An investigation on the latest technology of marine vehicles underwater coating and its efficiency as anti-fouling paints

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Abstract

The report presents the progress of research related to antifouling coating and its efficiency in ships. The process of biofouling is a huge challenge for marine vehicles, and over the years numerous technologies and substances have been developed to prevent biofouling, improve ship performance while reducing operating costs and to minimize the influences of antifouling paints to the marine region. Towards understanding the effect of antifouling coatings on ship hulls, the interim report in the project highlights the background for the research along with the management of accumulation of macro fouling from the context of industry and academia along with literature review in brief. The research idea, the significance of the work, along with the aims and objectives of the project, are developed and presented. The programme and methodology discuss the approach followed for the research along with the inputs and expected outcomes. The potential impact of this research on the shipping industry is conceived and highlighted. Lastly, the resources needed for conducting the project, project activities and schedules, and the outline of the main report structure is provided.

Keywords: Biofouling, antifouling coatings, protection, marine environment, comparison, antifouling paints

Nomenclature

- A_{BT} : Bulb Transverse section area
- A_T : Traverse area of immersed part of the Transom stern
- B : Breadth of ship
- C_b : Block Coefficient
- C_m : Mid-ship coefficient
- C_{wp} : Waterplane coefficient
- C_f : Coefficient of frictional resistance
- C_a : Coefficient of correlation
- C_{aa}: Coefficient of Air resistance
- C_{ad}: Air drag coefficient
- C_w: Wave resistance
- C_p : Prismatic coefficient
- D : Depth of Ship
- D_V : Volumetric Displacement
- F_n : Froude number
- g : Acceleration due to gravity
- h_b : Vertical distance from the baseline to the centre of bow bulb cross-sectional area
- i_E : Angle of half entrance
- $(1 + k_1)$: Form factor
- IMO: International Maritime Organization
- ITTC: International Towing Tank Conference
- LWL: Length of waterline
- L_R: Length of Run
- lcb: Longitudinal centre of buoyancy
- P_E: Effective Power
- R: Reynold's number
- S: Wetted surface area
- v: Viscosity of water
- V: Vessel forward ship
- T_F: Forward Draft
- ρ: Density

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1. Introduction

Ships and marine vehicles, platforms such as rigs, etc. that are constantly in contact with salt water, temperature fluctuations and biological attacks experience the process of marine biofouling over time. Marine biofouling refers to the accumulation of living organisms on the surface of immersed machines and especially ship hulls immersed in water are vulnerable to marine biofouling. The process of biofouling is complex because the biofouling process is influenced by temperature variations and changes in the marine environment. The factors related to the environment are water salinity and temperature, nutrients in aqueous environments, the velocity or flow of water during motion, depth, pH and light. The physical components that play a role in biofouling are the attributes found in the surface, namely harshness, micro- texture, wettability, colours and contours. Therefore, biofouling results due to complex interactions between the immersed surface material, dissolved compounds, fluid-flow parameters and micro-organisms. Fouling is an organic process and occurs due to the accumulation of algae, plants and other microorganisms found on wetted surfaces. In ships, biofouling refers to the collection of organisms that are either macro or micro such as algae or plants or animals on ship hulls and this accumulation on ship hulls is a significant problem that must be addressed. The problem of biofouling can also damage the hull structure and propulsion systems in ships (Zabin et al., 2018). Marine biofouling is identified as a major challenge to marine ecosystems by the International Maritime Organization (IMO). According to IMO, the problem of biofouling must be addressed on priority from both the ecological and economic perspective. Biofouling endangers the ecology of the oceans by the transfer of invading species or animals found in oceans. These invasive species impact the hydrodynamic performance of ships and lead to increased fuel costs along with more amounts of greenhouse gas (GHG) emissions. To protect the hull and other structures from biofouling, protective organic coatings are used widely in the shipping industry. The protective coatings are also known as antifouling paints and coatings on ships provide a range of functions that includes resistance to corrosion, easy to maintain, appearance, in addition to the preclusion of fouling on the hull by marine creatures. The usage of antifouling coating on hulls of ships is used for many decades. IMO has also provided guidelines for biofouling management plans and suggested that such organic coatings must be used on all types of ships. The management plans indicate that choosing an appropriate antifouling system provides certain key decisions in ships in terms of ship speed, orientation, the ship operating profile, dry-docking periods and legal compliance (IMO, 2011).

Antifouling coatings on ship hulls have the potential to minimize the fouling process. Also, antifouling coatings provide benefits such as less fuel consumption as the resistance of the ship during its operation. A variety of technologies are available in the industry for antifouling coatings.

The more recent such coating technology is the silicon-based anti-fouling system (Pradhan, Kumar, Mohanty, & Nayak, 2019). The use of the silicone-based antifouling system has the potential to augment the speed and performance of the ship and at the same time prevents biofouling and is considered eco- friendly in marine environments. Further silicon-based antifouling systems do not release biocides into the sea and have advantages such as protecting the hull from fouling effects (Atlar et al. 2018).

In this project, the latest technology of underwater coating is investigated in marine vehicles for its efficiency to prevent biofouling. To investigate the antifouling efficiency comparison of two different antifouling coating systems is chosen. The noon data for two ships that have the same working profile is selected. Each ship is applied with one type of antifouling system. The effect of fouling is investigated for the two ship hulls. Also, the effect of fouling in terms of ship resistance during its operation and other factors such as fuel consumption, performance, and speed are estimated for both the coatings and compared to determine the effectiveness of the two chosen antifouling systems. Over the years, numerous developments in the area of antifouling systems for ships are available. The study will provide a comparative analysis of two recent antifouling systems in terms of their performance and cost factors.

The report is structured as into the introduction section, which provides the overall challenge of fouling and the research project in brief. The section on Academia/industry context discusses the project in the context of academia and industry. The sequence of events that led to the development of anti-fouling coatings is highlighted. The chapter on Related work provides the literature review on the topic. The reviews are made from secondary research sources and references to industry sources are provided. The reviews discuss the viewpoints and research outcomes from similar studies and experiments done by researchers in this area of anti-fouling coatings in ships. The chapter on Program and Methodology explains the methods followed in this research report. The resources required are provided along with the envisaged impact of the project. Lastly, the progress done till date is mentioned to note the completed milestones so far.

2. Academia/ industry context

In the context of academia and industry, antifouling paints have a long history for protection from the marine environment. The process of biofouling is grouped into different stages of growth namely the initial accumulation of absorbed organic material, settlement and growth of bacteria towards the creation of a biofilm matrix which in turn subsequently results as macro and macro foulers on ship hulls (Chaudhari, 2017). However, the mortality of species is unpredictable because higher fouling organisms exploit the ecological niche. The formation of biofilm is the initial stage of subsequent fouling and subsequently biofouling which is tested experimentally by the removal of algal layers in restricting fouling. The existence of biofilm on ship hull is recorded as this biofilm influences the settlement of algal zoospores or inhibits the settlement of barnacles (Antunes, Leão, & Vasconcelos, 2019). Studies related to bio-corrosion and biofilm influence to corrode metals are available. Due to these reasons, it is essential to create control biofouling as they ultimately result in a corrosive environment and result in decomposed products (Su et al. 2018).

The growth of biofouling in saline aqueous environs cannot be eliminated. Therefore, applications to prevent fouling on marine systems are researched and developed. In the case of ships, ship hulls constitute up to 24% of fouling (Railkin, 2004). Ship hulls make use of a variety of materials such as aluminium, steel and glass-reinforced polymer composites. Since ships move between different marine environments, they are in constant contact with the most productive regions. Antifouling coatings are used to protect the hull from fouling, but antifouling coatings do not protect the hull from the accumulation of inorganic salts, the exopolymeric release of substances and calcium carbonate substances found in skeletal matter contribute to fouling organisms. Besides, the accumulation of marine organisms in the hull surface negatively affects the hydrodynamics (Hunsucker, Hunsucker, Gardner, & Swain, 2017). Due to this process, when the hull is navigating through water, it experiences a frictional force due to drag and hull surface. Biofouling will affect skin-friction drag due to the average roughness of the hull and shear stress in the wall. The use of antifouling paint varnishes like self-polishing copolymer (SPC) and foul release coatings (FRC) on the layer of hydrodynamic boundary increases the friction velocity (Yeginbayeva, Granhag, & Chernoray, 2019). Some studies show the adverse influences of biofilm coarseness on drag.

In earlier times, the use of toxic substances in antifouling coatings on ship hull was used to control biofouling. However, the release of biocides, namely, mercury or lead or arsenic along with harmful derivatives, are banned as they pose big and long-term risks to the marine environment. Further research in this area led to the development of a self-polishing copolymer technique. In this technique, antifoulant tributyltin (TBT) was used along with toxic material to dissuade marine organisms. The use of such organotins is banned globally as they pose extinction or deformities of certain creatures dependent on the sea. This damage led to the legislation on the global ban of tributyltin culminating in the ban of TBT (Filipkowska, Złoch, Wawrzyniak-Wydrowska, & Kowalewska, 2016). Other alternatives of antifouling applications include thermoplastic, non-convertible surface organic coatings that have a property to remain dry due to evaporation and are available as volatile organic compound (VOC) control. However, these applications have limitations in antifouling effects. The development of newer antifouling systems are environmentally acceptable and are on the increase during the last decade.

In the current context, ship operators prefer environmentally compliant anti-fouling coatings. Some of the recent developments in this area of anti-fouling coatings include the advanced nano-structured surface for control of biofouling under the AMBIO project focuses on the need for further research on applying nano-sciences to resolve the challenge of aquatic biofouling. The results from this research yielded reduced drag behaviour; however, did not fulfil the effective measures to control biofouling without harming the environment (Callow, 2010). Further Targeted Advanced Research for Global Efficiency of Transportation Shipping (TARGETS) is another research project to improve energy efficiency in shipping. This is based on a dynamic energy model where energy consumed on board was analyzed. The procedure followed on this project was to improve the roughness function database for typical clean antifouling for foul releasing and SPC type coat base on test data. The improved database was used to modify the hull skin friction and the friction of propellers in the blade section that were coated by FR coat (Papanikolaou et al., 2019). Towards the development of synergetic fouling control technologies, the SEAFRONT project aims to reduce environmental impact, enhanced biofouling prevention and efficiency gain. The project made use of three fouling control technologies, namely surface-structure based, surface-chemistry based and bio-active combinations for reducing drag (CORDIS, 2017).

