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# Investigation of fuel consumption on an operating ship due to biofouling growth and quality of anti-fouling coating

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**Abstract**. This article will look into to the environmental and economic issues in the maritime sector that arise due to biofouling. For the shipping industry, biofouling is known to increase hull roughness that would lead to an increase in friction resistance and fuel consumption. Here we present a short review regarding ship-hull roughness due to biofouling and its associated increase in skin friction drag, and analysis of fuel consumption from an operating ship with two different anti-fouling coating. The data shows that a higher quality antifouling would result in a low biofouling attachment on the hull surface, resulting in a lower fuel consumption.

## 1. Introduction

The issue of climate change and global warming has become an important topic in recent years due to the increase in human activities that continue to release carbon dioxide into the atmosphere. This would lead to the increase of earth temperature [1], resulting in the melting of polar ice caps, rising sea levels, longer drought, a more frequent extreme weather, etc. A recent report by Intergovernmental Panel on Climate Change (IPPC), predicts that the global temperature, from 1990 to 2100, will increase by 1.1 °C to 6.4 °C [2]. Another report by Aral and Guan [3], shows that the sea level rise will increase 60-150 cm from 1990 to 2100. Maritime sector is known to contribute to the release of 2.2% of global carbon dioxide into the atmosphere in 2012 [4] and it is predicted to increase by 50% to 250% by 2050 [5]. To address this issue, the International Maritime Organisation (IMO) has applied the limit of Energy Efficiency Design Index values on ships through EEDI program [6, 7]. This index limit policy is expected to reduce the level of emissions caused by ship engines or creating generations of the environmentally friendly fleet.

One effort to improve the efficiency of energy usage on operating ships is by optimizing the hydrodynamic performances. This can be done by keeping the hull surface clean from biofouling [8, 9]. Surface roughness, such as those caused by biofouling, will results in an increased friction resistance [10-17], leading to an increase in the power requirement and fuel consumption. Beyond this, biofouling that are attached to the ocean-going ship hull may also carry invasive species that would hurt local marine life. To reduce the risks caused by biofouling, it is crucial to conduct a regular dry-docking for cleaning and to applies anti-fouling system. Although antifouling is an efficient way to combat biofouling, they are known to contains tributyltin (TBT) that damage the marine environment [18]. Hence this type of antifouling system has been banned by the IMO since 2008 [19]. As a result, many current antifouling producers in the market has abandoned the TBT-based antifouling based system.

In this paper, a brief review of the roughness effect due to biofouling against ship operations, ship resistance, and fuel consumption are discussed. Here we also report a two-year-long observation from an operating ship, comparing the usage of two different antifouling quality and its correlation to the fuel usage. Statistical analysis in the form of linear regression was carried out to determine the effect of biofouling growth and the quality of antifouling paint against fuel consumption.

## 2. Ship Resistance and Propulsion

### *2.1. Ship resistance*

One critical component in a ship is its main engine, which use fuel to rotate propellers and push the ship forwards, overcoming fluid resistance. In general, fluid resistance on an operating ship consists of viscous resistance and residual resistance. Viscous resistance includes the skin frictional resistance and part of the pressure resistance force, while residual resistance is usually dominated by wave resistance. For operating ship, the total ship resistance formula can be defined as:

$$R_T = R_F + R_R = R_F + R_{VP} + R_W = (1+k)R_F + R_W \tag{1}$$

where $R_T$, $R_F$, $R_R$, $R_{VP}$, $R_W$, (1+k) are Total Resistance, Frictional Resistance, Residual Resistance, Viscous Pressure Resistance, Wave Resistance, hull shape coefficients, respectively [20]. These resistance components are non-dimensionalised by dividing each term by the dynamic pressure and wetted surface area of the ship hull, resulting in:

$$C_T = C_F + C_R = C_F + C_{VP} + C_W = (1+k)C_F + C_W \tag{2}$$

where $C_T$ is the total resistance coefficient, $C_F$ is the frictional resistance coefficient, $C_R$ is the residuary resistance coefficient, $C_{VP}$ viscous pressure resistance coefficient, $C_W$ is the wave resistance coefficient.

