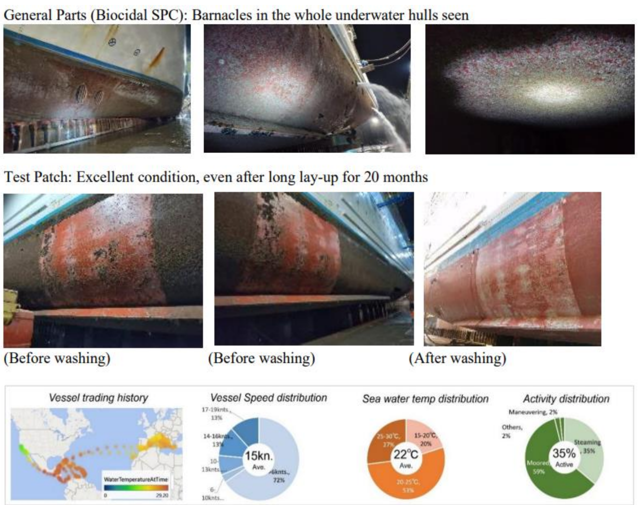


Fig.5: The case of long idling off La Spezia, Italy

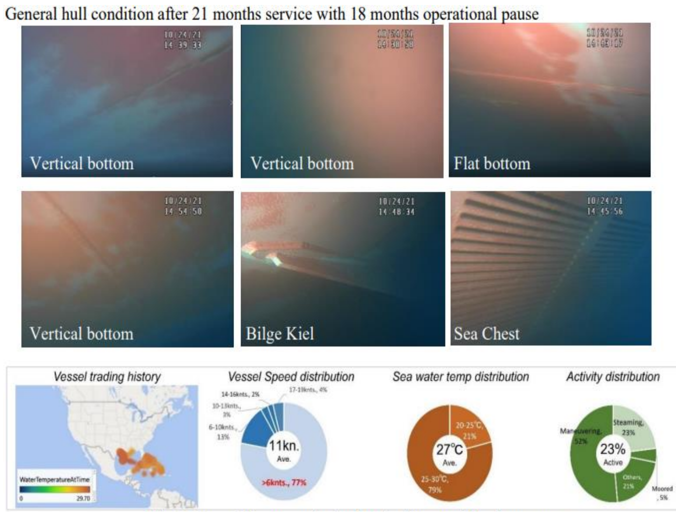


Fig.7: Case of the operation in the Caribbean with a long pause

Source: Yamashita, 2022

[4] This technology is currently used in medical devices, where the author suggests they took an hint from. Anti-thrombogenic surfaces are specially developed to be very slippery and prevent the formation of clots.

This new technology seems particularly promising once we consider that new regulations regarding biofouling management are expected, requiring clean hulls before entering in national water, and banning IWC on vessels coated with biocide-paints. The author points at development of new paints and proactive cleaning as the possible solutions to the expected tightening of regulations. However, it would have been interesting if the author also explained what are the weaknesses of this new technology, for example, how does it compare to other solutions in costs? And if it was more expensive, would the price premium be compensated by reducing fuel consumption and required cleanings?

Jasper Cornelis, Luc Van Espen, Jean-Pierre Maas – "*Underwater Cleaning in the Flemish Ports: Lessons Learned and Challenges for the Future"*

This paper describes the experience of the Flemish ports with underwater hull cleanings and propeller polishing in the last few years. In 2019, the Flemish ports issued a common policy on underwater cleaning. In doing so, the ports tried to develop a framework that could balance between not being too strict to stifle innovation but at the same time ensuring the protection of the aquatic environment. Since 2019, 120 hull cleanings and 281 propeller polishing operations have been conducted. It's interesting to note that propeller polishing operations are more than double that of hull cleanings, due to their high impact (low cost, high rewards). In 2022, only 2 operators were operating in the Flemish ports, after receiving approval. The common framework requires operators to only capture and filter biofouling, so it does not limit cleaning operations to only biocide-free coating or allowing cleaning of only microfouling. In particular, during operations the values of certain elements (Copper, Aluminium, Iron, Nickel, Zinc and suspended matter) cannot be higher than 5% of the average value. Before the release of the permit, the applying company performance are tested both ex-situ and in-situ. The authors of the paper believe that having an international standard on IWC policies is crucial, because it will establish the level playing field for operators. Then, the authors describe the uncertainties that still surround pro-active cleaning, mainly how we differentiate micro and macrofouling (a quantifiable differentiation should be included in the reviewed biofouling guidelines coming in July 2023), and if microfouling really is not harmful to the environment and can thus be not captured. Then the authors give their views of future developments, agreeing that a combination of new biocide-free coatings and proactive cleaning could be a good option, but the shipping community often chooses the easiest solution, and doesn't reward innovation.

Michael Lehmann, Tone Knudsen Fiskeseth
"Independent Testing of In-water Cleaning Companies"

This paper, from two DNV senior engineers, describes the independent testing of In-water Cleaning Companies, referring to the industry standards and guiding document issued by BIMCO in 2021 and 2022. According to the "Approval procedure for in-water cleaning companies" (BIMCO 2022), IWC companies will be independently tested on the effectiveness and efficiency of the following criteria:

- Cleaning (criterion A), at least 90% of macrofouling is removed (in this context macrofouling means visible to human eye).
- The impact on local water quality and capture of materials (criteria B, C and D).

According to the industry standards three cleaning tests will be conducted, each on a different ship. To judge on the effectiveness of capture, samples are collected during the three tests. Representative samples are crucial, and the selection of sample locations and the sampling process must be carefully planned, with a suggestion that at least one sample should be taken from an area where one excepts the highest concentration of material being removed and the lowest capturing rate. The samples are analyzed for total suspended solids, particle size distribution, and relevant biocides. The samples should be analyzed by an independent testing center and then approved by a recognized organization (e.g. classification society). The approval body audits the cleaning company, while the testing organization provides instructions for sample collection, processing, and analysis. The sampling and analysis processes must be independent to ensure reliability.

Karl Lander – HullPIC 2022 "*Frequent and Habitual: How Autonomous Robots Can Make Routine Grooming and Inspection Accessible"*

These contributions come from Armach Robotics, an American "Clean hull provider for a subscription fee" that uses autonomous ROVs to offer a proactive cleaning solution to shipowners. Compared to other players in the industry Armach's answer to the biofouling problem is to offer proactive cleaning using a fleet of small autonomous robots (called Hull Service Robots HSR). The HSRs are equipped with soft brushes for cleaning, are1 approximately 1m long, weigh less than 35kg, and can clean about 650 m^2/h individually. The robots move thanks to 6 thrusters that allow a full range of motion and use a low-pressure adhesion system to attach themselves to the hull, and they are equipped with cameras to documents the conditions of the ship before and after cleaning. Because of the small cleaning, and simple launching and retrieving operations, the HSRs require minimal infrastructure and workforce. Since the robots are autonomous, they also don't need a pilot to perform the cleaning, but one operator is sufficient to monitor the whole fleet (4-6 depending on operations). Thanks to the fleet of HSRs, cleaning times of a medium-large vessel can be cut down to 8-10 hours. To be sure to achieve 100% cleaning coverage, the company developed a positioning system that uses the ship as a reference (they call it "hullographic position), instead of classic earth relative positioning (i.d. GPS[5]). Having an accurate navigational system is important to achieve 100% cleaning, and avoid biofouling spreading from uncleaned area, and also to ensure that the HSRs doesn't run on the same spot of the hull, even though the cleaning is gentle, repeated contact with the same spot, especially if cleaned is suboptimal both in time and in potential damage to the coating. The author concludes that Armach's solution overcomes all the current barriers of proactive cleanings being, little awareness of the shipowners, and the limited capacity of proactive cleaning lead to reactive cleanings being the only alternative. Another important point made by the author is that while ROVs clean the ship they also generate intelligence on the hull, thanks to their cameras and sensors. The data can be collected and analyzed by the clients for performance management, but also used as documentation to enter ports that require proof of biofouling management.

[5] The Global Positioning System is the Global Navigational Satellite System developed by the US army, and it's the commonly used positioning system in the western world.

Figure II.4 The Hull Service Robot

Source: Lander (2022)

Ole Christian Troland – “*Taking Biofouling Not Seriously Today Will Have Serious Effects Later*” and Yusik Kim – “*Joint Efforts among a Ship Builder, an AFC Maker, Maritime Research Institutes and an IWC Company for GHG Emission and Biofouling Reduction”*

I think it’s interesting to consider these two contributions jointly, as they make the same point, but from two different positions. The first paper comes from ECOsubsea, one of the industry leaders of IWC (Bertram, 2022),that started operations in 2008, and talks about the main challenges faced by IWC operators, and their proposed solution. The author reports a lack of quality data and peer review research, that creates a knowledge gap both in academic research and for shipowners that are not able to differentiate between high-quality and environmental conscious solutions (Closed-loop IWC) and sub-par services that pretend being environmentally sustainable (open-loop IWC).[6] The author criticize some of the ideas proposed for open-loop proactive cleaning, saying that there’s still not enough data to support the idea that removal of microfouling with no capture does represent a threat to the marine environment. Then, the proposed solution is to close the knowledge gap through collaboration between the stakeholders. IWC providers shall collect data and share it with researchers, regulators, shipowners, and coating manufacturers to generate quality data and publish peer reviewed research. The solution proposed by ECOsubsea is exactly what the other paper talks about. The author discusses the rationale, the current challenges, and the expected

[6] Closed-loop IWC is another way of saying IWC with capture, instead open-loop means cleaning without capture.

outcomes of the collaboration between several Korean stakeholders. The author points out that with the coming regulations on energy efficiency[7] and biofouling management the demand for IWC and integrated biofouling management services is expected to rise. Currently IWC is limited by an inconsistent legal framework, few operators concentrated only in specific areas (e.g. the North seas, or the USA), little awareness from the market, and the technology (cleaning times, ability to withstand currents, capturing and filtering capabilities). Then, the author describes some of the cleaning operations they are already able to conduct (Table II.4) and where they expect to be in future. Interestingly, the author says that hull cleaning is getting faster every year due to technology improvements[8], and he's confident that in 3 years full autonomous IWC and inspection will be possible. The author also believes that more operations will be conducted in strategic positions, for example he points out at Singapore anchorage while waiting for bunkering, or at canals (Panama and Suez) while waiting for transit.

Table II.4 IWC results

Vessel name	Cleaning scope	Constraint	Working hours	Input Asset
Maersk Alfirk (LOA 337m)	Vertical, bottom hull & Niche areas	Only 9 hrs available, heavy fouling	8 hrs	5 divers, 4 ROVs
Leverkusen Express (LOA 366m)	Vertical, bottom Hull	Light fouling	10 hrs	4 divers, 4 ROVs
C. Creator (LOA 336m)	Vertical hull	2,5 kts current speed, light fouling	8 hrs	4 ROVs
VL Prime (LOA 3333m)	Vertical hull	2,5 kts current speed, light fouling	4.5 hrs	4 ROVs

Source: Yusik (2022)

[7] According to the Korean Registry, as of 2019 48,4% of all ships were rated D and E on their CII scores. The author points out that IWC is a low-hanging fruit to achieve better score, to an increase in demand is expected.
[8] The author points states that cleaning times are improving by 20-30% every year, but I propose cautious with this statement.

Runa Skarbø – "*The Clean Hull Initiative One Year Later: Towards an ISO Standard on Proactive Hull Cleaning*"

This contribution, from the The Bellona Foundation, discusses the work already done and what remains to set a ISO Standard on proactive cleaning under the Clean Hull Initiative (CHI). The initiative is led by the Norwegian NGO foundation and the Norwegian Coating manufacturer Jotun, and was launched in April 2022 and gathered experts on biofouling management from different stakeholders to fast-track the development and implementation of an industry-wide standard on proactive cleaning. In September 2022 the initiative counted more 30 contributing members, illustrated in Figure II.5, of these ten were then selected to participate in the working group to develop the industry standard to be summited to the ISO. The working group then had to submit their proposal to the International Organization for Standardization via a New Work Item Proposal (NWIP) to a Technical Committee (TC) and a sub-committee (SC) for review and approval. The NWIP was submitted to TC8 "Ships and marine technology" and SC2 "Marine Environment Protection".