In addition to the emerging developments in antifouling coatings towards protecting the environment, the role of industry in the area of biofouling scenarios is viewed in terms of vessel performance, levels of fouling and bio-security risks. At the same time, there are differences found between maritime shipping and environmental stakeholders on biofouling requirements and policies. There are ongoing initiatives to resolve issues through collaboration to promote antifouling technologies to narrow the gap between industry, academia and biosecurity. Over the year the development of different coatings using antifouling elements, have significantly reduced the number of organisms transferred by ships (Davidson et al., 2016). It is noted that environmentally friendly coatings have the potential to reduce pollution, minimize impact on marine life and improve operating efficiency. For example, the Ecospeed electronic fuel management system (EFMS) provides optimum vessel seed in maximum fuel efficiency (Hellenic, 2019). There ae studies to indicate that anti-fouling and fouling resistance coatings are applied on different surfaces of the same ship to reduce biofouling accumulation in certain hotspots in the hull (Dobroski et al., 2015). It is noted that one of the main challenges facing shipping industry is air pollution and GHG (green house gas) emissions. This challenge is closely linked with biofouling management as reducing fouling on ships leads to reduced fuel consumption, thus reduced emissions (IMO, 2015). Biofouling is an inherent challenge in shipping industry, however the alignment of industry and environmental stakeholders can help maintain marine ecology and improve industry performance metrics while reducing risks to marine environment.

Challenges Addressed.

The following challenges are addressed in this research project:

- Provide a comparison of two ship noon data for ships having same profile, but are coated with different anti-fouling paint
- To examine the effects of different biofouling on the performance of ships
- To analyze and conclude the effective anti-fouling paint for its behaviour in deterring fouling on ship hull

Related past and current work

Since the beginning of shipping transport, ship hulls were vulnerable to fouling. Earlier, the use of toxic anti-fouling coatings was used to control fouling to result in the discharge of lead, arsenic and mercury and other harmful derivatives into the oceans that posed big risks to marine life and to its environment. TBT was developed as a self-polishing coating to deter marine organisms and fouling. However, during the years, TBT was banned for its environmental impact. The use of antifouling paint coatings such as self-polishing copolymer (SPC) and foul release coatings (FRC) on the layer of hydrodynamic boundary increases the friction velocity (Yeginbayeva et al., 2019). Some studies show the negative effects of biofilm roughness on drag.

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Literature review: papers, industry practice or designs

Zhang et al. (2017) state that silicon-centred components are susceptible to biofouling. Numerous application areas have led to implementing antifouling approaches for materials based on silicon. The authors summarize two main approaches that involve the functions of silicon and silicon-centred components, along with particles that support antifouling. The materials based on silicon are fabricated with nano or micro-structures in the study. The authors show their approach provided a significant reduction in biofouling. Their findings were justified by reviews that studied fouling prevention because of the presence of bacteria, marine beings and proteins found in silicon-based materials.

Hunsucker et al. (2017) explain that to evaluate the performance of marine coatings before they are used on ship hulls, static immersion tests are used. These tests provide useful data as they do not provide the coatings to hydrodynamic and fouling conditions present when the ship is in operation. Therefore, it is difficult to extrapolate the results to ship hull performance. To verify their claims, the authors present data related to two commercial ships with hull coatings. One ship with antifouling coating and one ship with fouling release coating were analyzed. Both the ships were exposed concurrently to static and dynamic ocean conditions for 4 months. The evaluations show that coatings when exposed to static conditions developed macrofouling which had tubeworms, tunicates and encrusting bryozoans. The coatings that were subject to dynamic conditions showed fouling due to green macroalgae and biofilms. The ships showed different coating performance based on the immersed environment (static vs dynamic) and coating type. The authors highlight the necessity for utilizing dynamic tests concurrently with static immersion coating evaluation to have a better understanding of how the system will respond to hydrodynamic stresses. Further, this study concludes by examining how the performance of a coating is affected in real-world conditions which can support hull management and also determine which coating will be appropriate for the ship's operation.

Khanna et al. (2017) provided the study to evaluate superfine nanocomposites anti-fouling (AF) coatings for ship hulls'. The authors explain that due to efforts on alternative approaches to developing antifouling coatings for ship hulls, the concept of creating a highly smoothed surface on which seaweeds and barnacles cannot attach themselves is explained. The other concept explains the development of superhydrophobic (SH) coating. This coating can behave similarly to the surface of a lotus leaf. These methods involve the use of polymers based on fluoro and the inclusion of nanoparticles to them. The essentials of AF paints are its resistance to corrosion and erosion and strong adherence. This coating was prepared using epoxy as a base resin and modified through a series of steps such as low-surface energy additives. The other step included the use of hydrophobic-silica nanoparticles to develop SH coatings to obtain outward coarseness value in the category of 300-800 mm, which will mimic a lotus leaf surface. The coatings were tested for different characteristics, namely morphology, surface composition, contact angle and surface roughness. The authors carried our actual tests by exposing the panel in seawater to note AF characteristics. The results showed that the SH coating was intact and unsoiled after an extended duration of immersion at lesser depths beneath sea waterline. This is because the development of ultra-smooth coating resulted in better performance at higher depths and flowing water.

In literature, different methods are available that explain the process of mitigating biofouling. The most important or critical requirement is to protect ships from biofouling through antifouling coatings. Towards realizing this need, two different antifouling coating systems are available. They are self-polishing copolymers (SPC) and controlled depletion polymers (CDP), mainstream paints and foul release (FR) coatings. Though these coats will work through various mechanisms, they are categorized into biocidal and non-biocidal coatings. Biocidal technologies involve material having SPC, CDP and other accepted coating paints that discharge ions of copper and booster biocides to mitigate fouling. Also, SPC, CDP and essential paint varnishes are competent in preventing invertebrate organisms. Further SPC coatings possess greater preservation span (around half-a-decade) in comparison to CDP (around 3 years) and conventional paints (around 12-18 months). Further, the foul release coatings do not release toxic substances and hence are environmentally-friendly (Uzun, Demiel, Coraddu, & Turan, 2019).

In one study, ship hull fouling estimates were done from shipboard measurements, models and resistance components. The study by Foteinos et al. (2017) present a method or estimating hull conditions regarding fouling. Here the focus is on the increase in power demand over a period. The study used onboard data, performance reports and noon reports of four Panamax bulk carriers that were identical sister ships from one shipping company. In the study, the engine power onboard vessels were calculated using a torque meter. The torque measures are considered to have different reliability. However, the accuracy of the study was required. Thus, an engine simulation software was tuned for each engine to calculate the propeller shaft torque calculations were provided with recorded engine data. The effect of fouling was determined by deducting the wave added resistance, air resistance and calm water resistance from the total resistance of the ship. The resistances were calculated using the methods of STAwave-2, Fujiwara regression and empirical methods. The resistance to fouling was estimated by increasing the propeller law coefficient and fouling resistance coefficient during the period of dry dock. The fouling indicators from this study show that propeller law coefficient is less scatter compared to the fouling resistance coefficient based on a detailed thermodynamic model to predict engine torque.

Safaei et al. (2019) explain the importance of fuel-saving to make effective decisions when cost efficiency and environmentally friendly aspects are a priority. In ships, the fuel consumption rate is a variable and is affected by different parameters. The parameters include displacement of the ship, the daily average speed of sailing, cargo, bunker, sea conditions, and so on. The authors make use of noon report (NR), automatic identification system (AIS) of four very large crude containers (VLCC) to determine a prediction model. The accuracy of the statistical model is dependent on consistency and quality of data, and hence a combination of data involving ship speed, fuel consumption and sea state are applied to NR and AIS. This application is made to obtain a series of pure and valid data. The consistency of data is improved by eliminating outranged or unwanted data using t-test, normality control and outlier score base. Finally, considering the fuel consumption influential parameters, multiple linear regression was applied. The results of this study indicate a high correlation between dependent and independent variables. Further, the developed prediction model was able to predict fuel consumption of all the vessels, at different conditions. The results from the prediction model were found to be in agreement with recorded fuel data.

The importance of periodic hull cleaning is highly emphasized for ship performance and fuel efficiency. According to Adland et al., (2018), hull cleaning of oil tankers led to energy efficiency and performance. This study was done using real 2012-2016 data and weather data extracted from noon reports in a fleet of 8 Aframax size crude oil tankers. After the vessel was cleaned, changes in fuel consumption were noticed and estimated for both, before and after cleaning differences were noted and estimated. From this study, the results based on differences before and after cleaning indicate that periodic cleaning of the hull will result in a significant reduction of fuel consumption. Further, the dry-docking leads to higher and significant reductions in fuel usage compared to underwater hull cleaning. Lastly, it was noted that the energy efficiency effect is higher when the vessel is on sail in laden rather than in ballast conditions. The findings were considered as significant in optimizing maintenance of ships and based on noon data.

Marceaux et al. (2018) provided the study on the effect of accelerated ageing determinants on the mechanisms of chemically operative antifouling varnishes. To envisage the extended-duration antifouling coating usefulness, the research was conducted to advance an ageing exam; this test can determine extensive duration antifouling activity with the procedure that is a type of normal ageing process. Self-polishing copolymer (SPC) and Controlled Depletion polymer (CDP) have been chosen for their distinctive mechanism of activity. To investigate both types of coatings, five static simulated circumstances were involved in the whole process to note the influence on ageing to two coatings. The two main parameters, which are erosion of coating and the formation of depleted layer surface of dual varnishes, were examined in accelerated and in situ exams. The outcomes indicate that the static simulated circumstances were revealed to impact the lingering antifouling efficacy in a different manner. The study provides a connection amid in vitro and in situ ageing of dual veneers.