### *2.2. Ship propulsion*

The ship engine power is estimated from the multiplication of the resistance and speed, combined with the loss of energy factor due to the type of propulsion system used, such as the long shaft, gearbox etc. Additional environmental factors such as waves would add further uncertainty because the calculation of the resistance is calculated by assuming calm water. Accordingly, the calculation formula becomes:

$$P_{I(R_T, V)} = \frac{R_T \times V}{\eta_D} \times \frac{1}{\eta_T} + \text{margin} \quad \text{(Roughness, fouling and weather)}, \tag{3}$$

where total resistance ($R_T$) is the value of the ship's resistance at a speed (V). Quasi-propulsive coefficient (QPC) ($\eta_D$) is a losses factor due to changing in rotational power to translational by propeller and $\eta_T$ is losses by transmitting from engine to propeller through the shaft. Finally, we need to add a margin due to external factors such as roughness, fouling, and weather [20]. If there is an increase in resistance due to fouling, and $\eta_D$ = 0.55, $\eta_T$ = 0.95 with margin 30 %, then equation 3 becomes

$$P_I(R_T, V) = R_T \times V \times 250\% \tag{4}$$

where in addition to the need for power to drive the ship, there are other power requirements that are lost 1.5 times.

## 3. Problems Due to Biofouling

Biofouling is the accumulation of aquatic organisms such as microorganisms, plants, and animals on wetted surfaces and structures. This includes microfouling and macrofouling. Microfouling are bacteria, diatoms, and the slimy substances produced, which usually referred to as slime layers.

Macrofouling is a large multicellular organism that can be seen by the human eye such as barnacles, tubeworms, or algae leaves [21]. There are more than 4000 species of animals and plants that are classified as biofouling throughout the world [22].

Biofouling attachment on an ocean-going ship begins when the structure is immersed in the sea water. First, organic compounds begin to attach, then bacteria and unicellular settle and group into layers of a film called slime. Then the slime produces several chemical secretions that trigger multicellular and macrofouling species to sit due to the abundance of food for them and calcareous fouling occurs [22, 23, 24]. The classification of the member species of biofouling is shown in Figure 1 [25].