Figure II.5 Members of the Clean Hull Initiative

Shipping industry	Port authority	Coating industry	IWC technology and service providers	Science/research institution	Others
Wallenius Wilhelmsen	Port of Antwerp Bruges	JOTUN	AAMACH Robotics	University of Maryland Center for Environmental Science	BSH Bundesamt für Seeschifffahrt und Hydrographie
Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping		HEMPEL	SCRUFY	ENDURES	Royal HaskoningDHV
Hapag-Lloyd		AkzoNobel	CLEANSUBSEA	LimnoMar	LITEHAUZ
SOLSTAD OFFSHORE		i-tech	notilo plus	Florida Institute of Technology	Standards Norway
Stolt Tankers			HullWiper		
DNV			Shipshave		
DORIAN LPG			TAS GLOBAL		
			DG-DIVING GROUP		

Source: Skarbo (2022)

The initiative organized regular workshops and meetings to develop the NWIP, and the results can as follow:

- Align the CHI as much as possible to the IMO revised biofouling guidelines.[9]
- The standard needs to provide guidance to coating manufacturers and ensure that hull coating can withstand regular gentle cleaning without damages.
- The cleaning methods and equipment will be standardized, this recalls the modular design approach proposed by Bertram (2022).
- The group didn't decide how to address safety standards both for ROVs and divers, with some thinking of referring to already established standard codes while others want to impose minimum safety requirements regardless.

The author states that the NWIP will be submitted to ISO in Q4 2022 and it will be subject to comments and approval by the Committee. After receiving the go-ahead, the initiative forecasts a timeline of 36 months to develop the industry standards. Unfortunately, there is currently no further publicly available news on the development of the initiative.

[9] Although this may seems strange, one must remember that many members of the initiative are also involved in the revision of the IMO biofouling guidelines, and in 2021 a revised draft version of the guidelines was already circulating.

II.3 2nd GloFouling Forum and Partnership

Table II.5 Contributions from the GloFouling Forum and Partnership (2022)

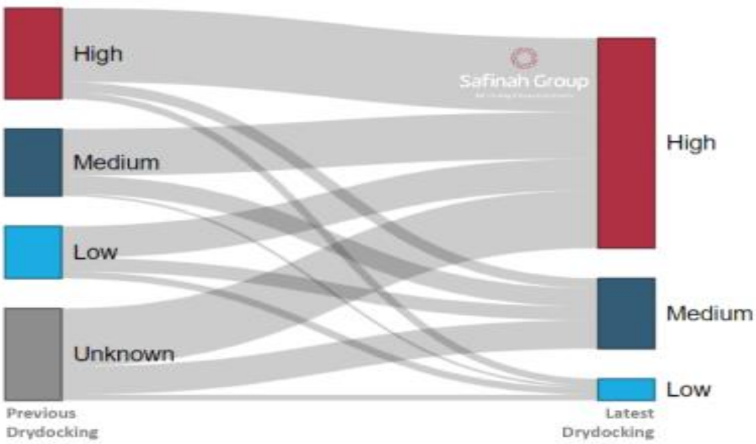
Authors & Title	Research topic	Geography destination / (origin)	Contribution: Type / (company)
Ralitsa Mihaylova – *"Data driven approaches to acoating selection and the challenges with ship-specif functional specification"*	Coating selection	World Fleet (UK)	Independent coating consultant (Safinah Group)
Eirik Eide – "*In Transit Cleaning of Hulls"*	Proactive cleaning	World Fleet (Norway)	Industry – IWC provider (Shipshave)
Lisa-May Alvarez "*Impact of ultrasounds on micro- and macro-fouling development"*	Ultrasounds as an AFS	World fleet (Greece)	Innovation accelerator (EXUS)
Neil Oxtoby – "*UVC antifouling: Design & Vessel trails of next generation samples"*	Ultraviolet radiation as an AFS	World Fleet (The Netherlands)	Industry - Coating manufacturer (AkzoNobel)

Source: Author

Ralitsa Mihaylova – *"Data driven approaches to acoating selection and the challenges with ship-specif functional specification*

This contribution from the British independent coating consultant provides insights into the coating industry, such as factors to consider when planning the dry-docking schedule, observed trends in the coating selection process and explaining why even premium antifouling coating could fail. The optimal solution to be identified need careful consideration based on multiple ship-specific factors. These include but are not limited to operation profile, environmental conditions, seasonality, expected activity, speed patterns, location of the ships compared to shipyards, availability of others biofouling management options. These multiple factors make the coating selection process extremely difficult and long, considering it will impact the operations of the ships for many years. The author reports that the marine coating market is currently very competitive, there's a high variety of coatings products, and shipowners are spoilt for choice. This often results in coating manufacturers offering fleet discounts and group deals to shipowners to influence their selection process and possibly prevent the optimal solution to be identified and selected. However, this phenomenon seems to be changing, possibly also thanks to an increased awareness of the consequences of the biofouling problem, and more shipowners are improving the quality of the coatings used on their fleets (Figure II.6).

Figure II.6 Technology level transitions



Source: Mihaylova (2022)

Of course, this high representation of high-quality coating should not be transferred also to average shipowners, because it's more likely that a shipowner that contacts a coating consultant is more likely to invest in a high-quality product. Moreover, we should consider that even a high-quality coating is not infallible. The author lists some of the root causes of why some coatings fail before their claimed lifetime:

- Incomplete or inaccurate historical data,

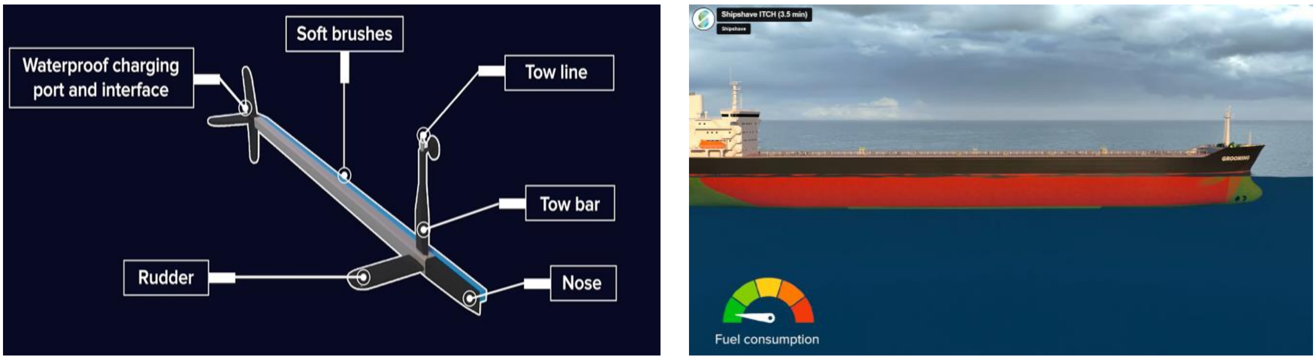
- Poor collaboration between client and paint manufacturer
- Errors in tender offers
- Commercial pressures (fleet discounts vs optimal coating selection)
- Mistakes in the surface preparation, or during the application

And the author concludes remarking on a point shared by many others, that there's a lack of independent and reliable data, and a systematic approach to coating selection should be adopted, with periodic reviews.

Eirik Eide – "*In Transit Cleaning of Hulls*"

This contribution comes from the Norwegian company Shipshave that offers an innovative solution to proactively clean the vertical walls of the hull, while the ship is sailing through the water. The company uses a cleaning device operated by the crew called In Transit Cleaning of Hulls (ITCH). The device consists of cameras, a rudder and a tow line to be moved and operated, To remove biofouling it can be equipped with different cleaning brushes depending on the level of biofouling experienced. The ITCH is secured from the bow to a winch and to a rope on the stern. The ITCH is lead out of the Panama fairlead on the bow and deployed on one of the sides of the ship. The crew will operate the winch on the bow and ensure that ITCH will move astern following a vertical pattern. When the device reaches the "Safe Distance" from the stern will change direction and will be retrieved from the winch on the bow. Once one side is cleaned, the crew will change the configuration of the device and deploy it on the other side. The ITCH only cleans the vertical sides of the hull (80-90%), so for the moment it can't be employed on the flat bottom or for niche areas. Even though this solution doesn't provide a complete coverage compared to others (Armach Robotics was stressing the importance of reaching 100% cleaning coverage), results shows that also incomplete cleanings can reduce drag and increase fuel efficiency of the vessel (Prudhomme, 2022). Shipshave solution also present other benefits such as the ability to perform regular cleaning while the ship is sailing and thus being independent of shore-side infrastructures, avoiding costly off-hire deviations or complex cleaning planning schedules. Shipshave also reports that the OPEX for using this solution will be 250$ per cleaning.

Table II.6 In Transit Cleaning of Hulls (ITCH)



Source: [Company website]

This solution recalls what was expected by Bertram (2022), with the development of on-board solutions to make up for the limited capacity of shore-based IWC providers and policies, and even though it's not a complete solution to the biofouling problem it's one of the solutions in the toolbox to solve the biofouling problem, and help shipowners face the coming regulations. The fact that ITCH is currently not equipped to capture biofouling is something that needs to be addressed and clarified.

Lisa-May Alvarez "*Impact of ultrasounds on micro- and macro-fouling development*"

This contribution comes from the innovation accelerator EXUS a British company established to provide antifouling solutions through the implementation of guided ultrasounds waves. Their solution is applicable to ships, power stations, food and chemical industries. The rationale behind their solutions is to use transducers in direct contact with the interior of the hull to emit low-power ultrasonic pulses. Microorganisms cannot flourish due to the flow of water molecules over the hull's full underwater profile. Ultrasounds can be used both for preventive approach, to reduce or delay biofilm formation; or for a curative approach to remove established biofilm. The author conducted both a laboratory testing and an "In situ" testing. The results of the laboratory testing were shown and ultrasounds were able to both prevent and remove biofouling when applied. However, when the transducers were applied on antifouling coating and exposed on real underwater environment the results were less positive. The author reports that although exposure to ultrasounds reduce micro-fouling formation, they are not a sufficient antifouling method to prevent macro-fouling, and further investigation is required.

Neil Oxtoby – "*UVC antifouling: Design & Vessel trails of next generation samples*"

This paper from AkzoNobel discusses their efforts to develop a Antifouling system that uses UVC LEDs in collaboration with Royal Philips. UVC light is already commonly used to sterilize water and surfaces in various applications, like industrial water treatment plants, swimming pools and healthcare. Their solution involves embedding low voltage, low power UVS LEDs in a transparent silicone material to create a UV-emitting "skin" on the ship hull. This "skin" would have a sterilization zone of a few millimetres, effectively preventing biofouling. The development of the solution aspires to create a sustainable, eco-efficient, biocide-free, and solvent-free antifouling system. Then the author discusses what are the main aspects that are being developed in the next generation of panels.

- Thickness reduction, the new panel will be only 4mm thick, the reduced use of materials will lead to lower costs per panel
- Increasing panel size (50x50cm),
- Wireless powering, the current wire powering has weaknesses due to potential water ingress in the circuit that creates damages, using a wireless powering will resolve this issue.
- Production technology, this should allow scalability of the product and reduce costs.
- Increase the lifetime of the LEDs with pulsing and intensity modulation.

Then, the author presents three case studies proving the effectiveness of this method, with panels remaining spotless where the LEDs were active. However, some fouling has been observed on the edges of the panels where the intensity of the UV light is below the threshold. For the moment the solution was only applied on test panels, and there are no panels completely covering the hull. In conclusion, the data shows that the solution works and the area around the panel is kept completely clean and free of biofouling, but for the moment the biggest bottleneck of this method is the lifetime LEDs that only lasts around 2 years, so it's outside of most dry-docking schedules, but great developments in this area are expected.