Janssen (2017) explains that the potential impact on the environment is due to numerous issues such as accidental oil or chemical spills, greenhouse gases, water pollution, etc. In the case of marine environments, biofouling and ballast tank corrosion are major environmental threats. It is vital to remember that the marine biofouling process involves over 4000 different species, and the process are divided into micro and macro fouling. Micro fouling is due to biofilm, which subsequently results in macro fouling. As on date, the principle behind the use of paint structures monetarily available is centred on the gradual discharge of noxious compounds into their surrounding marine environment. These substances affect other organisms in the marine environment. For instance, the use of TBT (now banned) has shown prompt gender alterations in the snails and even affects whale beachings. Other alternatives after TBT are antifouling paints that are made using copper-based biocidal pigment, or zinc oxide, which is less potent. These combinations are improved by adding a single or more supporter biocide, namely Igarol 1051, Duiuron and Seanine 211. In the given scenario, the researcher evaluates the risk to the marine environment due to antifouling coatings; the evaluation has been done by comparing the measured and projected ecological absorptions with nontoxic and allowable concentration for the marine bionetwork. The comparisons are deliberated and demonstrated by evaluating the comparative perils of older and fresher antifouling paints. The article also presents a brief overview of antifouling technologies that are environmentally friendly, that do not use toxic substances and based on improved biological principles in relation to biofouling are provided.

There are different approaches to handle biofouling. The most recent advances in biofouling resilient thin-film amalgamated crusts are available for different applications (Misdan, Ismail, & Hilal, 2016). It is noticed that due to biofilm growth in hulls, it can become hard to remove them even in high shear flow conditions. The long term accumulation of marine biofouling will significantly increase the weight of the ship, thus impacting its performance, operations and fuel costs. At the same time, the issue of environmental impact due to antifouling coatings must be considered to avoid harm to marine ecology. Towards overcoming these issues and to have environment-friendly antifouling veneers the usage of superhydrophobic coatings to release fouling is adopted in ship hulls (Ferrari, Benedetti & Santini, 2015). The use of various coating materials such as polymers, a water-soluble polymer and organic compounds, namely polyethene glycol (PEG) and so on. Also, multiple strategies for antifouling coatings are available in the literature that highlights the benefits and drawbacks.

3. Research idea, Aim and Objectives

Project idea

The prominent aim of this research is to compare two recent antifouling coating systems to understand its operational profile in terms of corrosion, environmental acceptability, cost and affordability, compatible with the underlying system, the life of the coating and its resistance to biodegradation, and erosion. The evaluation of the selected antifouling system will analyze the chosen coating material on factors such as toxicity, cost, chemical properties or chemically stable, and its persistence to the environment. To evaluate the durability and service life demands of antifouling coatings, ageing tests are available (Marceaux, Martin, Margaillan & Bressy, 2018). Therefore, the idea behind the project is to understand marine antifouling systems based on different parameters related to engineered antifouling coatings, on ship hulls in the marine environment.

Importance/ Timeliness of Project

The protection of ship hulls from biofouling is a significant aspect as the accumulation of micro and macro fouling increases fuel consumption, extensive requirements for operating capabilities and GHG emissions. The frictional resistance of the ship is made up of two parts, namely the frictional resistance and residual resistance. Frictional resistance implies the roughness of the surface and residual resistance is the result of waves created by the ship when it is sailing. Besides, biofouling on ships significantly upsurges the coarseness of the hull surface and results in damage to the hull along with an increase in frictional resistance. To overcome these negative effects, advances in chemistry and materials, science has developed various solutions and a range of antifouling coating paints. Antifouling paints can be further divided into two groups; namely, biocide maintained self-polishing copolymers (SPC) and foul release (FR) antifouling coatings.

It is important to note that the selection of antifouling coating for the ship is a difficult task. This is because antifouling paints for a ship will relate to different parameters, namely the performance of the antifouling coat, operational profile of the ship, route of the ship, and so on. This implies, one antifouling coating can be viewed as better than another system as each antifouling paint involves costs related to its life cycle and its environmental impact. Hence, for the given ship profile, an evaluation of which antifouling system to choose is carefully assessed and decided. Some of the points to consider in selecting the antifouling coating include,

- Costs of the antifouling coating based on ship profile
- Fuel savings and energy consumption
- Emission of GHG

- Effect on the marine environs
- The durability of the paint
- Benefits of coating in terms of frequency of hull cleaning and painting

The evaluation of the antifouling capability of the chosen paint is through the analysis and settlement of substance and an analysis of its components. This implies the substances and components include seaweeds, barnacles and other macrofouling and their removal based on the percentage covered in the hull surface area. However, the main challenge is the discrepancies with coating substances and the approaches utilized to evaluate newer mixtures and their characteristics related to surface coating. Therefore, based on the above discussions, there is an essential requirement to assess antifouling coating technology for its effectiveness in reducing biofouling.

Aims and Objectives

Aim: The project will focus on the analysis of a ship's noon data to determine the efficiency of the antifouling paint. Two identical ship profiles are selected. Each ship profile is coated with different antifouling paint. The efficiency is determined by estimating the actual cost of the fouling paint life cycle. The effectiveness of the antifouling paint is compared based on different parameters to understand its performance.

Objectives:

- To study the effects of various Bio-fouls on the performance of marine vehicles.
- To study various anti-fouling paints and their behaviour for the release of fouling.
- To select two different types of antifouling paints that are commonly used
- Selecting two ships with similar working profile and region, but uses a different antifouling paint
- Determine the effects of fouling on both ships through an individual set of equations
- Estimate the resistance of the ship to macro-fouling using inputs such as fuel consumption, etc.
- Compare the ship-noon data of various marine vehicles and comparing the outcomes with two anti-fouling paints on ship speed
- Analyze and discuss the results

Programme and Methodology

The methodology followed in the project will analyze ship noon data of two ships that have an identical profile. The performance analysis of the ship is done to understand the required propulsion power and monitor the hull resistance to fouling. The performance of the ship will help to understand the factors that affect fuel consumption. For example, resistance to sped and increase in fuel consumption can be affected by weather conditions, increase in draft and displacement or when the hull is worsened, and the propeller is experiencing roughness. With an increase in fuel consumption, CO_2 emission is also a concern. During sea trials, the ship's power vs speed calculations are estimated. Power is easily measured because it is a constant stricture in comparison to fuel ingestion. To compute the speed and fuel consumption with accuracy, reliable estimates of fuel are required, and hence two sister ships are used.

The method followed will develop a set of equations to estimate the effect of fouling on the two sister ships for the antifouling coating used on them. The inputs are ship speed and change in fuel consumption during operation. The ship resistance will be determined due to fouling and how this will affect the fuel consumption rate. The other parameters or factors such as weather conditions contribute towards drag and water currents during operation. At the same time, mechanical factors such as loss in efficiency due to mechanical problems and wear are not considered in ship resistance.

The importance of estimating the effect of macrofouling on ship fuel consumption for different coatings on two similar sister ships is to have a comparison on ship speed vs power (fuel consumption) to appreciate the type of antifouling coating that can realize less fuel cost in the similar operating environments. This comparison will support the shipowner/ operator on choosing the right antifouling coating for the ship to finally decrease the operating cost of the ship. The method for comparing ship speed versus fuel consumption required to achieve the required power is as follows.

In the course of the sea trials' deliveries, the ship power versus speed curve is generated. Here, the parameter control is steadier in comparison to fuel ingestion. The increase or decrease in fuel consumption is affected by (Nicolas Bialystocki & Dimitris Konovessis, 2016) the parameters:

- Worsened conditions such as weather, or hull and propeller roughness
- There is an increase in draft and displacement.

Both the ships are similar in terms of length, breadth, height, working mechanism etc. and travelling along the same route. The two similar sister ships use different antifouling paints for each ship.

Resistance due to fouling paint 1 =

$$Total\ Resistance\ due\ to\ Fouling\ 1 = Total\ Resistance\ - Total\ calm\ water\ resistance$$

Resistance due to fouling paint 2 =

$$Total\ Resistance\ due\ to\ Fouling\ 2 = Total\ Resistance - Total\ calm\ water\ resistance$$

(Alternatively, If the Resistance on the hull(R(hull)) due to the specific paints at different time intervals is calculated, the calculation of resistance on the hull will be overly simplified.)

The calculation of resistance in both cases is made based on the following:

- We need the average speed of both ships at around 20 different times, Deadweight Tonnage (DWT) measured at the same time of measuring the shipping speed, percentage of the total power required to move the ship forward.
- In addition to these, we need to calculate the Resistance at each recorded time for both ships as resistance will be varying depending upon the wind resistance, draft resistance and resistance due to steering.

Though, there are multiple ways to measure the impact of anti-fouling paints on ship's speed (Sonak, Giriyan, & Pangam, 2010) above approach is used to achieve the desired outcomes. However, the above procedure may be modified or changed based on the available data).

After this step, the data-points as below for 20 different time intervals for both ship with different anti-fouling paint is obtained. The data points are:

1. Resistance
2. Average Speed
3. DWT
4. Percentage of total power generated power used to move the ship.
5. Average Power generated by each engine

These data points are fit in a Linear Regression model to calculate the shipping speed with equal DWT, an equal percentage of total power generated used to move the ship and similar average power. A comparison between the anti-fouling paints and their impact on the ship will be done after applying the Linear Regression algorithm.

To achieve the proposed results in methodology, the activities planned are:

- Research on biofouling, and its impact on ships and to the environment
- The parameters needed to estimate the effects of antifouling coating
- The selection of two sister ships with the same operating profile
- Two antifouling paints, one each for each ship
- To estimate the resistance of antifouling paints on each ship's hull
- To compare the resistance between two ships in terms of speed versus fuel consumption

- To estimate the set of five data points, for 20 different time intervals
- To apply the linear regression algorithm to compare the two antifouling paints and their impact on the ship.

Resources required

The following resources are required in the project:

The computer system, Pentium i4 core, 500 GB HDD, 8 GB RAM, 100 Mbps NIC with standard I/O.

Software: Windows 10 64-bit OS, Excel, and related software, tools

Impact of the project

The project will compare the effectiveness of two different antifouling coatings on two ships, each having a different paint coating. The main objective is to study the effects of two biofouling preventive coating on the performance of marine vehicles. The project is expected to [provide the following outcomes with potential benefits for industry,

- Cost-effectiveness or reduced operating and fuel costs for the shipping company. Cost is a major factor in ship operations. Since costs are bound to increase due to biofouling, the use of appropriate antifouling coatings on the hull will likely reduce costs significantly.
- From comparing two antifouling coatings, an understanding of effectively preventing the formation of diverse categories of fouling: micro fouling and macro fouling is obtained. Due to increased fouling, there is a likely increase in fuel consumption.
- Improvements in maintenance and ship smoothness. Antifouling coatings will avoid hull roughness and heighten the vessel's hydrodynamic shape, which has a straight-forward impact on fuel ingestion.
- From the point of view of the shipping company, the lifetime antifouling system must be implemented for the ship's life cycle, or at least this can extend its lifetime.
- Regulatory compliance: Compliance to international standards as mandated by IMO. Reduced impact on marine ecology and its environment.
- Maintenance of the ship is reduced, and the ship is easy to maintain, thus reducing costs.

4. Data Analysis

Ship description

In order to test the hypothesis, experimental ship data was obtained for LNG carriers, namely CONV A and CONV B, which are two moss-type spherical tanks having a total capacity of 147,000m³. The two vessels have a gross tonnage of 123,000, and a net tonnage of 36,900, The ships have a length of 277m, breadth of 49m, depth of 26.8m, and a draught of 11.5m.

These vessels generate power of 23,600 kW, and a speed of 19.5 knotts. The coating on CONV A is Jotun Seaquantum X200, while that on CONV B is IP 1100. Seaquantum X200 is intended to be used for low-speed vessels. The coating is based on the latest development in hydrolysing silyl methacrylate copolymers. This copolymer dissolves in seawater at a rate permitting the continuous exposure of fresh antifouling and minimizing the build-up of leached layers (Jotun, 2020). IP 1100 is a micro fouling-focused fluoropolymer based slime release technology specifically designed to tackle the impact of slime. The coating is the same for both the ships before and after the drydock period.

Similarly, QMAX A and QMAX B, have a total capacity of 164,000m³. The two vessels have a gross tonnage of 123,000, and a net tonnage of 36,900, The ships have a length of 332m, breadth of 54m, depth of 27m, and a draught of 12.2m. QMAX A has an IS 700 coating before the drydock, while there is a IP 1100 coating after the dry dock. QMAX B has an IP1100 coating for both periods.

Table 1 below describes the dimensions of the four ships and calculated the required coefficients such as the block coefficient, midship coefficient, waterplane coefficient, prismatic coefficient and air drag coefficients.

Table 1 Dimensions and coefficients of the ships under analysis

Vessel Name		**CONV A**	**CONV B**	**QMAX A**	**QMAX B**
Principal Dimensions					
Length Between Perpendiculars (LBP)	LBP	270	283	332	332
Length on Waterline (LWL)	L	275	289	339	339
Breadth	B	43	46	54	54
Depth	D	26	26	27	27
Longitudinal Center of Buoyancy fwd of Midship	lcb	2.7000	2.8300	3.3200	3.3200
Floating Status					
Mean Draft at Midship	T	12	11.25	12	12
Trim (trim by aft +ve, by fwd -ve)	Trim	0	0	0	0
Coefficients					
Block Coefficient	Cb	0.7900	0.7900	0.7974	0.7959
Midship Section Coefficient	CM	0.98	0.98	0.98	0.98
Waterplane Coefficient	CW	0.75	0.75	0.75	0.75
Prismatic Coefficient	Cp	0.81	0.81	0.81	0.81
Air Drag Coefficient	Cad	0.80	0.80	0.80	0.80

Calculation of Resistance

Coefficient of total Resistance

The calm water resistance for the above-mentioned ships is analysed in calm water using the two-dimensional method established at the International Towing Tank Conference in the year 1978 (ITTC-78), which divides the total resistance C_{ts} into frictional resistance $C_{\mathbf{f}}$ and the residual resistance $C_{r.}$ Thus the total resistance C_{ts} is given by:

$$C_{ts} = (1 + k)C_{\mathbf{f}} + C_A + C_{\mathrm{W}} + C_{AA} \qquad (1)$$

Where k is the form factor which is determined from the resistance test.

Coefficient of frictional resistance

The frictional resistance $C_{\mathbf{f}}$ is measured as the resistance of a flat plate with the same wetted surface area as that under the wave-free condition. As given in the International Towing Tank Conference in 1957 (ITTC-1957)

$$C_{\mathbf{f}} = \frac{0.0)^*}{(R_n) - /\}^2} \qquad (2)$$

Where R_n is the Reynolds number for the given ship.

Correlation Allowance (C_A)

The correlation allowance is determined from the comparison of the model and trials on full scale. As recommended in the 19th ITTC the correlation allowance can be determined as following:

$$C_A = (5.68 - 0.6 log R_e) \times 10^{-4} \quad (3)$$

Coefficient of air resistance

In order to calculate the air resistance, the following equation is used:

$$C_{AA} = C_{ad} \left(\frac{\rho_{a\$r} * A_{bt}}{\rho_{(ater} S} \right) \quad (4)$$

Where,

C_{ad} = Air drag coefficient (Ideal value, 0.80)

$\rho_{a:r}$ = Density of air (1.23 Kg/m^3)

$\rho_{;ater}$ = Density of water (1025 Kg/m^3)

A_{bt} = Bulb transverse section area

S = Wetted surface area

Coefficient of wave resistance

The propagation of waves following a ship is associated with the gravitational field. Due to the viscosity present in water, a ship experiences resistances, due to stresses acting tangentially on the ship's body, as well as, due to the boundary layer growth and separation, that may yield resistance that may be resulting by stresses that normally integrate over its body. The impact of resistance is largely dependent on the wave profile, which may, in turn, be dependent on various factors. The calculation of wave resistance is tricky, and several assumptions have been taken. The calculation is done using the following equation:

$$C_{;} = C_{TM} - C_{FM}(1 + k) \quad (5)$$

where, the form factor k and the coefficient of total resistance are determined using the ITTC 7.5-02-02-01.

Effective Power

According to the ITTC-78 proceedings the effective power can be calculated as following:

$$P_E = C_{TS}.\frac{A}{/}\rho_s V^4 S.10^{-4} \quad (6)$$

While the quasi propulsive efficiency can be calculated as:

$$_D\eta = \frac{P_E}{N_P.P_{DS}} \quad (7)$$

The value of quasi-propulsive efficiency lies between 0.55-0.66. In this study, a value of 0.60 has been considered to determine the effective power from actual power.

4.4 Resistance due to fouling

Finally, the resistance due to fouling was calculated by subtracting the total calm water resistance from the total resistance as described below:

$$Resistance\ due\ to\ Fouling = Total\ Resistance - Total\ calm\ water\ Resistance$$

The values obtained are described in the table below:

Total Calm Water Resistance						
	Notation	***Conv A***	***Conv B***	***Qmax A***	***Qmax B***	***Units***
Coefficient of frictional resistance	**Cf**	103.18	108.65	142.99	142.87	MT
Form factor	**k1**	0.1223	0.1275	0.1524	0.1521	
Coefficient of wave resistance	**Cw**	2.03	1.44	0.78	0.78	MT
Correlation Resistance Coefficient	**Ca**	20.43	20.62	22.95	22.93	MT
Air Resistance Coefficient	**Caa**	0.0000009	0.0000008	0.0000006	0.0000006	MT
Total Calm Water Resistance, RC		**125.77**	**130.84**	**166.88**	**166.74**	**MT**
Effective Power, PE = RC x V x g (in kW)						
Effective Power	**PE**	12374.57	12873.91	16419.73	16405.78	kW
Total Resistance						
	2018					
Period		***Conv A***	***Conv B***	***Qmax A***	***Qmax B***	***Units***
Before dry docking		1468.05	2286.35	3121.79	2723.12	MT
After dry-docking		1542.42	1839.98	2513.95	1966.76	MT
Change		**5.07%**	**-19.52%**	**-19.47%**	**-27.78%**	MT
	2019					
Full-year		1761.30	1966.76	2796.51	2503.27	MT
Resistance due to fouling						
Period		***Conv A***	***Conv B***	***Qmax A***	***Qmax B***	***Units***
Before dry docking		1342.29	2155.51	2954.92	2556.38	MT
After dry-docking		1416.66	1709.14	2347.08	1800.03	MT
Change		**5.54%**	**-20.71%**	**-20.57%**	**-29.59%**	MT
	2019					
Full-year		1635.54	1835.92	2629.63	2336.53	MT

Table 2 Results summary

The following chapter will deal with the results and their meaning in detail.