Figure II.7 UVC LEDs testing panel

Source: Oxtoby (2022)

II.4 Summary comparison table of the literature

Research Topic	Academia	Industry	Regulators
Biofouling Growth	Farhat et al. (2016), Uzun et al. (2019), Green & Grosholz (2020), Blackburn et al. (2011), Atalah et al. (2017)		
Increase in drag due to biofouling	Schultz (2007)		
Antifouling coatings	Bressy & Lejars (2014), Rittschof (2009), Townsin & Anderson (2009), Ciriminna & Pagliaro (2015), Devanny & Riastuti (2019), Sánchez & Yebra (2009)	Yamashita A, (2022), Hoffmann M. (2022), Tan et al. (2022), Mihaylova (2022), Oxtoby (2022)	Sørensen A. (2022)
In-Water Cleaning (Hull & Propeller)	Davidson et al. (2008), Swain et al. (2022), Tribou & Swain (2015), Di Fino et al. (2022), NIWA (2012)	Ballegooijen & Muntean (2016), Noordstrand A. (2020), Hearin et al (2015, 2016), Doran S. (2022), Oftedahl et al. (2022), Lander K. (2022), Eide E. (2022)	Floerl et al. (2010), Betram V. (2022), Lehmann & Fiskeseth (2022)
Regulations	Leeuwen & Mohnen (2017)		GEF-UNDP-IMO (2022 b, c, d, e), IMO MEPC.207(62) (2011), Watermann et al (2022), Cornelis et al. (2022)
MGPS		Cioanta & McGhin (2017), Alvarez LM (2022)	Grandison et al. (2011)
Comprehensive biofouling management	Woods Hole Oceanographic Institution (1952), Schultz (2011), Report CEBRA (2021), Moser et al (2017), Davidson et al. (2014 & 2016), Coutts & Dodgshun (2007)	Kim Y. (2022), Troland (2022), Skarbo R. (2022)	IMO Resolution A.751 (1993), Lewis (2016), NSTM Chapter 081 (2006), GEF-UNDP-IMO, 2019, GEF-UNDP-IMO, 2022 a.
Best Practices	Luoma et al. (2022)	INTERTANKO Guide (2017), BIMCO Industry standard on IWC (2021)	Georgiades et al. (2018), Interreg COMPLETE Project (2021)

Table II.7: Summary comparison table. Source: Author

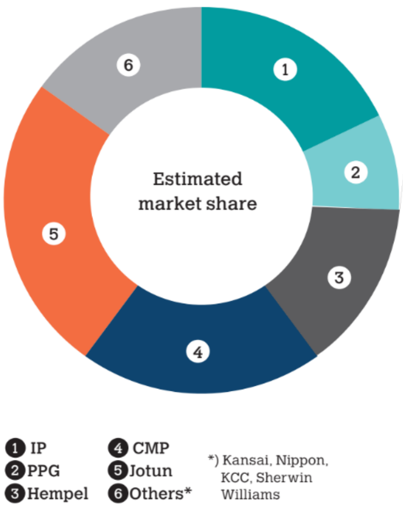
III. Active companies with proactive solutions

After the theoretical introduction proposed in the first two sections, section III will cover active companies that offer biofouling management solutions. To select the companies, I decided to focus the research only on the largest European companies by revenue in both the coating and IWC industries. The data was collected through the Companies' reports, and the Amadeus database[1], which only covers European companies.

III.1 Active companies with preventive solutions

As saw, the antifouling coating market is currently dominated by a handful of well-established paint companies. Six of them have a global reach and other 3 major companies that operate only at a local level (I-tech, 2022). The companies and estimated market shares are shown in Figure III.1. For several years, the largest players presented very similar product portfolios and technologies. With the increase of awareness of the biofouling problem, changes in regulations, and the development of substitute technologies and products we started to see a greater differentiation between the companies.

Figure III.1 Major players in the antifouling coating market



Source: I-tech company report (2022)

[1] Amadeus is a database of comparable financial and business information on Europe's largest public and private companies. The Amadeus database is offered by Bureau Van Dijk, a Moody's Analytics Company

Some companies started to invest in new types of paint (see Nippon Marine Paints), others are continuing to develop traditional and established products (SPC, FRC), others adopted a combination of both paints and cleanings (see Jotun). Different systems divide the market into different segments, but the goal of the companies is to match the buyers' needs with their supply. The buyers' needs remain the same, to prevent or reduce the biofouling problem, what changed is the size of the demand and the context in fact, due an increased awareness and coming regulations we expect an increase in demand both for antifouling coatings and In Water Cleaning. Knowing that the demand for transport is a derived demand of the demand for a certain good in another area, one could suppose that the demand for antifouling coatings depends on the number of newbuilds and drydocks. The demand for newbuilds depends on the demand for seaborne transport and the demand of drydocks depends on many factors such as the number of ships in the world fleet, the activity of vessels, the cost of labour, and cost of materials and others. So knowing where and when newbuilds are constructed, and drydocks carried out is crucial for the success of marine coating manufacturers. As antifouling coatings can only be applied on land, we can expect that most of the revenues come from countries where there's a high concentration of shipyards either for new buildings or ships repairs.

Figure III.2 Deliveries of newbuilds by type and country

Table 2.8 Deliveries of newbuilds by major vessel type and country of construction, 2021 (thousand gross tons)

	China	Republic of Korea	Japan	Philippines	Rest of the world	Total	Percentage
Bulk Carriers	13 764	960	5 730	624	73	**21 151**	35%
Oil Tankers	4 791	6 376	2 064		358	**13 589**	22%
Container ships	4 170	4 675	1 954		131	**10 929**	18%
Gas Carriers	918	7 052	159		10	**8 138**	13%
Ferries and passenger ships	390	50	83	20	1 567	**2 110**	3%
General cargo ships	1 017	56	223		256	**1 552**	3%
Offshore vessels	641	402	9		317	**1 370**	2%
Chemical tankers	662	109	226		50	**1 047**	2%
Other	510	6	278		97	**892**	1%
Total	**26 863**	**19 687**	**10 726**	**643**	**2 859**	**60 780**	
Percentage	*44%*	*32%*	*18%*	*1%*	*5%*	***100%***	

Source: UNCTAD calculations, based on data from Clarksons Research.

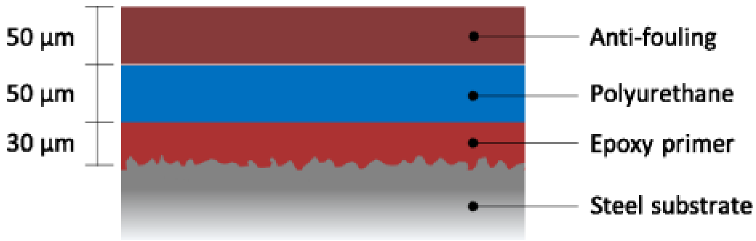
Notes: Propelled seagoing merchant vessels of 100 gross tons and above.
For more data on other shipbuilding countries, see http://stats.unctad.org/shipbuilding.

Source: UNCTAD (2022)

As shown in Figure III.2, currently the majority of the orderbook is being built and delivered in East Asian countries, so we can expect high sales in the region to serve the Korean, Chinese and Japanese yards (95% of total deliveries). For what concerns ship repairs we cannot expect a ship, employed in regional traffic, to conduct an empty trip to Asia just to conduct repairs and apply antifouling coatings, so it will be dry-docked in regional shipyards. It’s common knowledge that most cargo vessels employed in European waters conduct ship repair in Turkey, because its shipyards provide a fair service, and they are less expensive compared to other European countries. This creates an opportunity for the coating manufacturers to expand also to other areas and develop their network.

Trying to size this global and complex market from the revenues of active companies is not an easy task, because as we will see later, coating companies do not serve only the marine industry, so their business is diversified. And also having the percentage of revenues that comes from the marine industry is not enough, because the largest coatings manufacturers sell antifouling coating and deck coatings, cargo tank and cargo holds coatings. So it’s better to approach this problem from another perspective, using the above-supposed drivers of coatings demands. Every year the number of deliveries changes but, according to UNCTAD and Clarksons data, it should be around 1000-3000 new ships constructed every year. Currently, the world fleet consists of around 100’000 ships, and according to a 5 years dry-docking schedule, around 20’000 dry-docks should be conducted every year. The costs for the application of an antifouling coating could easily reach half a million dollars depending on the size of the vessel. So, although the market reports cannot precisely estimate the value of the antifouling coatings market, it’s safe to say that it’s valued at billions of dollars. Another important factor to consider is that the construction of a ship presents the possibility of generating higher revenues compared to drydocks because ships hulls are protected with multiple layers of coatings, with the first layers protecting the steel plates from corrosion and the final layer usually as an antifouling coating as shown in Figure III.3. When a new ship is being constructed it will have to apply all the layers of coatings, instead when a ship enters a drydock, after cleaning the hull from biofouling, it’s often not required to reapply all the layers, but it will only be done if necessary (e.g. if paint damages are spotted).

Figure III.3 The multiple layers of a ship's hull coating



Source: Devanny & Riastuti (2019)

To develop section III, I relied on the report "Worldwide Antifouling Paint and Coating Competitive Analysis and Leadership Study" released in March 2023 and others. Although I was not able to access the first report in full, the table of contents and other information were publicly available online, and I took a hint from it to structure this section and identify the largest players of this market. The first two sections of the report describe the antifouling paints and coatings market in general, analysing the market by product type, by type of application and by region. Then, the report compares the companies with a leadership and competitive analysis. In conclusion, the report gives a full description of the 7 largest companies in the market. The companies mentioned in the report are Jotun, AkzoNobel, Hempel, BASF, PPG, Sherwin-Williams, and Chugoku Marine Paints[2]. Of these 7 companies PPG and Sherwin-Williams are American companies, instead Chugoku Marine Paints is Japanese, so these 3 companies are excluded in the report for being non-European. The next exclusion regards the German BASF SE[3], which is the largest chemical producer in the world. The company is mentioned in the report because it produces the chemicals used in paints, but it does not produce nor sell antifouling coatings, so it is thus excluded. Among other important companies that sell antifouling coatings, there is the Italian Boero Yacht Coatings which was not included because it focuses its products on yachts and not on merchant vessels. The analysed companies are then the Norwegian Jotun A/S, the Dutch AkzoNobel N/V and the Danish Hempel A/S. These three companies share a similar structure, being very large organizations divided into multiple business

[2] Compared to the companies shown in Figure III.1 AkzoNobel is the parent company of International Paints (IP).
[3] BASF SE stands for Badische Anilin- und Anilin and Sodafabrik Societas Europaea

divisions that share the same markets. All three companies in fact, present almost the same business divisions that cover: marine coatings (the object of this study), protective coatings (used on infrastructures or industrial plants), decorative paints (interior decorations[4]), and powder coatings (applied as a free-flowing, dry powder instead of conventional liquid paints). The analysis of the companies will follow a similar pattern:

- Description of the company (brief history and overview, organizational chart, operations, Mission and, Vision)
- Products portfolio
- Balance sheet

[4] Here we can see the difference in meaning between paints and coatings, that have been used so far interchangeably.

Jotun A/S

Jotun A/S is a Norwegian company that has gained worldwide recognition for its excellence in producing paints, coatings, and marine coatings. The company was founded in 1926 by the Norwegian business entrepreneur Odd Gleditsch in Sanderfjord, a small city that sits on the west bank of the Oslofjorden, and close to the Norwegian capital. The company started as a local small paint manufacturer that sold marine paints to whaler shipowners, however, driven by a commitment to quality and a passion for innovation, the company steadily grew and expanded its operations. With a rich history spanning over 95 years, Jotun has firmly established itself as a global leader in the industry, offering innovative solutions and high-quality products to customers in more than 100 countries. Jotun's success can be attributed to its unwavering focus on research and development. Jotun is recognized as a global leader in marine coatings, serving the maritime industry with a diverse range of specialized products. Beyond its commitment to delivering top-quality products, Jotun places great emphasis on sustainability and corporate social responsibility. The company strives to minimize its environmental impact through responsible manufacturing practices and the development of eco-friendly coatings. Jotun actively collaborates with partners, customers, and industry stakeholders to promote sustainable development and drive positive change within the coatings industry. To this day, the company is still in the firm hands of the Gleditsch family. With its Norwegian heritage and a global reach, Jotun continues to inspire trust, deliver value, and set new benchmarks for quality and sustainability.

Figure III.4 Jotun logo

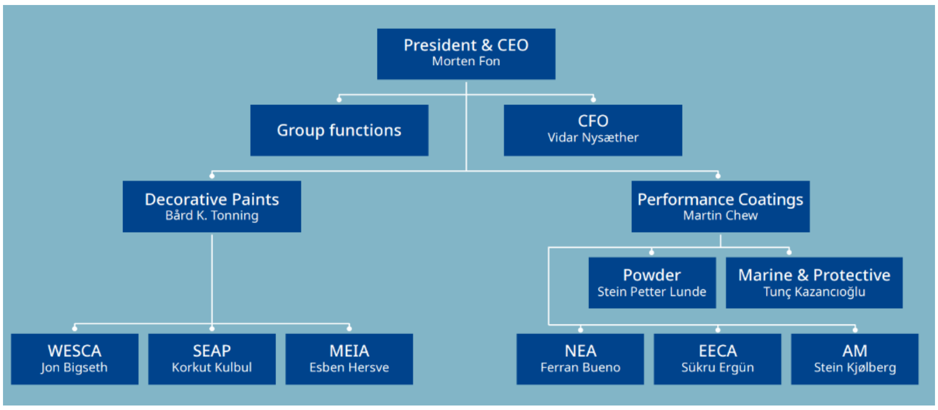
Source: Jotun Group annual report (2022)

Figure III.5 Jotun values

Source: Author

As shown in Figure III.6 the Jotun group is a matrix of organizations each with a focus on different markets and spread across six regional organizations. Currently, the company operates in the markets of: Decorative paints (38% of revenues), Marine coatings (27%), Protective coatings for infrastructures (27%) and powder coatings (8%). The group currently operates in more than 100 countries and it employs more than 10’000 employees globally.