5. RESULTS & DISCUSSION

Resistance Calculation Pre & Post Dry Docking of the Vessel CONV A

The two similar sister vessels, namely CONV A and CONV B, covered up the voyage in different routes in different periods of time. Hence, the observation of change in the amount of resistance due to the increase in the rate of bio-fouling is observed separately. The vessel CONV A underwent voyage with average distance coverage of 302 Nautical Mile / Day with an average speed of 7.40 Nautical Mile/ Hr whereas, covered a total distance of 19960 Nautical Miles in 66 days. The consideration of above averages is calculated from the data sources available, and with the consideration of other environmental factors taken into account, as discussed in previous chapters. Hence, the observations of change in resistance as per the voyage data available shows the significant decrease in the resistance of the vessel. The decrease in resistance during the voyage isn't expected from the vessel with a highly fouled hull and which is approaching the dry docking. The change in resistance can be seen in the graph demonstrated below:

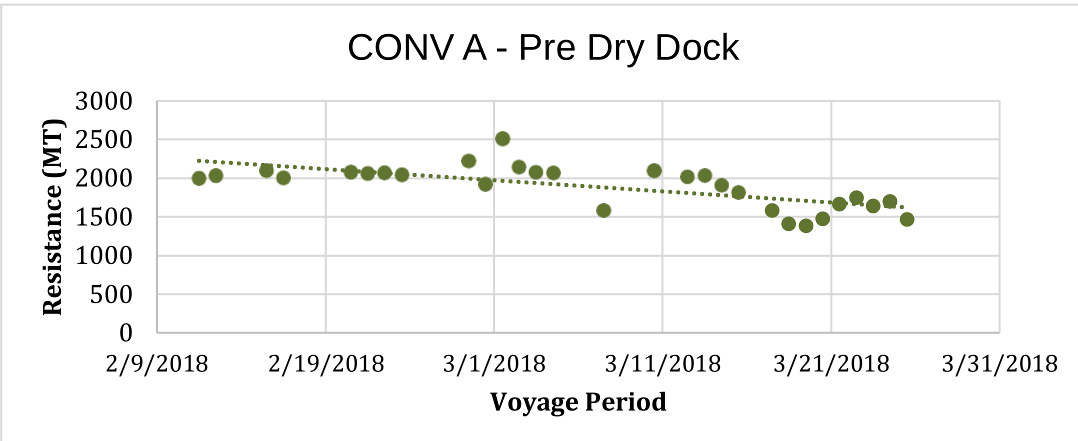

Figure 1 CONV A, fully fouled hull (pre-dry-dock), Hull resistance calculation

For this study and the comparative analysis of full fouled hull and the voyage data, considered for the hull resistance calculation is considered 66 days before the dry dock period. Hence, the calculation of hull resistance, which depends on the speed and the distance covered during the voyage will also play a significant role in analyzing the effect during the period. The decrease in the resistance observed in the vessel CONV A is due to fewer voyages when the vessel is approaching towards the dry-docking period.

When the fully fouled hull is cleared in the dry dock, the clearance of heavily fouled hull and the further application of anti-fouling paint **“Jotun Seaquantum X200”** which eventually resisted the further growth of bio foul on the surface, hence shown the no further increase in resistance during the post dry dock voyage period. The graph demonstrated the change in resistance of the vessel due to biofouling is demonstrated in the graph below:

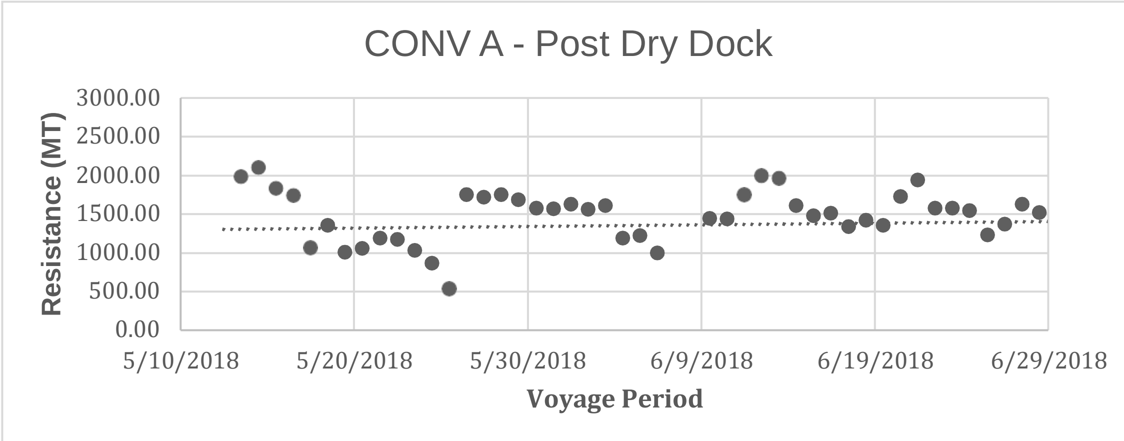

Figure 2 Conv A, fully fouled hull (Post dry dock), hull resistance calculation

Further, to analyze the efficiency of the vessel hull's anti-fouling paints in resisting the further growth of biofouling observed during the voyage of the year 2019. The anti-fouling paint **"Jotun Seaquantum X200"** significantly decreases the growth of biofouling which shows the great vessel voyage performance, decrease in vessel fuel consumption due to the decrease in resistance growth. The additional drag which affects the resistance of the vessel during the voyage is due to the drag on the wet surface area caused by the air-water interaction drag on the vessel hull, wave resistance and the current drag which is the environmental constraints which cannot be quantified because these factors change drastically with respect to time. Hence, the graph below shows the change in resistance due to the growth of biofouling in the next year voyage of the vessel.

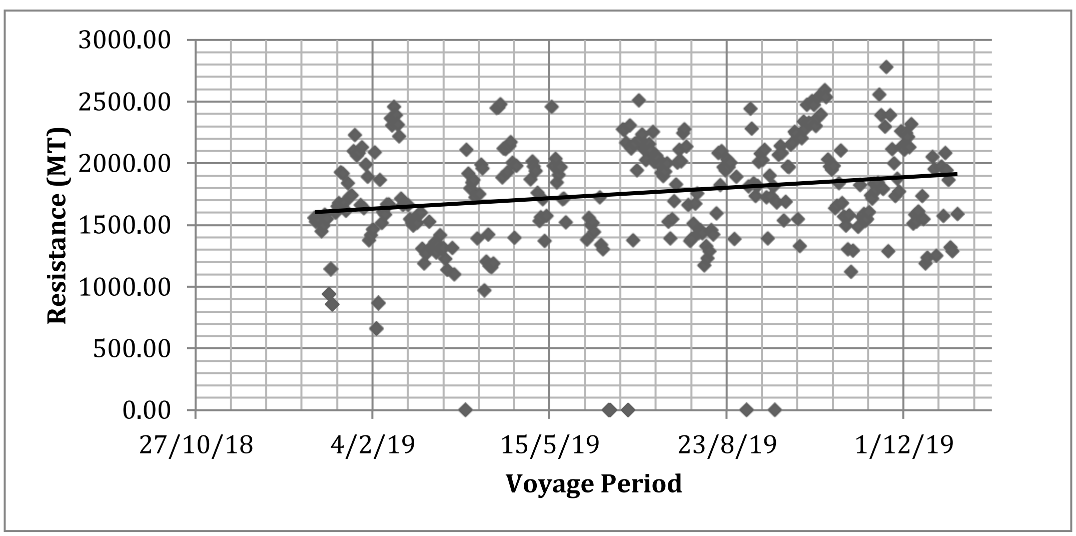

Figure 3 Conv A, Increase in hull fouling, hull resistance calculation (2019)

Resistance Calculation Pre & Post Dry Docking of the Vessel CONV B

The vessel CONV B underwent voyage with average distance coverage of 405 Nautical Mile / Day with an average speed of 9.30 Nautical Mile/ Hr, whereas it covered a total of 27174 Nautical Mile in 67 days. The consideration of above averages is calculated from the data sources available, and with the consideration of other environmental factors taken into account, as discussed in previous chapters. Hence, the observations of change in resistance as per the voyage data available shows the significant increase in the resistance of the vessel. The increase in resistance during the voyage is expected from the vessel with a highly fouled hull and which is approaching the dry docking. The change in resistance can be seen in the graph demonstrated below:

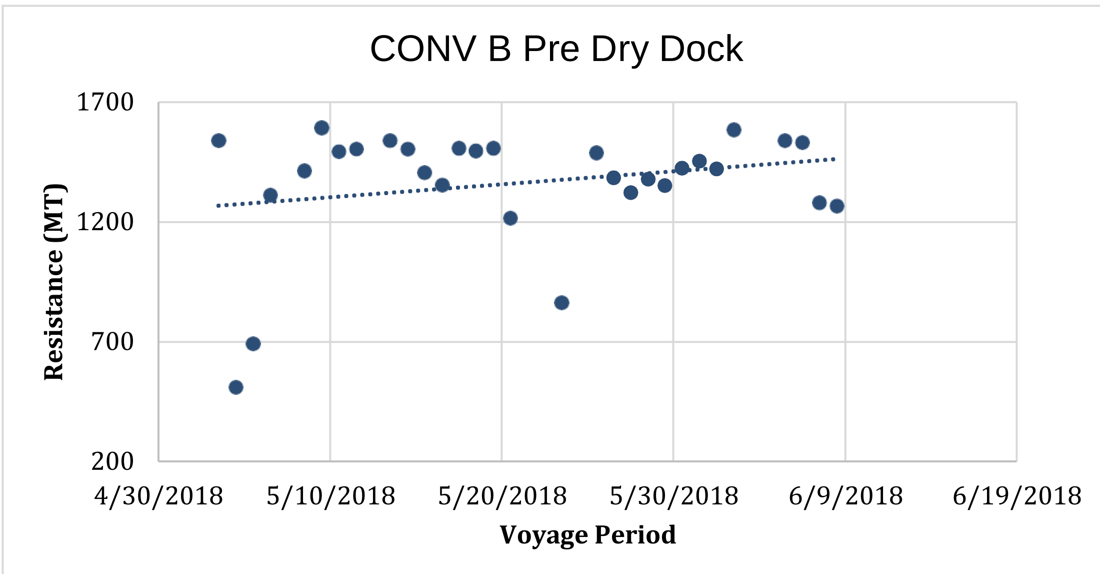

Figure 4 Conv B, fully fouled hull (Pre dry dock), hull resistance calculation.

For this study and the comparative analysis of full fouled hull and the voyage data, considered for the hull resistance calculation is considered 67 days before the dry dock period. Hence, the calculation of hull resistance, which depends on the speed and the distance covered during the voyage will also play a significant role in analyzing the effect during the period. The increase in the resistance observed in the vessel CONV B is due to heavily fouled hull vessel voyages approaching towards the dry-docking period.

When the fully fouled hull is cleared in the dry dock, the clearance of heavily fouled hull and the further application of anti-fouling paint **"IP 1000"** which eventually resisted the further growth of bio foul on the surface, hence shown the no further increase in resistance during the post dry dock voyage period. The graph demonstrated the change in resistance of the vessel due to biofouling is demonstrated in the graph below:

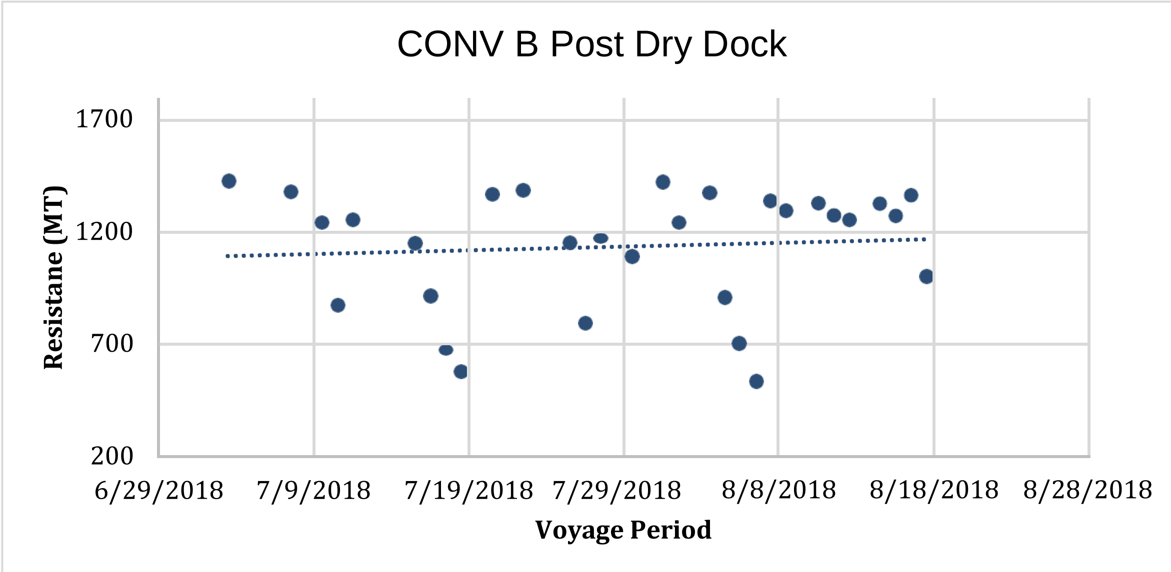

Figure 5 CONV B, Fully fouled hull (Post Dry Dock), Hull Resistance Calculation.

Further, to analyze the efficiency of the vessel hull's anti-fouling paints in resisting the further growth of biofouling observed during the voyage of the year 2019. The anti-fouling paint **"IP 1000"** significantly decreases the growth of bio fouling which shows the great vessel voyage performance, decrease in vessel fuel consumption due to the decrease in resistance growth. The additional drag which affects the resistance of the vessel during the voyage is due to the drag on the wet surface area caused by the air-water interaction drag on the vessel hull, wave resistance and the current drag which is the environmental constraints which cannot be quantified because these factors change drastically with respect to time. Hence, the graph below shows the change in resistance due to the growth of biofouling in the next year voyage of the vessel.

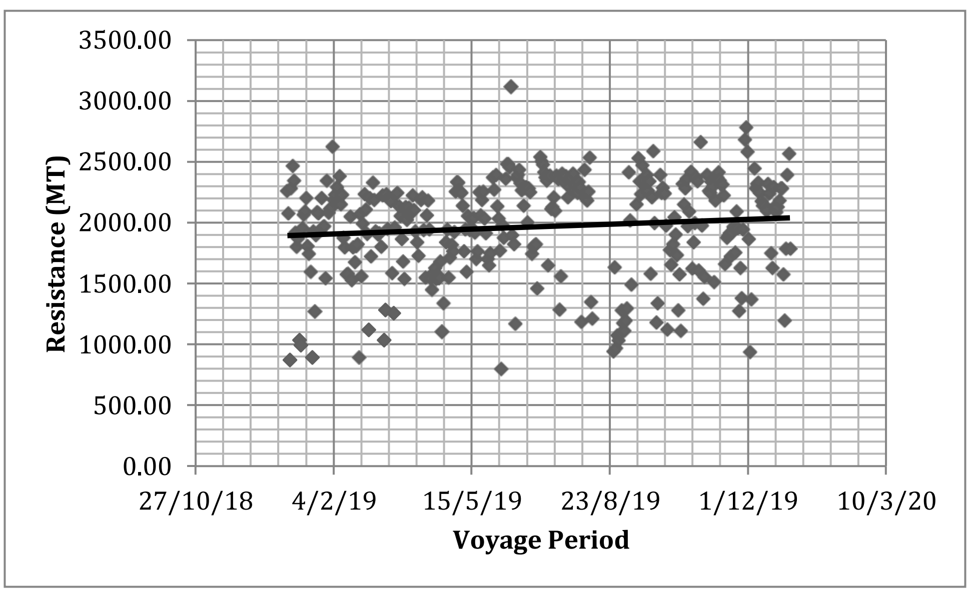

Figure 6 CONV B, Increase in Hull Fouling, Hull Resistance Calculation (2019)

Resistance Calculation Pre & Post Dry Docking of the Vessel QMAX A

The two similar sister vessels, namely QMAX A and QMAX B, covered up the voyage in different routes in different periods of time. Hence, the observation of change in the amount of resistance due to the increase in the rate of bio-fouling is observed separately. The vessel QMAX A underwent a voyage with average distance coverage of 370 Nautical Mile / Day with an average speed of 8.50 Nautical Mile/ Hr whereas, covered a total distance of 41818 Nautical Miles in 113 days. The consideration of above averages is calculated from the data sources available, and with the consideration of other environmental factors taken into account, as discussed in previous chapters. Hence, the observations of change in resistance as per the voyage data available shows the significant decrease in the resistance of the vessel. The decrease in resistance during the voyage isn't expected from the vessel with a highly fouled hull and which is approaching the dry docking. The change in resistance can be seen in the graph demonstrated below:

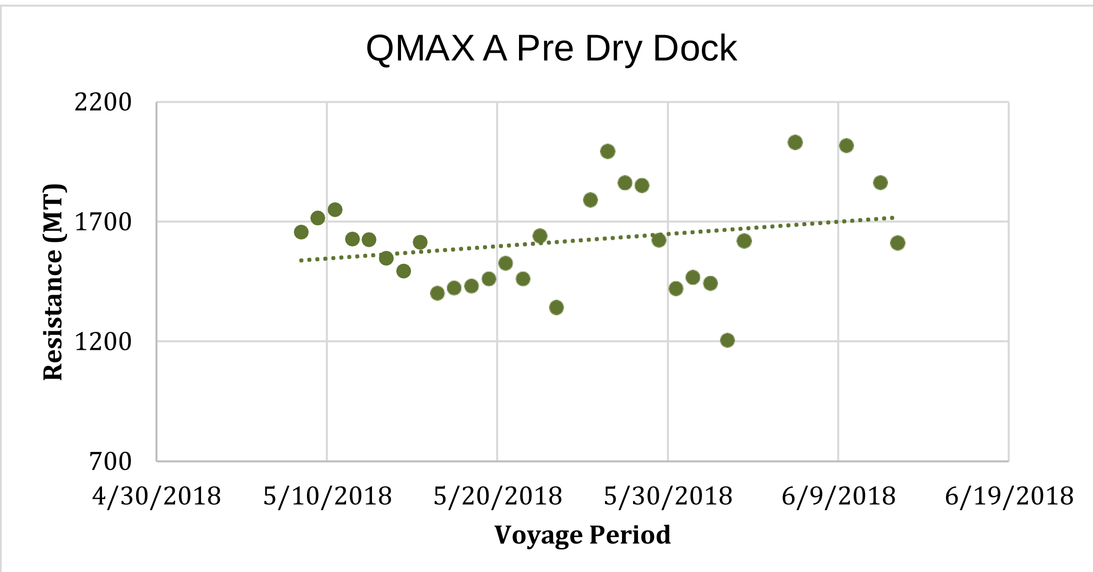

Figure 7 QMAX A, Fully fouled hull (Pre Dry Dock), Hull Resistance Calculation.

For this study and the comparative analysis of full fouled hull and the voyage data, considered for the hull resistance calculation is considered 113 days before the dry dock period. Hence, the calculation of hull resistance, which depends on the speed and the distance covered during the voyage will also play a significant role in analyzing the effect during the period. The decrease in the resistance observed in the vessel CONV A is due to fewer voyages when the vessel is approaching towards the dry-docking period.

When the fully fouled hull is cleared in the dry dock, the clearance of heavily fouled hull and the further application of anti-fouling paint **"IS 700"** which eventually resisted the further growth of bio foul on the surface, hence shown the no further increase in resistance during the post dry dock voyage period. The graph demonstrated the change in resistance of the vessel due to biofoulingg is demonstrated in the graph below:

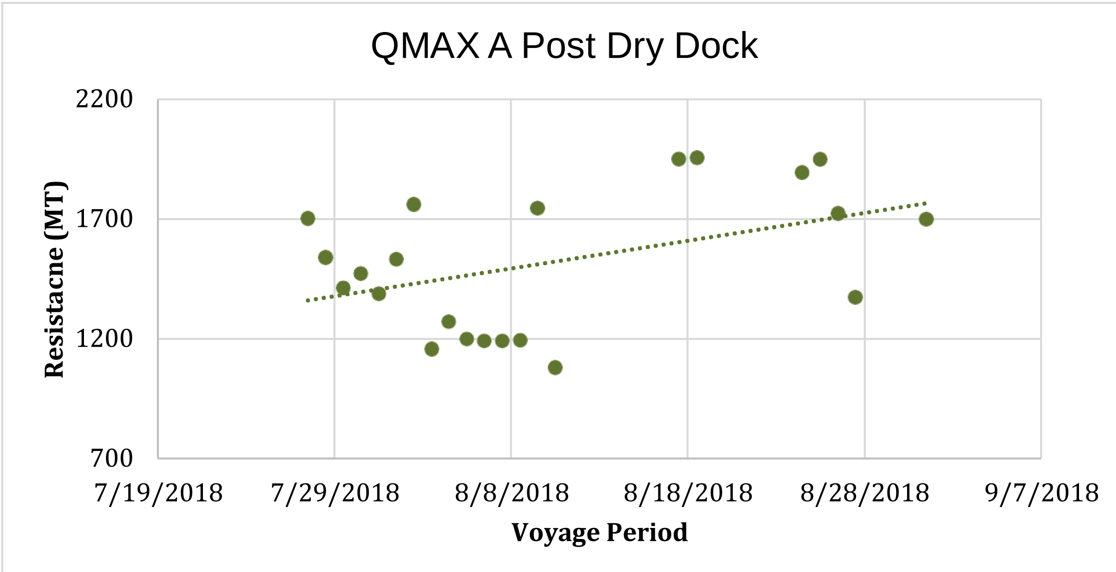

Figure 8 QMAX A, Fully fouled hull (Post Dry Dock), Hull Resistance Calculation

Further, to analyze the efficiency of the vessel hull's anti fouling paints in resisting the further growth of bio fouling observed during the voyage of the year 2019. The anti – fouling paint **"IS 700"** significantly increases the growth of bio fouling, initially which shows the decrease in vessel voyage performance, increase in vessel fuel consumption due to the increase in resistance growth. The additional drag which affects the resistance of the vessel during the voyage is due to the drag on the wet surface area caused by the air water interaction drag on the vessel hull, wave resistance and the current drag which is the environment constraints which cannot be quantified because these factors change drastically with respect to time. Hence, the graph below shows the change in resistance due to the growth of biofouling in the next year voyage of the vessel.