Figure III.6 Jotun group organizational chart[5]

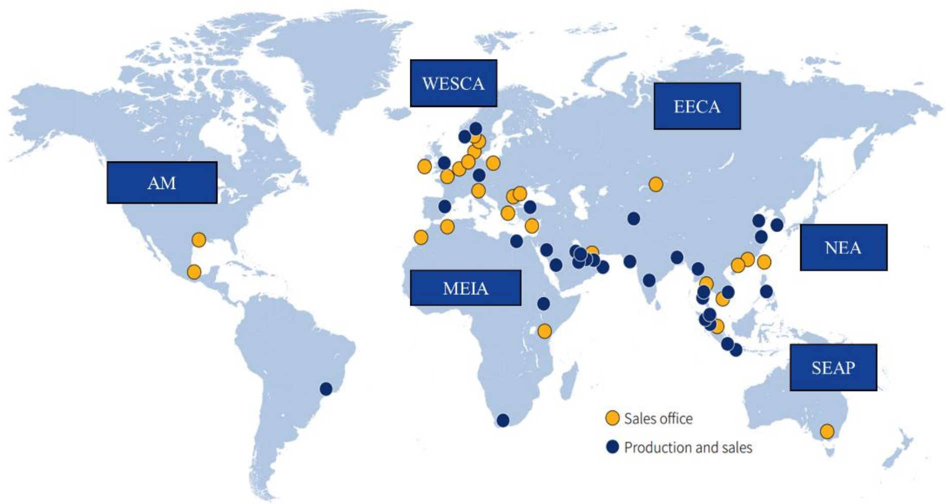


Source: Jotun Group sustainability report (2022)

[5] WESCA (West Europe and Scandinavia), SEAP (South East Asia and Pacific) MEIA (Middle East, India and Africa), NEA (North East Asia), EECA (East Europe and Central Asia) AM (Americas).

The group has a global network of both factories and sales offices, but with a higher concentration of production facilities in the middle east and South Asian countries, and instead a lower representation in the American market, which might be harder to penetrate due to the incumbent position of PPG and Sherwin-Williams. In Europe, we mainly have a sales network and R&D centres, but fewer production facilities and of course the Headquarters of the company.

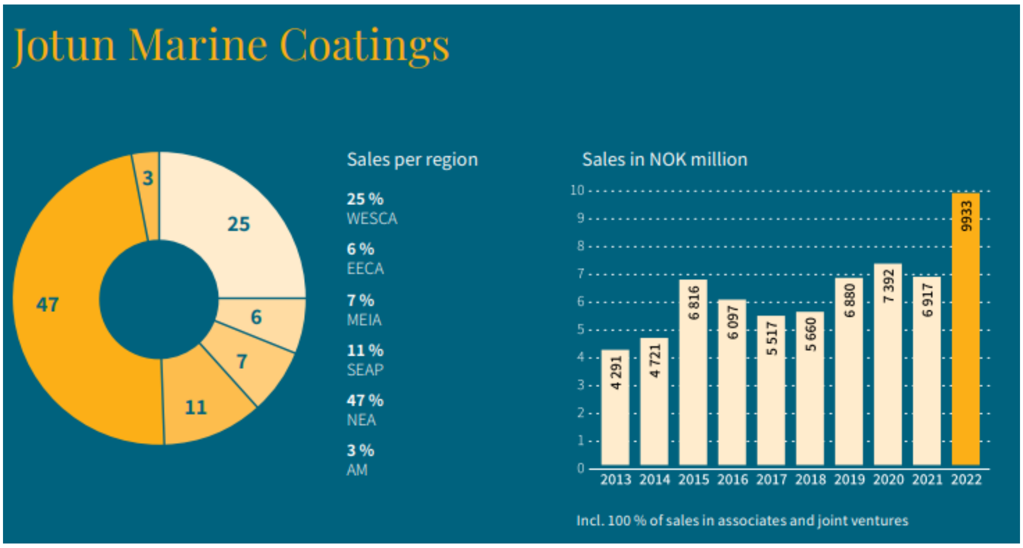
Figure III.7 The productions and sales network



Source: Jotun group sustainability report (2022)

Currently, the marine coatings segment of Jotun is worth almost 1 billion (NOK/EUR = 0,09509 on 31/12/2022), and the biggest regions are North-East Asia (NEA) which includes China, Korea, Japan and generates 47% of the revenues, and West Europe and Scandinavia that generates 25% of the revenues, which confirms what anticipated at the beginning of this section. Anyway, I think it's important to note that although the NEA area has 94% of new ships construction, it only creates 47% of the revenues, so the focus of the company is not exclusive to newbuilds but also to dry-docks. Another important aspect to point out from these results is the overall positive trend in revenue growth (CAGR =8,76%),which sharply increased in the last year (+44% YoY). The group attributes this success to the increase in seaborne trade and the increased number of deliveries. Moreover, increasingly strict environmental regulations lead shipowners to invest in premium hull coatings and achieve reduced emissions.

Figure III.8 Jotun Marine Coatings figures

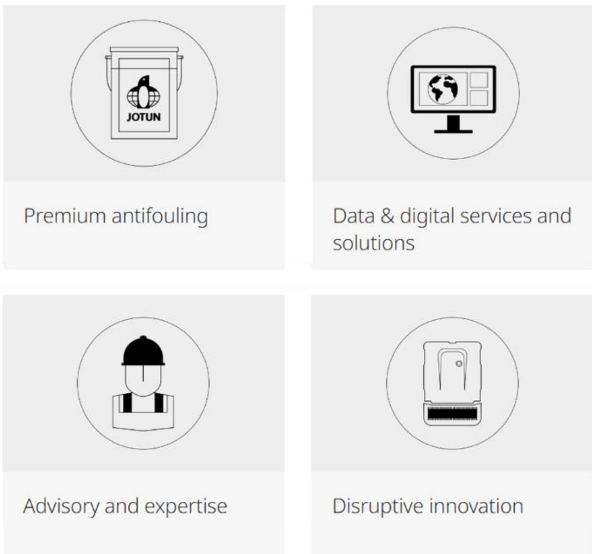


Source: Jotun Group sustainability report (2022)

Product Portfolio

Visiting Jotun's website on the page dedicated to shipping products the company display 4 macro areas of solutions to its client shown in Figure III.9.

Figure III.9 Jotun solutions for the shipping industry



Source: Jotun's website

The first solution presented regards the premium antifouling coatings that made the company famous then, the company expanded its offer also towards service solutions. This shouldn't come as a surprise considering the servitization of manufacturing phenomena experienced in the last years. This can be attributed to the fact that services usually have higher margins, and a more stable revenue stream, leading to better cash flow performance, and companies use services as a new way to achieve a competitive advantage as product technological advantages are becoming harder to reach and maintain (Gebauer & Fleisch 2007). The services offered by the Company include an IT-based monitoring solution that supports clients to monitor, measure and improve the performance of their fleet called Hull Performance Solutions (HPS); and advisory services to select the appropriate antifouling product and recommend the most appropriate biofouling management solution. Lastly, Jotun invested heavily to develop its own ROV for proactive cleaning called Hull Skating Solutions (HSS). The ROV is supposed to be stored on board and regularly launched by the crew of the vessel to perform grooming, the ROV is supposed to be used on a specifically developed coating (the SeaQuantum Skate). Unfortunately, this unit does not perform biofouling capture.

Regarding marine coatingsthere are currently 135 products available for the shipping industry. Narrowing down our research, under the products category we can filter for fouling protection, and we end up with 21 products. Of these, only 2 are Fouling Release Coatings (FRC), one biocide free (SeaQuest) and one that contains biocide (SeaQuest Endura). The remaining 19 are all Self Polishing Coatings (SPC), divided into categories and qualities, ranging from ultra-low frictional coatings that promise more than 12% of fuels savings, to products that meets "basic needs at an affordable price" with a high concentration of biocides.

Balance Sheet

The consolidated results of the company for the 2020-2022 period are reported in Table III.1 (income statement) and Table III.2 (assets and liabilities). The company managed to close all three years with a healthy profit of more than € 200 million. In the same period the revenue grew substantially from above 2 billion to more than 2,7 billion. Although the revenue grew, the profits didn't, profitability was negatively impacted by high raw materials prices, costs related to the supply chain disruptions and closing of operations in Russia, an important market for Jotun (Jotun Group sustainability report, 2022).

Table III.1 Jotun consolidated income statement

**Figures in thousands Euros*

Consolidated income statement

	2022	2021	2020
Exchange rate: NOK/EUR	0.09509	0.10010	0.09554
Revenue	**2.718.338**	**2.332.831**	**2.084.301**
Cost of goods sold	*- 1.515.830*	*- 1.249.248*	*- 1.016.832*
Payroll expenses	*- 350.502*	*- 339.239*	*- 313.085*
Other operating expenses	*- 402.896*	*- 342.442*	*- 342.415*
Depreciation, amortisation and impairment	*- 93.759*	*- 87.688*	- 78.725
Operating profit	**355.351**	**314.114**	**333.339**
Net financial items	*- 51.919*	*- 24.825*	*- 31.624*
Profit before tax	**303.432**	**289.289**	**301.715**
Income tax expense	*- 97.372*	*- 77.978*	*- 74.521*
Profit for the year	**206.060**	**211.311**	**227.194**

Source: Amadeus

From the second table, we can see that most of the profits generated in the years were kept inside the company as reserves, and the company decided to keep a rather low Share Capital compared to its dimensions. In the three-year period, the company experience an expansion of total assets of around 25%, mainly attributed to the increase of current assets (almost 40% increase in the period), due to an increase in stock (almost doubled) and an increase in credits from the clients. The company uses mostly equity to finance its operations (more than 50%). The company increased the short-term financing and decreased the long-term financing, but the company has enough current assets to cover current expenses and liabilities.

Table III.2 Jotun consolidated statement of assets and liabilities

**Figures in thousands Euros*

Statement of assests and liabilities			
	2022	2021	2020
Exchange rate: NOK/EUR	0.09509	0.10010	0.09554
Assets			
Fixed assets	**1.060.317**	**1.026.875**	**932.727**
- *Intangible fixed assets*	*118.003*	*115.221*	*104.995*
- *Tangible fixed assets*	*774.390*	*761.997*	*667.325*
- *Other fixed assets*	*167.924*	*149.657*	*160.406*
Current assets	**1.445.705**	**1.318.880**	**1.032.945**
- *Stock*	*458.415*	*403.823*	*274.860*
- *Debtors*	*672.361*	*575.903*	*475.678*
- *Other current assets (Cash & cash equivalent)*	*314.929*	*339.155*	*282.407*
TOTAL ASSETS	**2.506.021**	**2.345.755**	**1.965.672**
Equity & Liabilities			
Shareholders funds	**1.378.098**	**1.248.206**	**1.063.135**
- *Capital*	*9.794*	*10.311*	*9.840*
- *Other shareholders funds*	*1.332.171*	*1.202.659*	*1.022.150*
Non-current liabilities	**265.959**	**357.074**	**351.194**
- *Long term debt*	*217.946*	*299.800*	*287.289*
- *Other non-current liabilities*	*48.012*	*57.274*	*63.905*
Current liabilities	**861.965**	**740.575**	**551.344**
- *Loans*	*265.864*	*226.837*	*145.980*
- *Creditors*	*331.759*	*292.907*	*222.983*
- *Other current liabilities*	*264.342*	*220.831*	*182.380*
TOTAL SHAREH. FUNDS & LIAB.	**2.506.021**	**2.345.855**	**1.965.672**

Source: Amadeus

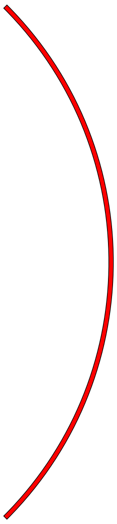
AkzoNobel N/V

AkzoNobel is a multinational company renowned for its leadership in paints, coatings, and chemicals. With a presence in over 150 countries, the company has a diverse portfolio of brands and a commitment to delivering innovative solutions that enhance and protect surfaces in various industries and applications. AkzoNobel was formed in 1994 through the merger of Akzo and Nobel Industries, combining the expertise of the two companies in artificial fibres and chemicals. In 1998, the newly formed AkzoNobel conducted an acquisition of International Paints, a British company founded in 1881 a maritime coatings specialist. From its inception, International Paints demonstrated a passion for innovation, developing products that set new industry standards. Notably, in the 1920s, International Paints introduced a game-changing anti-fouling paint called "Intersmooth" which revolutionized the prevention of marine organism growth on ship hulls. Over the years, International Paints continued to expand its product range and global presence thanks to its dedication to research and development. Their comprehensive range of products encompasses antifouling coatings, tank coatings, deck coatings, and other specialized coatings tailored to meet the unique challenges faced by the marine industry. Being part of the AkzoNobel conglomerate International Paints to provide customers with not only superior products but also comprehensive technical support, training, and expert advice. In conclusion, AkzoNobel, with its subsidiary International Paints, has a combined legacy of almost two centuries of innovation, expertise, and a commitment to delivering high-quality coatings and solutions. With a rich history rooted in technological advancements, both companies have continuously adapted to the changing needs of their customers and the industry, while upholding their commitment to sustainability. Of the analysed companies, AkzoNobel is the only publicly traded company, its common shares are listed on the Euronext Amsterdam exchange.

Figure III.10 AkzoNobel and International logos

Source: Companies' websites

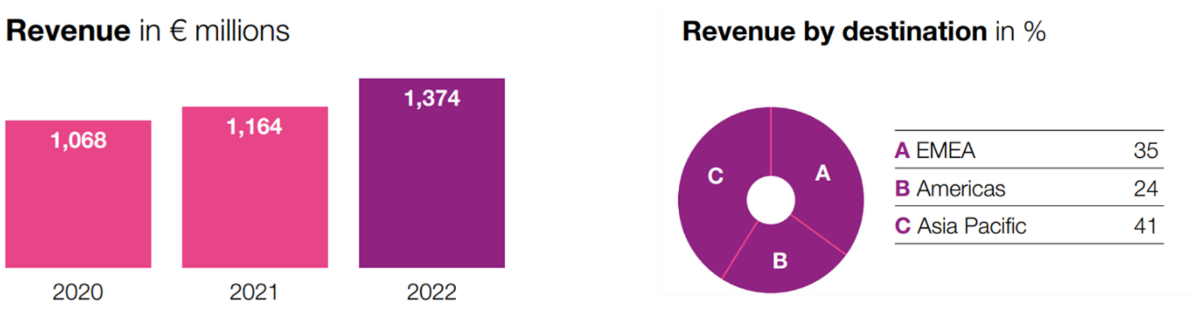
Figure III.11 AkzoNobel Values



Source: Author

AkzoNobel is the third-largest company in the paint and coatings industry, behind Sherwin-Williams and PPG Industries. The company divides itself into decorative paints and performance coatings. The company operates using two business divisions, decorative paints (40% of revenues) and performance coatings (60% of revenues), subsequently divided into the different industries of Marine and protective, Industrial, Automotive, Specialty and Powder coatings. Focusing on the marine coatings, in Figure III.12 we can see a similar pattern experienced by Jotun where the Asian and European countries represent the biggest market for AkzoNobel. On the other hand, the American market is much more important for AkzoNobel representing 24% of revenues from marine coatings.

Figure III.12 AkzoNobel Marine and Protective coatings division



Source: AkzoNobel report 2022

Products Portfolio

AkzoNobel's webpage for "Marine, Protective and Yacht coatings" immediately informs that the company operates in this division using other brands of the group such as International, Sea Hawk and Awlgrip, and suggests visiting their website for further information. I decided to visit the International-marine website to search for the proposed solution. They were proposed differently but they were similar to those of Jotun. In fact, International offers both biocide-free FRC and SPC and CDP coatings with biocides. Moreover, International also offers performance monitoring solutions (Intertrac), and in collaboration with HullWiper an integrated hull management solution called HullCare. The goal of this proposal is to combine high-performance antifouling coatings with proactive cleaning with capture. According to the HullCare program, the ROV is not expected to be carried on board, but rather the proactive cleanings will have to be scheduled with the ROV cleaning company.

Balance sheet

The results of the group are shown in Table III.3 and Table III.4. The growth of revenues comes together with an increase in costs, due to higher costs of raw materials and logistics, which negatively affect profitability, especially in the last year. In fact, the growth in revenue (+27% in the three-year period) didn't lead to a growth in profits, which instead experienced a downturn (-44%). Nevertheless, the company still closed all three years with a positive result but with a reduced Net profit margin, from around 8%. close with industry average, to 3,5% in 2022. In the 2023 outlook, the company stated that margin management and cost reduction are the areas where the company will focus. AkzoNobel also expects a reduction in the costs of raw materials that will help the company in margin management and increase profitability.

Table III.3 AkzoNobel consolidated income statement

**Figures in thousands Euros*

Consolidated income statement			
	2022	2021	2020
Revenue	10.846.000	9.654.000	8.530.000
Cost of sales	- *6.923.000*	- *5.683.000*	- 4.745.000
Gross Profit	**3.923.000**	**3.971.000**	**3.785.000**
Selling and distribution expenses	- *2.308.000*	- *2.041.000*	- *1.921.000*
General and aministrative expenses	- *649.000*	- *582.000*	- *663.000*
Research and development expenses	- *258.000*	- *230.000*	- 238.000
Operating profit	**708.000**	**1.118.000**	**963.000**
Net financial items	- *106.000*	- *13.000*	- *44.000*
Profit before tax	**602.000**	**1.105.000**	**919.000**
Income tax expense	*-214.000*	- *246.000*	- *241.000*
Net profit / (loss) for the year from discontinued operations	*-10.000*	*6.000*	- *7.000*
Profit for the year	**378.000**	**865.000**	**671.000**

Source: Amadeus

Looking at AkzoNobel's structure we see that fixed assets represent around 60% of the company and both fixed and current assets grew in the period, even though current assets grew more, which lead the company to have a more flexible structure. Surprisingly, while the assets grew, the Shareholders' funds experienced a decrease (-23%), this is mainly explained by a strategy of share buybacks (€660 million just in 2022), actuarial losses and negative currency effects. With withdraws of shareholders fund, the company had to increase the debt capital. Both long-term and current liabilities increased. The company issued two bonds with a nominal value of € 600 million. Lastly, the net working capital of the company remains positive but was greatly reduced in the period from € 2 billion in 2020 to € 500 million in 2022.

Table III.4 AkzoNobel statement of assets and liabilities

**Figures in thousands Euros*

Statement of assests and liabilities			
	2022	2021	2020
Assets			
Fixed assets	**8.497.000**	**8.530.000**	**8.113.000**
- *Intangible fixed assets*	*4.072.000*	*3.690.000*	*3.554.000*
- *Tangible fixed assets*	*2.259.000*	*2.104.000*	*1.945.000*
- *Other fixed assets*	*2.166.000*	*2.736.000*	*2.614.000*
Current assets	**6.244.000**	**5.348.000**	**5.064.000**
- *Stock*	*1.843.000*	*1.650.000*	*1.159.000*
- *Debtors*	*2.951.000*	*2.546.000*	*2.299.000*
- *Other current assets (Cash & cash equivalent)*	*1.450.000*	*1.152.000*	*1.606.000*
TOTAL ASSETS	**14.741.000**	**13.878**	**13.177**
Equity & Liabilities			
Shareholders funds	**4.548.000**	**5.636.000**	**5.950.000**
- *Capital*	*87.000*	*91.000*	*95.000*
- *Other shareholders funds*	*4.461.000*	*5.545.000*	*5.855.000*
Non-current liabilities	**4.447.000**	**3.373.000**	**4.134.000**
- *Long term debt*	*3.332.000*	*1.379.000*	*1.363.000*
- *Other non-current liabilities*	*1.115.000*	*1.994.000*	*2.771.000*
Current liabilities	**5.746.000**	**4.869.000**	**3.093.000**
- *Loans*	*2.543.000*	*1.556.000*	*119.000*
- *Creditors*	*2.801.000*	*2.948.000*	*2.580.000*
- *Other current liabilities*	*402.000*	*365.000*	*394.000*
TOTAL SHAREH. FUNDS & LIAB.	**14.741.000**	**13.878.000**	**13.177.000**

Source: Amadeus

Hempel A/S

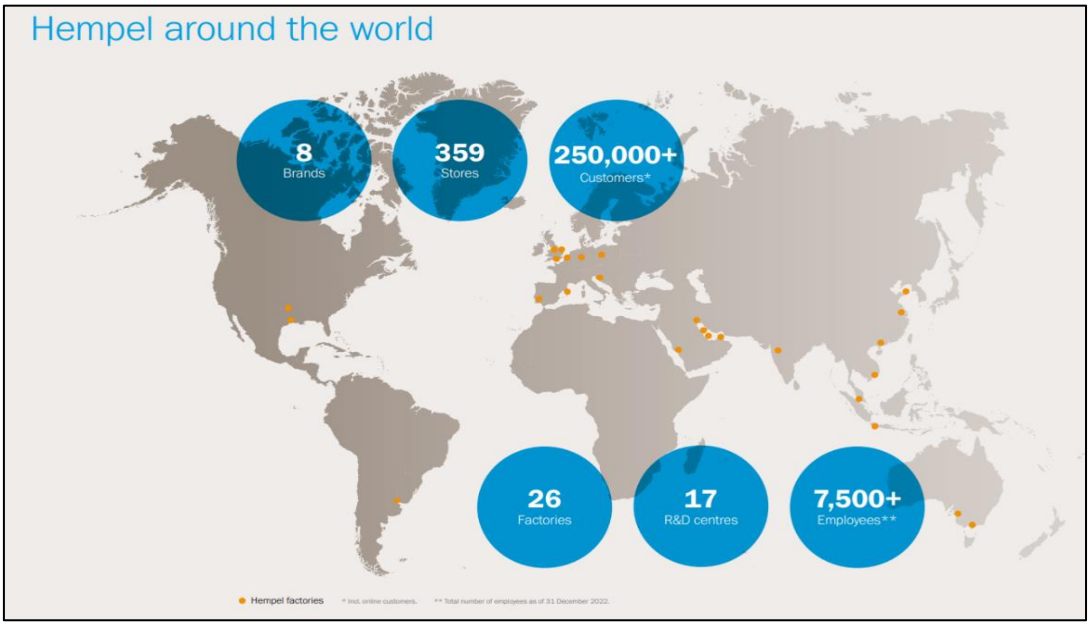
Hempel is a renowned Danish company specializing in coatings and paints for industrial, marine, and protective applications. With a rich history spanning over 100 years, Hempel has established itself as a global leader in the field, offering innovative and high-quality solutions to customers worldwide. Founded in 1915 by J.C. Hempel, the company initially focused on providing marine coatings for ships. Over the years, Hempel expanded its product range and diversified into various sectors, including infrastructure, oil and gas, wind energy, and industrial manufacturing. With a global presence and an extensive network of manufacturing facilities, Hempel ensures that its products are readily available and tailored to local market requirements. The company is owned by the Hempel Foundation, established by the Hempel family in 1948. The foundation's purpose is to safeguard the interest of the Hempel Group and to provide funding and support for scientific research, education, and philanthropic work. The stable ownership of the Hempel Group allows it to maintain and expand a leading position in the global coatings market. Under the ownership of the Hempel Foundation, the company operates with a strong sense of corporate social responsibility. Hempel strives to minimize its environmental footprint by developing eco-friendly coatings, reducing waste, and implementing sustainable practices throughout its operations. Furthermore, the company actively engages in social initiatives, supporting local communities and contributing to charitable causes. Hempel's dedication to excellence, continuous innovation, and commitment to sustainability has solidified its position as a leading global coatings and paints provider. With the backing of the Hempel Foundation, the company maintains a strong focus on both business success and making a positive impact on society, contributing to a brighter and more sustainable future.

Figure III.13 Hempel logo

HEMPEL

Source: Company website

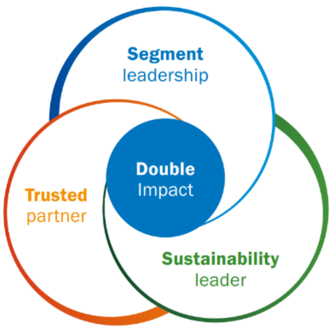
Figure III.14 The Hempel group in numbers



Source: Hempel annual report (2022)

The Hempel Group is a company with a global production and sales network. It is divided into 4 business divisions 1) Decorative paints, which generates 36% of revenues, 2) marine, 29% of revenues, 3) Energy 14% of revenues, 4) infrastructure, 21% of revenues. Although the core business of the company is to manufacture and sell paints and coatings, it's changing its strategy and it's working on the development of longer-lasting paints to reduce its carbon footprint. To balance the reduced revenues from paints, they are transition towards a more service-oriented business, where the company will leverage its knowledge and employees to offer tailor made solutions.