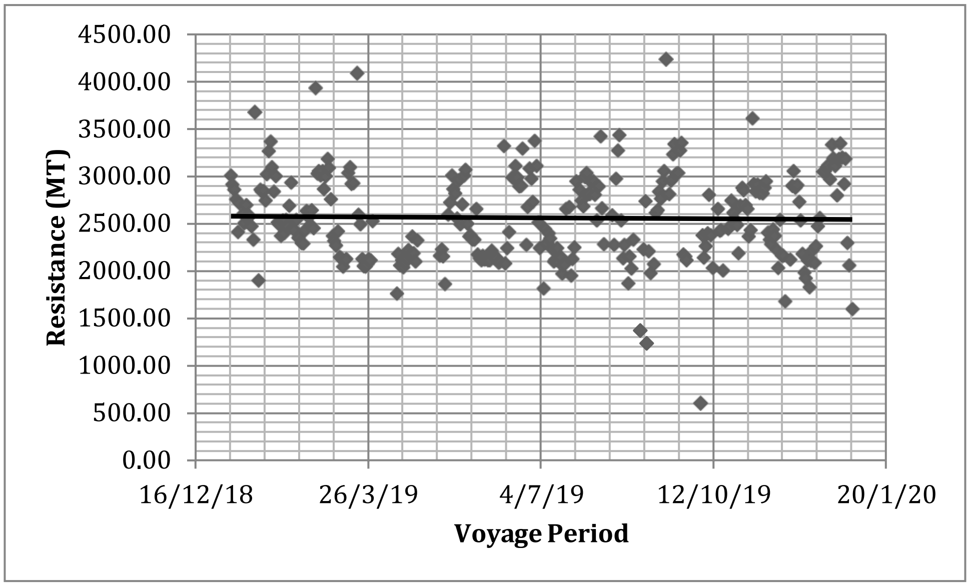

Figure 9 QMAX A, Increase in Hull Fouling, Hull Resistance Calculation

Resistance Calculation Pre & Post Dry Docking of the Vessel QMAX B

The vessel CONV B underwent voyage with average distance coverage of 356 Nautical Mile / Day with an average speed of 8.24 Nautical Mile/ Hr, whereas it covered a total of 50612 Nautical Mile in 142 days. The consideration of above averages is calculated from the data sources available, and with the consideration of other environmental factors taken into account, as discussed in previous chapters. Hence, the observations of change in resistance as per the voyage data available, shows the significant increase in the resistance of the vessel. The increase in resistance during the voyage is expected from the vessel with highly fouled hull and which is approaching the dry docking. The change in resistance can be seen in the graph demonstrated below:

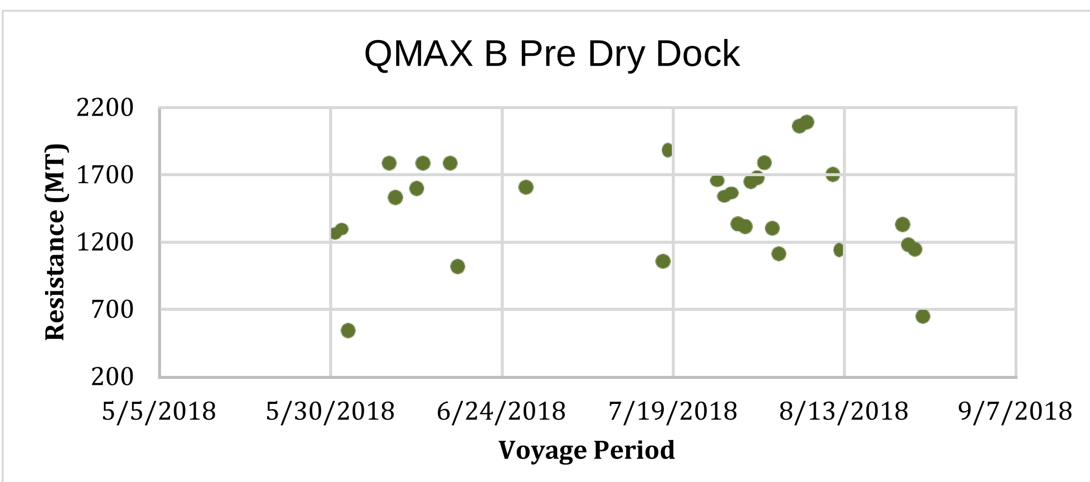

Figure 10 QMAX B, Fully fouled hull (Pre Dry Dock), Hull Resistance Calculation

For this study and the comparative analysis of full fouled hull and the voyage data, considered for the hull resistance calculation is considered 142 days before the dry dock period. Hence, the calculation of hull resistance, which depends on the speed and the distance covered during the voyage will also play a significant role in analyzing the effect during the period. The increase in the resistance observed in the vessel CONV B is due to heavily fouled hull vessel voyages approaching towards the dry docking period.

When the fully fouled hull is cleared in the dry dock, the clearance of heavily fouled hull and the further application of anti-fouling paint **"IP 1100"** which eventually resisted the further growth of bio foul on the surface, hence shown the no further increase in resistance during the post dry dock voyage period. The graph demonstrated the change in resistance of the vessel due to bio- fouling is demonstrated in the graph below:

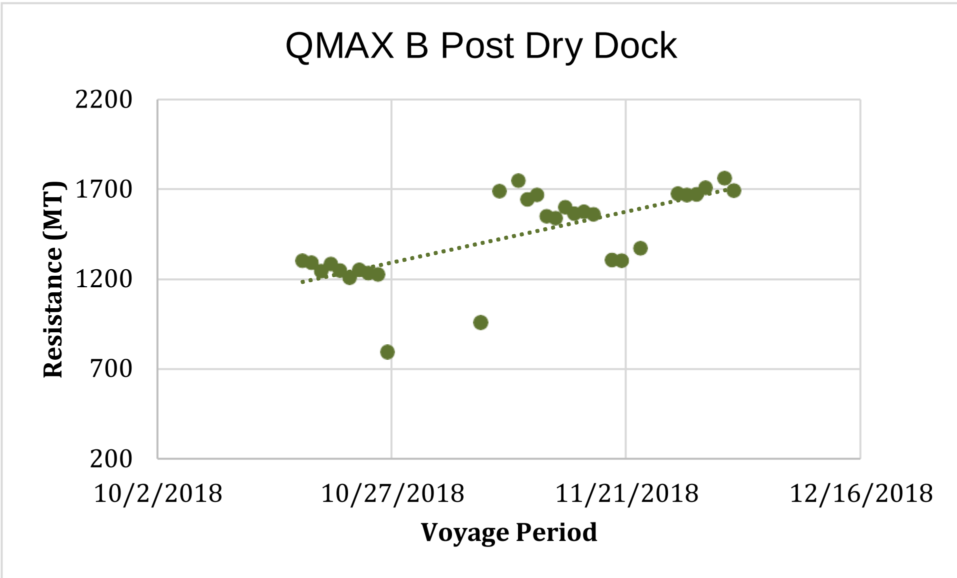

Figure 11 QMAX B, Fully fouled hull (Post Dry Dock), Hull Resistance Calculation

Further, to analyze the efficiency of the vessel hull's anti fouling paints in resisting the further growth of bio fouling observed during the voyage of the year 2019. The anti – fouling paint **"IP 1100"** significantly decreases the growth of bio fouling which shows the great vessel voyage performance, decrease in vessel fuel consumption due to the decrease in resistance growth. The additional drag which affects the resistance of the vessel during the voyage is due to the drag on the wet surface area caused by the air water interaction drag on the vessel hull, wave resistance and the current drag which is the environment constraints which cannot be quantified because these factors change drastically with respect to time. Hence, the graph below shows the change in resistance due to the growth of biofouling in the next year voyage of the vessel.