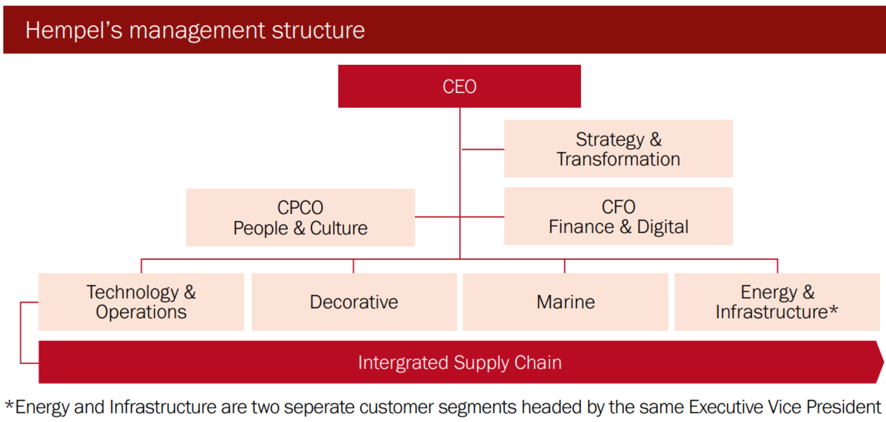
Figure III.15 Hempel priorities



Source: Hempel annual report (2022)

In 2020 Hempel set the goal to double its revenue by 2025, and they also plan to increase profitability and generated value. To do so they mapped its priorities (Figure III.15) and intend to scale operations with a harmonised global setup. In 2022, Hempel changed its organizational structure and introduced a globalised supply chain and support functions (Figure III.16). This reorganization allows the group to be customer-centric and together with continuous development they plan to achieve segment leadership in selected geographies and being considered a trusted partner by its customers. Moreover, Hempel pledged its commitment to sustainability. Focusing on the Marine customer segment, in 2022 it generated revenue of € 626 million, an increase of € 162 million, compared to 2021 (33% increase). This is the highest year-on-year increase ever for this customer segment. The increase was driven by an increasing adoption of the silicone hull coatings (3000 ships adopted the Hempaguard silicone-based coating). The product was chosen for its fuel consumption reduction and its low-environmental impact. The silicone coatings market is a low-volume business, but it presents higher margins.

Figure III.16 Reorganization of the Hempel Group



Source: Hempel annual report (2022)

Product portfolio

As previously introduced, Hempel currently offers a mix of products and services solutions to support their customers address the biofouling problem. Their digital performance monitoring solution is called Hempel SHAPE (Systems for Hull and Propeller Efficiency) and it is based on the ISO 19030 framework and it combines all the elements of efficiency optimisation. The group also offers a

Seastock solution that allows shipowners to reduce the paints stored on board and replace them with just-in-case deliveries exploiting Hempel group global networks of stock points. This allows shipowners and shipmanagers to reduce inventories costs associated with paints. For antifouling coatings Hempel has three categories, 1) Fouling defence which is a FRC with biocides. It provides a 6% fuel savings, and a idling guarantee of up to 120 days, and a claimed lifetime of up to 90 months. Moreover, Hempel is so confident of the Hempeguard coating that it offers a performance satisfaction guarantee, and it will refund the additional price compared to conventional antifouling if the client is not satisfied with the performance; 2) Antifouling coatings which use controlled release of biocides and guarantees protection from 36 up to 90 months. The products come in three different forms based on the polymers that constitute the coatings; 3) Fouling Release, the technology is based on biocide-free silicone and hydrogel, proving a smooth hull surface that leads to 5% fuel savings. The mix of products is summarized in Figure III.17.

Figure III.17 Hempel fouling control technologies

Hempel's product selector Fouling control coating matrix	Fouling defence	Antifouling			Fouling release
	Actiguard technology	Nano acrylate technology	Silyl acrylate polymers	Ion Exchange / Zinc Carboxylate	Silicone based
Low activity level	•	•	(•)	(•)	-
Flexible trading pattern	•	•	-	-	•
Instant effect on contact with water	•	•	-	(•)	•
High activity level	•	•	•	•	•
Recommended for slow steaming	•	•	(•)	(•)	-
Recommended for tropical waters	•	•	•	-	•
Microfiber-based for superior mechanical strength	-	•	•	•	-
Easy overcoating	•	•	•	•	•
Application in warm environment	•	•	•	•	•
Can be applied down to 0°C	•	•	•	•	•
Can be applied below 0°C	-	•	•	•	-
Low friction technologies	•	•	•	-	•
Full return on investment	*****	****	***½	**	****½
Guarantee (conditions apply)	Satisfaction/Fuel savings	Performance	Performance	Performance	Fuel savings
Docking interval up to 90 months	**Hempaguard**	**Globic**	**Dynamic**	-	**Hempasil X3+**
Docking interval up to 60 months	**Hempaguard**	**Globic**	**Dynamic**	**Olympic Protect+/ Olympic Flex+/ Oceanic Protect+/ Oceanic Flex+ Oceanic+/ Atlantic+**	**Hempasil X3+**
Docking interval up to 36 months	**Hempaguard**	**Globic**	**Dynamic**	**Olympic Protect/Basic/ Olympic+**	**Hempasil X3+**

Source: Hempel fouling control technologies

Balance Sheet

The results of the group for the 2020-2022 period are shown in Table III.5

(Consolidated income statement) and in Table III.6 (Consolidated statement of assets and liabilities). To achieve its goal of doubling revenues by 2025 Hempel must achieve a CAGR of 15%, in the last 2 years the group overachieved on this target because. revenue grew from € 1.5 billion to € 2,1 € billion. Similarly to the other two companies, the revenue growth didn't translate to profit growth, which increased in 2021 but later decreased in 2022, to even lower to 2020 levels. This company presents the lowest Net profit margin among the analysed company, well below the industry average, but it still managed to close all the years with a positive result. The low profits are due to the high production, sales and distribution costs.

Table III.5 Hempel consolidated income statement

**Figures in thousands Euros*

Consolidated income statement						
		2022		2021		2020
Exchange rate: DKK/EUR		0,1345		0,1346		0,1345
Revenue		2.159.000		1.744.000		1.541.000
Production costs	-	*1.375.000*	-	*1.084.000*	-	*938.000*
Gross Profit		**784.000**		**660.000**		**603.000**
Sales and distribution costs	-	*552.000*	-	*453.000*	-	*396.000*
Administrative costs	-	*121.000*	-	*121.000*	-	*109.000*
Other operating income		*4.000*		*20.000*		*2.000*
Other operating expenses	-	*1.000*		-	-	*1.000*
Operating profit		**114.000**		**106.000**		**99.000**
Net financial items	-	58.000	-	17.000	-	28.000
Profit before tax		**56.000**		**89.000**		**71.000**
Income tax expense	-	*19.000*	-	*31.000*	-	*21.000*
Net profit / (loss) for the year from discontinued operations	-	*2.000*		*5.000*		-
Profit for the year		**35.000**		**63.000**		**50.000**

Source: Amadeus

Looking at the statement of assets and liabilities, the company experienced a great expansion (+72% of total assets). In the period the company changed its structure from being more flexible into being more fixed, in fact over the years the company invested in fixed assets and conducted acquisitions. The group investments and acquisitions were financed with long-term debts. The interest rates of the loans are based mainly on EURIBOR, and also influenced by the Group's leverage and the achievement of the Group's sustainability targets. In 2023 the company expects to see mid to high revenue growth and increasing margin to due a normalization of raw materials costs and the distribution costs.

Table III.6 Hempel consolidated statement of assets and liabilities

Figures in thousands Euros

Statement of assests and liabilities			
	2022	2021	2020
Exchange rate: DKK/EUR	0,1345	0,1346	0,1345
Assets			
Fixed assets	**1.544.000**	**1.486.000**	**662.000**
- *Intangible fixed assets*	*765.000*	*766.000*	*151.000*
- *Tangible fixed assets*	*511.000*	*477.000*	*342.000*
- *Other fixed assets*	*268.000*	*243.000*	*169.000*
Current assets	**1.111.000**	**980.000**	**880.000**
- Stock	343.000	334.000	220.000
- Debtors	567.000	470.000	395.000
- Other current assets (Cash & cash equivalent)	201.000	176.000	265.000
TOTAL ASSETS	**2.655.000**	**2.466.000**	**1.542.000**
Equity & Liabilities			
Shareholders funds	**547.000**	**567.000**	**499.000**
- *Capital*	*15.000*	*15.000*	*15.000*
- *Other shareholders funds*	*532.000*	*552.000*	*484.000*
Non-current liabilities	**1.181.000**	**1.071.000**	**401.000**
- *Long term debt*	*1.030.000*	*908.000*	*264.000*
- *Other non-current liabilities*	*151.000*	*163.000*	*137.000*
Current liabilities	**927.000**	**828.000**	**642.000**
- *Loans*	*136.000*	*105.000*	*73.000*
- *Creditors*	*355.000*	*344.000*	*261.000*
- *Other current liabilities*	*436.000*	*379.000*	*308.000*
TOTAL SHAREH. FUNDS & LIAB.	**2.655.000**	**2.466.000**	**1.542.000**

Source: Amadeus

III.2 Active companies with reactive solutions

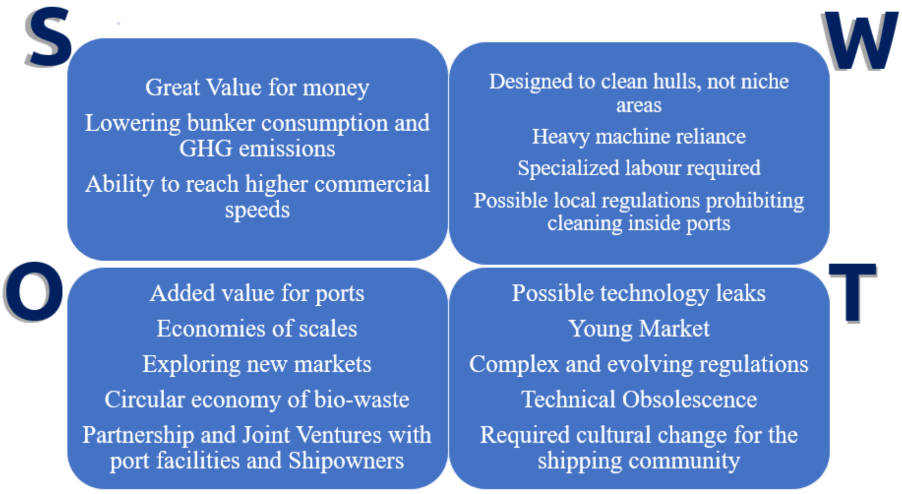
In this subsection, the two largest European companies that provide In Water Cleaning via ROV services will be examined. The company were selected according to Bertram (2022) and are the Norwegian ECOsubsea and the Dutch Fleet Cleaner.

If the coating market is concentrated with a handful of well-established corporations worth billions, the In-Water Cleaning market is totally different. Although research on ROV cleanings started in the 1980s it's only in recent years that companies started to be established and matured commercial applications. The industry is experiencing a variety of ROV designs and there's a lack of standardization, typical of young industries. However, most of the IWC solutions share similar features, such as:

- Highly specialized (Value Added Service), autonomous and semi-autonomous ROV require substantial investments in design and assembly but allows to cut down variable costs of each cleaning. The clients can claim they are using cutting-edge technology to take care of their ships and be environmentally sustainable.
- Mobile and flexible, the ROV can used to clean both vessels and fixed underwater structures such as offshore platforms or pipelines.
- Easily transferable, all the equipment can be conveniently loaded in a truck and transferred to another port. The companies usually have a network of regularly serviced ports, ad hoc services can also be arranged.
- No downtime, cleanings operations can be conducted while the vessel is in port engaged in commercial operations, or at anchorage waiting for berth or bunker.
- Fast, depending on the level of biofouling the cleaning speed can reach up to 3000 sqm/h so the service time for a medium-sized vessel is around 12h, a time that is compatible with most of the vessels' turnaround times.
- Safe and remotely operated, it does not require divers and all the ROV actions are safely controlled from shore.
- Not disruptive, it does not damage the expensive antifouling paints of the vessels.

The price of the service depends on the extension of the area that needs to be cleaned, the level of biofouling and where the cleaning takes place but is comparable or cheaper than cleaning with divers in the same area. Currently, most of the active companies operate in the Northern Europe region and other regions where there's already a biofouling management regulation or an IWC policy. To exploit the benefits of sailing with a clean hull, the service network needs to be expanded and scaled up. As we will see later, the structure of the assets of ROV companies appears to be fixed, so they sustain high fixed costs, and to reach the break-even point and profitability the need to carefully plan their schedule to ensure the maximum utilization rate of the ROV. Taken that into consideration, it appears that the best clients for this service are vessels with a high schedule reliability (cruise ships, ferries, and RO-RO). The company should then open a centre in areas that presents a high volume of the targeted segments to take advantage of the economies of scale. The legal framework on biofouling management and IWC is fragmented and diverse, so a strong knowledge and understanding of international and local regulations is essential to a correct business setup. Lastly, although the correlation between biofouling and fuel consumption is well known, it's often underestimated and shipowners should start to proactively manage biofouling on their vessel, considering all the variables described in the previous sections, In III.18 a SWOT analysis of the IWC with a ROV.

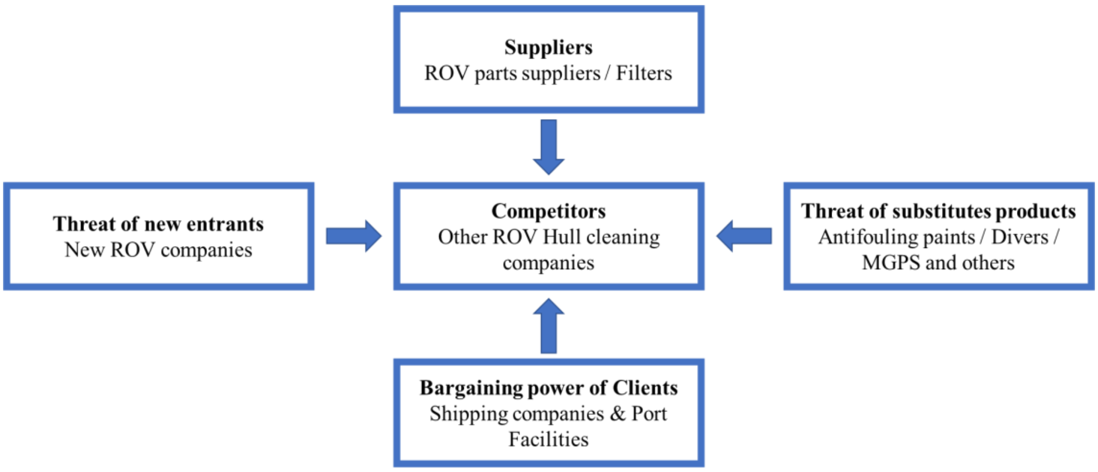
Figure III.18 SWOT analysis of IWC



Source: Author

To study the competitive environment of these companies, it might be worth it to use Porter's five forces model. ROV companies are often associated with environmentally cautious measure, such as biofouling capture, which is not possible, or not convenient to do with divers cleaning. As we saw, IWC without capture is discouraged or prohibited by most of the European ports. In the short-run ROV companies are in competition with diver cleaning companies located in Least Developed Countries (LDC) or Small Island Developing States where there are no biofouling management regulations or IWC policies. This aspect is relevant for vessels without a fixed schedule, or that perform oceanic voyages. The objective of ROV companies is to convince shipowners to utilize their service, instead of cleaning the vessels with divers and risking polluting the ocean and the local environment. Instead, on the long run, the greatest threats to ROV companies' competitive advantage come from new coating with higher antifouling capabilities and the bargaining power of clients. ROV companies can be considered at best Small and Medium Enterprises (Bertram 2022), while their clients represent multinational corporations worth billions of dollars.

Figure III.19 Porter's five forces model



Source: Author

ECOsubsea A/S

ECOsubsea was established in 2008 by the Norwegian Østervold brothers and it's considered one of the industry leaders of In-Water Cleanings with ROV. ECOsubsea focuses on the concept of sustainable ship operations by offering an innovative and efficient alternative to traditional hull cleaning methods. One of the key advantages of ECOsubsea technology is its commitment to protecting marine ecosystems. By utilizing a closed-loop system, the company ensures that no waste or debris is released into the surrounding water during the cleaning process. The removed fouling is captured via a suction pump and sent ashore where it's filtered, stored, and disposed of. With the collection of biowaste, ECOsubsea idea is to reuse the collected biofouling as biomass for energy production. The solution provided by the company has gained recognition for its effectiveness and environmental benefits. Although ECOsubsea is a Norwegian company based in Storebø, its main operational base is in Southampton. The company has already conducted more than 1000 cleanings, reduced 2,3 million CO_2 emissions, and collected numerous international prizes for sustainable solutions in shipping.

Figure III.20 ECOsubsea logo

Source: Company website

Product portfolio

The core business of the company is performing In-Water Cleanings with a patented ROV called "COLLECTOR". The ROV uses magnetic adhesion, and soft waterjet for cleaning and collecting the debris, giving "more than 97.5%" as collection rate. (NIWA report, 2012). The ROV dimensions are 3.0 m (L) x 2.0 m (W) x 0.7 m (H) and weighs 715 kg. Cleaning times depend, of course. on the size of the ships, but they are in line with industry standards. Currently, the service is offered in 19 ports according to the company's website, mainly covering North Sea and Baltic ports but cleaning operations can also be arranged on demand due to the flexibility of the solution. All the equipment needed can be loaded on a truck and transported where necessary. According to local regulations, cleaning operations can be conducted both shore-side and seaside if the equipment is loaded on a barge. In addition to its core service, ECOsubsea also offers hull inspections, primarily as a base service to allow clients to check their vessels' hulls for biofouling and if required conduct IWC. Underwater inspections are also used to visually inspect the hull for damages and estimate the capital expenditures of repairs. These inspections fall under the Underwater Inspection in Lieu of Drydocking (UWILD) framework. Moreover, ECOsubsea proposes to its clients to receive a "Biofouling passport", certifying that the vessel has been cleaned and biofouling is managed according to the IMO guidelines.

Balance Sheet

The following results (Table III.7 and Table III.8) cover the 2019-2021 period, unfortunately the results for 2022 were not available yet. ECOsubsea results have fluctuated over the period, with a decrease in revenues in 2020 due to the CoVID pandemic and a partial rebound in 2021, in accordance with Cornelis et al., (2022). The pandemic exacerbated a situation that was already difficult. In fact, the company has closed all three years with a substantial net loss, destroying shareholders value for €4,2 million. Unfortunately, without further information is difficult to make an accurate statement but in my opinion, the negative results are mainly due to the low number of sales of the company, and thus not reaching the Break-Even Point. ROV companies have generally high fixed costs, and high contribution margins, this means that business controlling, and BEP calculations are extremely important for these companies. The difficulties experienced by the company are represented also in the statement of assets and liabilities. The total assets of the company decreased from € 4,1 million in 2019, to € 3,7 million (a 10% decrease).

Table III.7 ECOsubsea income statement

Figures in thousands Euros

Income statement			
	2021	2020	2019
Exchange rate: NOK/EUR	0,10010	0,09554	0,10138
Revenue	1.354	1.061	1.551
Cost of sales	*1.230*	*1.150*	*1.328*
Gross Profit	**124**	**- 88**	**223**
Costs of employees	*578*	*401*	*541*
Depreciation & Amortization	*340*	*346*	*421*
Other operating items	*511*	*381*	*464*
Operating P/L	**- 1.304**	**- 1.216**	**- 1.202**
Net financial items	- *259*	- *116*	- *89*
P/L before tax	**- 1.564**	**- 1.332**	**- 1.292**
Income tax expense	-	-	-
P/L for the year	**- 1.564**	**- 1.332**	**- 1.292**

Source: Amadeus

As introduced before, the structure of ROV companies is rather fixed, fixed assets account for more than 80% of total assets, as the company invested heavily on their patented ROV. Regarding the funding of the company, the structure changed drastically over the years. If in 2019 it was balanced between shareholders' fundings (33%), non-current liabilities (30%) and current liabilities (37%). In 2021 the company presented a totally different structure, in fact the company presented a negative equity, notwithstanding additional fundings by the shareholders for €1,2 million due to the negative results; stable non-current liabilities while the current liabilities more than doubled in the period from € 1,5 million to almost €4 million in 2021, this also results in a negative Net Working Capital. In summary, the company is neither economically nor financially sustainable. This might explain the decision of the company to partner with the Norwegian shipping group Wilhelmsen, as it is advantageous for both companies, ECOsubsea to have financial support by a big group and for Wilhelmsen to have another advanced service to offer to its clients.

Table III.8 ECOsubsea Statement of assets and liabilities

**Figures in thousands Euros*

Statement of assests and liabilities

	2021	2020	2019
Exchange rate: NOK/EUR	0,10010	0,09554	0,10138
Assets			
Fixed assets	**2.996**	**2.971**	**3.468**
- Intangible fixed assets	*793*	*828*	*952*
- Tangible fixed assets	*2.105*	*1.857*	*2.063*
- Other fixed assets	*99*	*286*	*453*
Current assets	**654**	**468**	**594**
- Stock	-	-	-
- Debtors	*228*	*172*	*331*
- Other current assets	*426*	*296*	*263*
TOTAL ASSETS	**3.650**	**3.439**	**4.061**
Equity & Liabilities			
Shareholders funds	**- 1.630**	**- 63**	**1.347**
- Capital	*29*	*27*	*1.347*
- Other shareholders funds	*- 1.658*	*- 90*	-
Non-current liabilities	**1.311**	**1.049**	**1.204**
- Long term debt	*1.005*	*962*	*1.089*
- Other non-current liabilities	*306*	*87*	*116*
Current liabilities	**3.969**	**2.453**	**1.510**
- Loans	*1.892*	*657*	*814*
- Creditors	*336*	*182*	*110*
- Other current liabilities	*1.740*	*1.613*	*585*
TOTAL SHAREH. FUNDS & LIAB.	**3.650**	**3.439**	**4.061**

Source: Amadeus

Fleet Cleaner B.V.

The company was established in 2011 and is based in Delft, close to the port city of Rotterdam. The company is the successful outcome of a university spin-off, from a group of naval engineering students. In 2017, the company expands its service network to include all Dutch ports In 2019 the company start operations also in all major Belgian ports. Their primary service involves the use of autonomous robots equipped with advanced cleaning technologies to remove marine fouling and other contaminants from ship hulls. Exploiting The Netherlands and Belgium extensive network of inland waterways, Fleet Cleaner's solution is designed to be deployed from seaside. Currently the services are available in all the major ports of the ARAG area[6], other ports can be serviced but transportation needs to be arranged. Fleet Cleaner core values are 1) Efficiency, both inside the company in streamlining processes and promoting standardisation and automations, and outside to increase the energy efficiency of the ships serviced; 2) Quality, the company aims to set new standards in hull cleaning, by continuous improvements; 3) Environment, cleaning the ships from biofouling reduces fuel consumption and IAS spread; 4) Safety, by replacing divers with ROVs ships can be cleaned inside ports without putting people's lives at risk.

Figure III.21 Fleet Cleaner

Source: Company website

6 The Amsterdam, Rotterdam Antwerp, Gent (ARAG) area is one of the busiest maritime areas in Europe.

Product portfolio

Similarly to ECOsubsea, Fleet Cleaner offers both IWC and underwater inspections, but the ROV is transferred with a barge and deployed seaside. The ROV uses magnetic adhesion and cleans with high-pressure water jets. The ROV is relatively compact (2.0 m (L) x 1.8 m (W) x 0.6 m (H)). Cleaning a ship takes typically 10 h with the latest technology, and biofouling is collected properly disposed at shore (Bertram 2022). The company is able to offer complete hull cleaning of both flat, and curved surfaces with the ROV, and niche areas cleaning and propellers polishing in collaboration with certified diving companies. At the end of the operations and extensive cleaning report is produced for the clients. The company can deliver the service to any type of vessel, but its main segments are container vessels, bulk carriers and ATEX[7] certified Tankers because they are the most popular types of vessels in the area.

Balance sheet

Unfortunately, no information on the income statement was found for the company. However, just looking at the assets and liabilities I think one can get an idea of how an ROV company is structured. The company experienced a great expansion during the period and almost quadrupled the total assets, this is due to the expansion to include Belgian Ports in their network. The fixed assets represent the majority of total assets (around 80%), and current assets consist of only accounts receivables and liquidity, and no stock as it’s a service company. Without having information of the Profit/Loss account we can’t make accurate statements, but opposite to ECOsubsea, the liabilities structure is more rational, and positive. The fixed assets are covered with equity and non-current liabilities and, the company managed to reach a positive net working capital in the last year.

[7] The ATmosphere EXplosive (ATEX) directives are two EU directives concerned with safety of workers exposed to explosive atmospheres (ATEX 1999/92/CE) and potentially explosive products (ATEX 94/9CE).