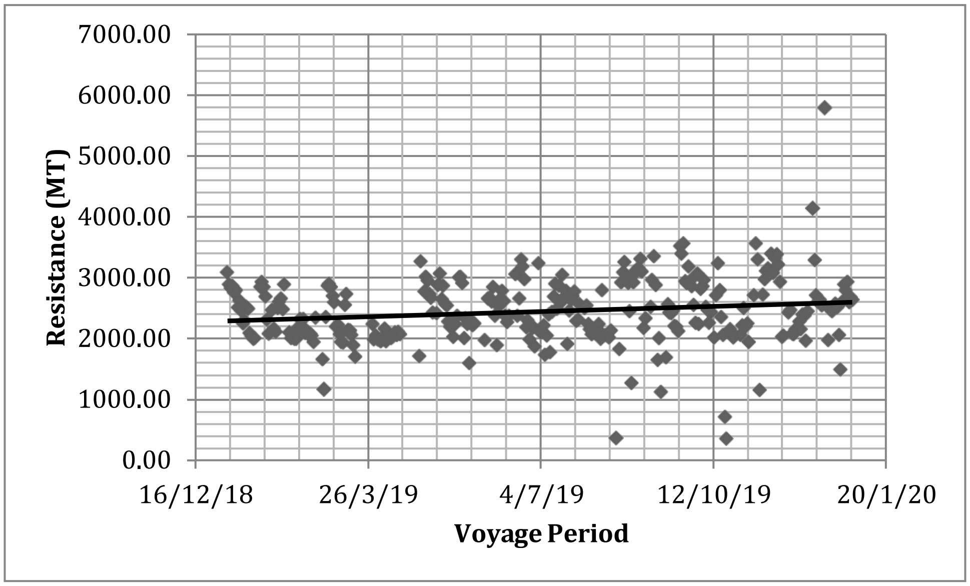

Figure 12 QMAX B, Increase in Hull Fouling, Hull Resistance Calculation (2019)

Change in vessel resistance, rate of marine growth and the voyage route significantly affects the performances of the marine vessels. The marine environment is unpredicted; hence the pre or post calculation and related studies are only indicative. But, these studies will provide us with performance based results which improvise the decision making process of the leaders in the shipping industry. Hence this study provides us an insight about the performance of anti- fouling paints and their performance on the marine vessels. The rate of growth of anti – fouling paints significantly effects the below mentioned factors:

1. Rate of Marine Growth over a period of time, eventually help us to plan the hull cleaning dry docking
2. Rate of Fuel Consumption, Increase marine growth affects the effective power of the vessel, which is directly related to the fuel consumption of the vessel.

CONV A Vs CONV B

During the study period, the sisters' vessels undergo almost similar voyage (although the distance of voyage for CONV B is much higher than the CONV A vessel and with much higher speed), but the vessel CONV A rate of growth of bio fouling is much faster as compare to vessel CONV B. which shows the effectiveness of Anti Fouling paint IP 1000 over Jotun Seaquantum X200. The rate of increase in resistance is directly proportional to the fuel consumption, if the vessel is performing as per maximum effective horse power limit. The Figure 13 : Change in Resistance & Fuel Consumption due to Fouling, Comparison between four Vessels shows the increase in the rate of growth of biofouling and its effect on resistance of the vessel.

When we compare the efficiency of marine antifouling paint on CONV A and CONV B vessel, the finding was the marine growth in CONV A vessel where Jotun Seaquantum X200 was used still allows the marine growth to grow on the hull surface whereas, the IP 1000 which was painted on CONV B vessel resisted the growth of bio components more efficiently as compare to the CONV A - Jotun Seaquantum X200 paint.

QMAX A Vs QMAX B

During the study period, the sisters' vessels undergo almost similar voyage (although the distance of voyage for QMAX B is slightly higher than the QMAX A vessel and with relatively similar speed), but the vessel QMAX A rate of growth of bio fouling is similar as compare to vessel QMAX B. which shows that the effectiveness of Anti Fouling paint IS 700 is similar to the IP 1100. The rate of increase in resistance is directly proportional to the fuel consumption, if the vessel is performing as per maximum effective horse power limit. The Figure 13 : Change in Resistance & Fuel Consumption due to Fouling, Comparison between four Vessels shows the increase in the rate of growth of biofouling and its effect on resistance of the vessel.

When we compare the efficiency of marine antifouling paint on QMAX A and QMAX B vessel, the finding was similar but QMAX B painted with IP 1100 resisted the marine growth over a longer period which enhance the vessel efficiency in longer voyage, whereas the growth observed was constant in longer period but it effects the vessel performance gradually.

Hence, with reference to the below Figure 13 : Change in Resistance & Fuel Consumption due to Fouling, Comparison between four Vessels , the above discussion is being relatively quantified with the change in resistance and fuel consumption. The voyage of all four vessels is:

Full year Voyage (2019)			
Fuel Consumption	**Distance**	**Fuel Consumption**	**Distance Travel Per KL of Fuel**
CONV A	97,074.30	12,142.10	7.99
CONV B	1,33,190.00	18,617.93	7.15
QMAX A	1,08,980.80	27,799.79	3.92
QMAX B	1,08,628.00	26,532.20	4.09

Table 3 Fuel consumption comparison during the voyage in 2019

The rate of fuel consumption of CONV B is higher than CONV A, whereas the fuel consumption rate of QMAX A is higher than QMAX B. Also, illustrated in the graph below:

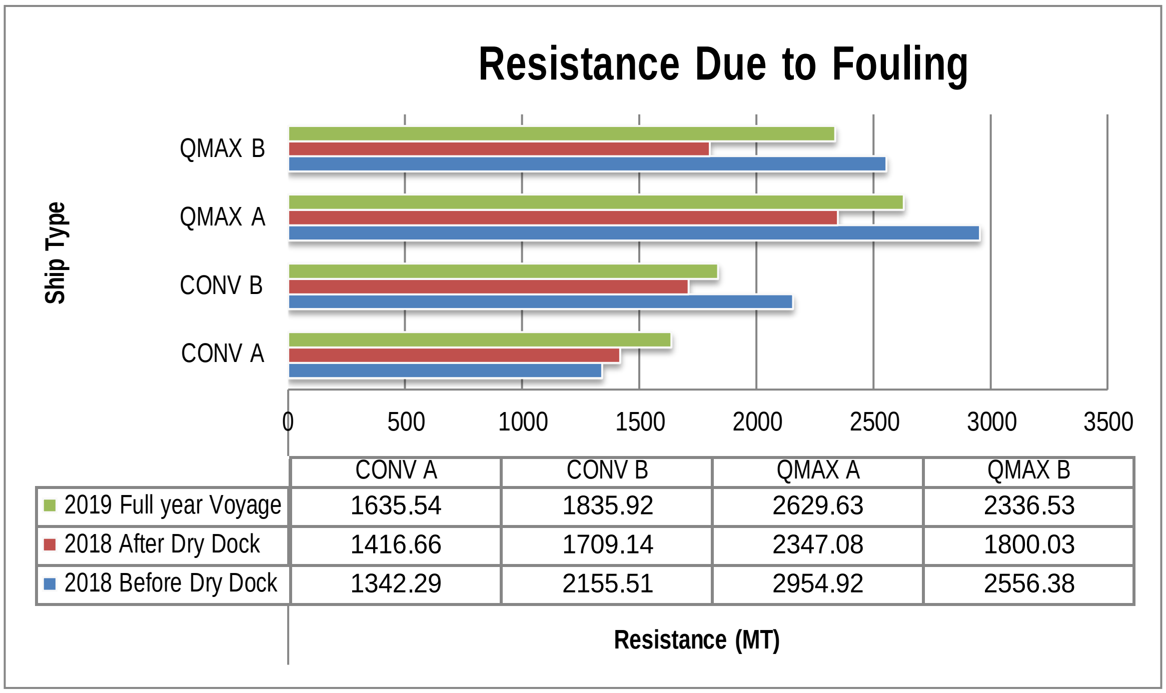

Figure 13 Change in Resistance & Fuel Consumption due to Fouling, Comparison between four Vessels

The effectiveness of antifouling paints used in the marine vessels clearly demonstrates the rate of bio fouling, change in resistance due to the growth of biofouling and the change in rate of fuel consumption as mentioned above in Table 1: Fuel Consumption comparison during voyage in 2019. The above study clearly shows the implementation benefits and comparison of various new technologies being implemented in the marine environment.

6. CONCLUSION

Based on the studies done on 4 vessels during the entire voyage period of 2018 & 2019 and analyzing the vessel's performance pre & post dry docking and continuous voyage after painting with the anti – biofouling paints on the vessel hull, below mentioned is the findings of this study:

1. Anti - Biofouling paint Jotun Seaquantum X200 painted on CONV A, restricted the marine growth in initial period, but when the vessel voyages intense during the year 2019 the rate of growth of bio fouling increases. This eventually affected the fuel consumption & increase in resistance during a longer period. The effectiveness of the paint could only resist the growth in initial days.
2. In CONV B, where the anti – biofouling paint IP 1000, the rate of marine growth is observed constant. The rate of increase in vessel resistance during the voyage period didn't increase drastically, which also controlled the rate of change in fuel consumption during the longer voyage as observed in 2019.
3. As it was observed in the initial voyage data and further calculation of vessel effective horse power and resistance on the vessel hull, the surface of QMAX A was very fouled in per dry dock phase. Whereas, IS 700, Anti – biofouling paint which was painted on the vessel QMAX A after the dry dock decreases the resistance of the vessel and enhances the vessel effectiveness. Also, this reduces the further rate of marine growth which eventually affects the fuel consumption.
4. IP 1100, which shows the best results as compared to any vessels and anti – bi fouling paints, the QMAX B vessel post dry dock initially increases the resistance, whereas on a longer period of voyage calculation and studies shows the reduction in resistance of the vessel. The reduction in resistance also decreases the fuel consumptions, resulting in degradation of marine growth from the hull surface during the voyage period.

Hence, our study shows that the effectiveness of IP 1100 shows the best results in marine environments during a longer period of time, whereas IP 1000 performs best in the initial post dry dock period. The effectiveness of IS 700 is still better than the Jotun Seaquantum X200 anti fouling paint, but still didn't restrict the marine growth. As it's not only the marine growth which affects the resistance and effective horse power of the vessel, marine environment also plays a significant role in vessel's performance. But, as we all know, the prediction of the marine environment is and planning according to the prediction is impossible, hence leanings and studies undertaken during the average voyage of the vessels provide us a great source of improvement.

6.1 Future Scope of Work

This study is done on two similar sister vessels, which take different cargo and undergo different voyage routes and different climatic conditions. Hence, there are some assumptions which made this study viable. As, the vessel's performance changes w.r.t and the environment conditions also differs w.r.t, the further study which can predict the results and provide us more accurate findings can a comparative study on the same voyage route of vessels with comparative study done on modeled scenario with the help of mathematical modeling. The simulated and actual performances of the vessel, when analyzed provide us with greater insights on our assumptions and also provide us the better comparative results when done with various different voyage routes and sister vessels preferring similar routes in similar climatic/ environmental conditions.

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APPENDIX 1: Gantt Chart to show project milestones and schedules