Table III.9 Fleet Cleaner statement of assets and liabilities

*Figures in thousands Euros

Statement of assests and liabilities	2021	2020	2019
Assets			
Fixed assets	**6.569**	**6.215**	**2.331**
- Intangible fixed assets	*379*	*470*	*232*
- Tangible fixed assets	*6.190*	*5.745*	*2.099*
- Other fixed assets	-	-	-
Current assets	**1.494**	**1.872**	**333**
- Stock	-	-	-
- Debtors	*810*	*556*	*323*
- Other current assets (Cash & cash equivalent)	*684*	*1.316*	*10*
TOTAL ASSETS	**8.063**	**8.087**	**2.664**
Equity & Liabilities			
Shareholders funds	**659**	**690**	**559**
- Capital	*18*	*18*	*18*
- Other shareholders funds	*641*	*672*	*541*
Non-current liabilities	**6.208**	**4.216**	**1.244**
- Long term debt	*6.208*	*4.216*	*1.244*
- Other non-current liabilities	-	-	-
Current liabilities	**1.196**	**3.181**	**861**
- Loans	1.196	3.181	861
- Creditors	-	-	-
- Other current liabilities	-	-	-
TOTAL SHAREH. FUNDS & LIAB.	**8.063**	**8.087**	**2.664**

Source: Amadeus

IV. Conclusions

As so far introduced, the biofouling problem appears to be a complex problem that requires a comprehensive approach to find one or multiple solutions, which of course, must be sustainable in the three dimensions of sustainability (economic, social and environmental). Sustainability challenges have three characteristics that make them particularly difficult to overcome: complexity, uncertainty, and evaluative nature (Ferraro et al,. 2015). Sustainability challenges are complex, because they are the results of the interaction of many actors (the "problem of many hands") interconnected among them, and no single actor can be identified as the root cause. The interconnectivity can lead to unintended negative consequences, or impact shifting. Uncertainty, today's world is ever so uncertain and rapidly changing, that short-term solutions are often preferred to longer-term solutions, but to create social and environmental value a long-term orientation is needed. Lastly, sustainability challenges are evaluative in nature, there are actors with opposing views on which are the most pressing problems, who can say that environmental concerns are more important than social or economic problems. It's easy to understand how the solutions to the biofouling problem can be found only considering the points of all the stakeholders of the shipping industry, from shipowners to port facilities, shippers, governmental organizations, and academia. (ibid.).

In a way, that is what the GloFouling Partnership was set up to achieve. The GloFouling Partherniship is a Multi-Stakeholder Initiative (MSI[8]), an alliance to tackle the biofouling problem, it has a five-year duration (2019-2023). The partnership is a global project funded by the Global Environment Facility (GEF)[9], the United Nations Development Programme (UNDP)[10] and the International Maritime Organization (IMO) that addresses biofouling as a pathway of Alien Invasive Species. The

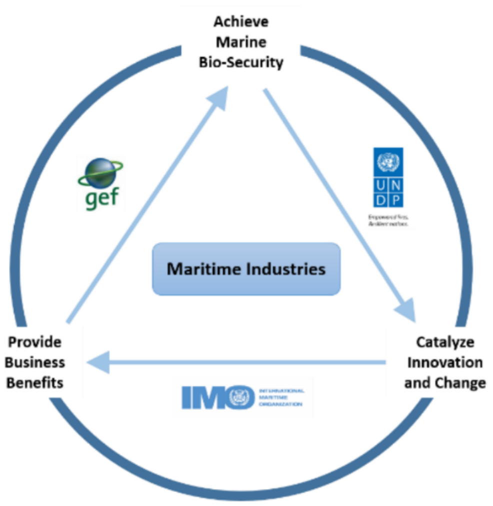
8 Multi-stakeholder initiatives (MSIs) are defined as private governance mechanisms involving multiple corporations of the value chain, civil society organizations, and sometimes other actors such as governmental organizations, academia or unions. Their scope is to address a problem in a comprehensive manner and ensure that all the voices are listened.

9 The Global Environment Facility (GEF) is a multilateral environmental fund that provides grants and blended finance for environmental cautious and sustainability projects.

10 The United Nations Development Programme (UNDP) is the United Nations' lead agency on international development. We support countries and communities as they work to eradicate poverty, implement the Paris Agreement on climate change and achieve the Sustainable Development Goals. https://www.undp.org/

Partnership will drive action to implement the 2011 Biofouling Guidelines, help develop global best practices and tools, and enable an environment for technology development and transfer, including the creation of a Global Industry Alliance (GIA) for Marine Biosafety (GEF-UNDP-IMO, 2019). The Glofouling Partnership will address biofouling related to shipping, recreational boating, aquaculture, pipelines and other offshore activities.

Figure IV.1 Glofouling Partnership



Source: GIA concept paper

The GIA is established under the GloFouling Partnership as an alliance of industry leaders for biofouling management. Members of the alliance are expected to collaborate to identify and solve common barriers and collectively promote the development and implementation of new technologies and best practices. The suggested priority areas for the GIA to work on are:

- In-Water cleaning and grooming technologies: promote the development of standardized methods to assess the performance of IWC technologies.
- Operational improvement: develop or review biofouling risk assessment systems based on the operational profile of ships.
- New and alternative coating solutions: integration between industry and academia to develop new coatings, or develop Decision support systems
- Ship design: study new ship designs that reduce biofouling (e.g. fewer niche

areas or increase their accessibility).

- Recreational boating: awareness-raising events in local marinas and demonstrating best practices for managing biofouling.
- Aquaculture: incentivise new net design to reduce biofouling or ease cleanings.
- Human element: training programmes for employees based.
- Global environmental benefits, industry collaboration, research and awareness-raising: identify issues and opportunities for partnerships, capacity building and technology transfer.

As the five-year period is coming to an end, the results of some of these actions are already concluded, while others are underway. Among the most notable results, there are two international conferences, awareness-raising events and a list of publications on different topics of biofouling management such as: 1) Guides for Governments, 2) Technical reports, 3) Conference proceedings. Financial support for the activities of the GIA is provided by the GIA Trust Fund administered by the IMO, and it is financed through the annual membership fees of the committed GIA members listed in Table IV.1. Most of the members of the alliance were already encountered through the previous section. Currently, the Alliance is mostly represented by IWC companies with ROVs and coating manufacturers, which is desirable to promote innovation of IWC technologies or develop new antifouling coatings. However, a critical actor is misrepresented, which is the shipowner. In fact, shipowners are the clients of both companies and those who primarily have to deal with the biofouling problem and will have to pay most of its associated costs. The results of the initiative are spreading existing knowledge and hopefully expanding the scholarship on biofouling management however, it could be argued that to have a successful MSI initiative, all the voices and concerns must be heard. With a under representation of shipowners, it’s possible that their concerns are not listened to.

Table IV.1 Global Industry Alliance for Marine Biodiversity members

AkzoNobel Fouling control systems manufacturer	Armach Robotics In-water cleaning	CleanSubSea In-water cleaning and BioPass
ECOsubsea In-water cleaning	Hapag-Lloyd Shipping	Hempel Hull Performance Solutions
HullWiper In-water cleaning	JOTUN Anti-fouling coatings manufacturer	JSTRA Technology Research
KCC Anti-fouling coatings manufacturer	Lloyd's Register Classification Society	SLM Global In-water cleaning
Sonihull Anti-fouling system	Tas Global In-water cleaning and Filtration System	IOGP* The International Association of Oil & Gas Producers

** Member with observer status*

Source: https://www.glofouling.imo.org/gia

Knowing that to effectively and efficiently manage biofouling, companies should take a comprehensive approach to the problem. We introduced the efforts done at an international and macro-level, so one could ask how they should manage it on an organizational level. Throughout the previous sections we encountered multiple solutions offered to shipowners and it should appear clear by now that there is not a one size fits all solution, but rather different antifouling systems suit different vessels and activities. The decisions of biofouling management don’t stop at the antifouling coating. but include also the drydocking schedule and evaluate if IWC is necessary during the period. These decisions will affect the efficiency of the vessels for years, and lead to great costs if they turn out to be not satisfactory. When the variety of solutions is so high and clients are spoilt for choice, the selection process takes time, and costs. Coating manufacturers currently offer their advisory services, and they are very knowledgeable about their products, but they are not independent, nor they are able to effectively compare products from different brands. So, one could wonder if we are approaching the birth of a new function for shipping companies and ship managers, that of the “biofouling expert”. This new figure would have to be a polymath and be knowledgeable or at least have a basic understanding of naval engineering, marine biology, and economics. It should know the major players in both the coating and IWC industries and be able to select the best biofouling management strategy for each specific ship of the fleet, rather than a common strategy. Considering the complexity of these requirements, the figure would be assisted in its work by industry best practices, decision support models (e.g. MCDAM) and vessel’s performance monitoring systems. Best practices are a good place to start as they will cut down costs of time, suggesting established biofouling management strategies for different types of vessels and activities. For example, a recent study conducted in the Baltic Sea tried to map the best practices for biofouling management for different activity levels in the area, the results are shown in Figure IV.2. The results proposed strategies are appropriate for the Baltic Sea, where the fouling pressure is moderate, in different areas with higher fouling pressure the strategies would be different. Again, this is a good place to start, but it’s definitely not the end. Possible upgrades could be to specify a particular coating and be more specific on the cleaning schedule.

Figure IV.2 Biofouling management strategies in the Baltic Sea

Region	Ship activity level	Coating recommendation	Cleaning strategy
Western and Southern Baltic Sea	High	-Biocide-free SPC for high activity level -Non-toxic hard coating in combination with cleaning -FRC except operation in wintertime	Proactive grooming in the biofilm stage
Western and Southern Baltic Sea	Moderate	-Biocide-free SPC for moderate activity level -Non-toxic hard coating in combination with cleaning	Proactive grooming in the biofilm stage
Western and Southern Baltic Sea	Low	-Biocide-free SPC for low activity level -FRC in combination with cleaning (not for operation in wintertime)	Regular cleaning on FRC
Kattegat to Central Baltic Sea	High	-Biocide-free SPC for high activity level -Non-toxic hard coating in combination with cleaning -FRC except operation in wintertime	Proactive grooming in the biofilm stage
Kattegat to Central Baltic Sea	Moderate	-Biocide-free SPC for moderate activity level -Non-toxic hard coating in combination with cleaning -FRC in combination with cleaning (not for operation in wintertime)	Grooming, weekly grooming in the fouling season
Kattegat to Central Baltic Sea	Low	-Biocide-free SPC for low activity level -Non-toxic hard coating in combination with cleaning -FRC in combination with cleaning (not for operation in wintertime)	Grooming, weekly grooming in the fouling season
Eastern and Northern part of the Baltic Sea	High, moderate and low	-Non-toxic hard coating in combination with cleaning -FRC except operation in wintertime	grooming, weekly grooming in the fouling season

Source: Guide on best practices of biofouling management in the Baltic Sea, Interreg COMPLETE project (2021)

Performance monitoring systems are a powerful tool for biofouling management. They collect and transmit real-time data on speed, fuel consumption, winds and current to calculate increased drag, performance and efficiency of the vessel. These systems are based on ISO standard 19030 “Measurement of changes in hull and propeller performance”. Performance monitoring systems can be developed in-house or bought from providers. Performance systems would be able to detect if the drag increased due to biofouling and signal it to the supervisor. The company can then take responsive action and decide if IWC is necessary.

Lastly, MCDAM would support decision-makers to select a comprehensive, case-specific and multi-dimensional sustainable biofouling management strategy (Luoma et al., 2022). The model allows the biofouling expert to compare different management strategies (coating and IWC) and assess them from an economic and environmental perspective in parallel and select the best one based on how the model is constructed.

With the ambitious new regulations that are set to decarbonise shipping, energy efficiency is of paramount importance, not only to meet regulations but also as costs cutting method. As commented by Greg Miller of Freightwaves in an interview, where he expanded on the difference between the newbuilds wave of 2008-2010 and the after-pandemic wave. In the first one, shipowners tried to lower unit costs via economies of scale by ordering bigger ships. In the second wave instead, the objective of lowering unit costs is done by improving the energy efficiency of ships. As explained, one of the best ways to increase the energy efficiency of the ship is to proactively manage biofouling on the hull and on the propellers. According to the 4th IMO GHG study (2020), all the technologies associated with biofouling management presented a negative marginal abatement cost (MAC), which means that the implementation of these technologies will reduce emissions and costs, or to put in other words, biofouling management makes environmental and economic sense. So, while the industry awaits for developments of new engine technologies, and alternative fuels, it should concentrate on the low-hanging fruits to rapidly reduce emissions, increase efficiency and saves money.

In conclusion, whether the figure of the “biofouling expert” will actually become a reality or the responsibility of the technical department will simply increase is unknown, as well as whether these functions will be kept “in-house” or outsourced. However, it’s safe to say that biofouling management will certainly become more and more relevant.

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