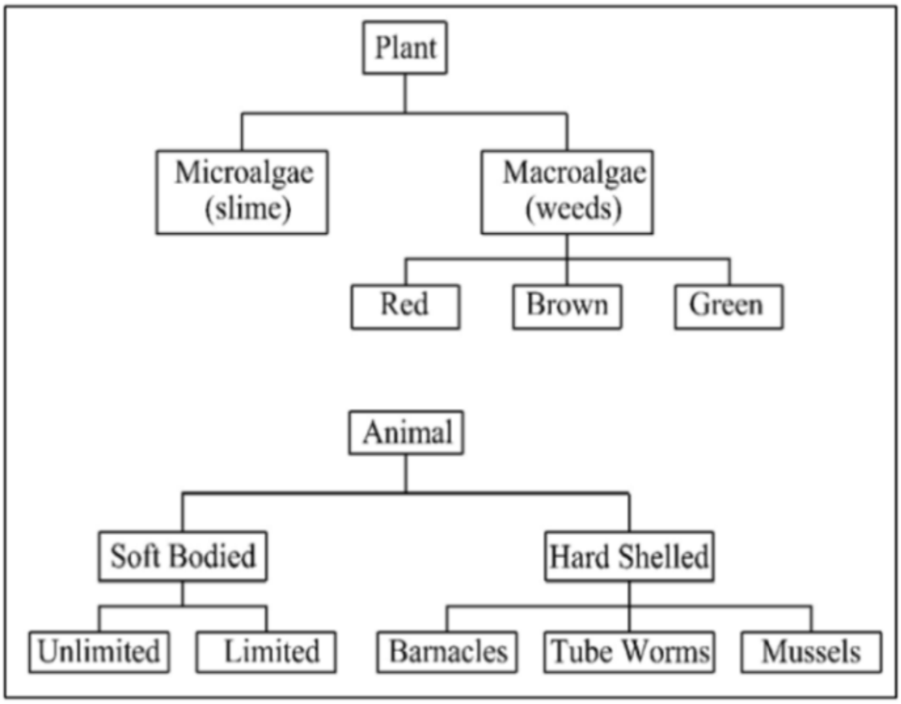



**Figure 1.** The classification of marine fouling [25]

The main problem due to biofouling attached to the hull is economic losses, climate change and damage to the environmental ecosystem [26]. The process of how biofouling can cause various problems can be explained from Figure 2. Here the biofouling would generate an increase in surface roughness that would contribute to the increase of fuel usage and CO2 emission, leading to a significant contribution towards climate change. The increase of fuel usage would also affect the ship's operator bottom line. With regards to the environmental ecosystem damage, biofouling would carry invasive species that would damage the local environment. Facing with these challenges, the IMO has issued regulations or guidance related to emission prevention [6] [7], prohibition of harmful substances in anti-fouling [19], and problems due to invasive species [21, 27, 28, 29, 30].

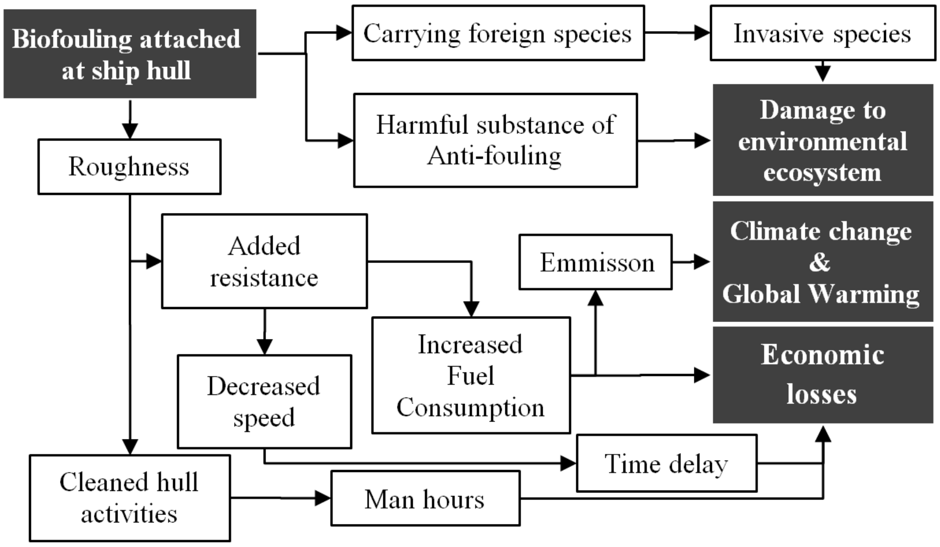



**Figure 2.** Relationship between several problems caused by biofouling

## 4. Effect of Roughness on Increasing Fuel Consumption

In the last few decades there have been many studies that look into the effector roughness on ships (due to biofouling, anti-fouling coating [11, 31], hull imperfection from shot blasting [14], or welding), these include lab experiment, Computational Fluid Dynamics (CFD), and in-situ measurement on an operating ship. Some of these studies, particularly the experiment, involves towing tank [11, 12, 32], wind tunnel [13, 33], and direct measurement on an operating ship [16]. To complement the experimental investigations, studies using CFD allows engineers to study the phenomenal from the different angle [10, 34, 17]. Based on these work it is clear that the surface roughness can increase the frictional resistance or coefficient of friction (CF) of an operating ship.

By assuming that the $C_F$ value increases by 30%, using equation 5 we can obtain a graph of friction resistance ($R_F$) such as in Figure 3(a) [15] [35]. Here $C_F$ is calculated based on the ITTC formula [36] (see equation 6) and then multiplied by 130%, where $C_F$ is a function of the Reynolds number (Re) shown in equation 7. From the curves, we can see that with the same power of Normal Continuous Rating (NCR), the speed will decrease from 14 knots to 12 knots. The reduced speed has an impact on the longer ship sailing time when referring to the condition, the sailing time increases by 16.7% and so does the fuel consumption.

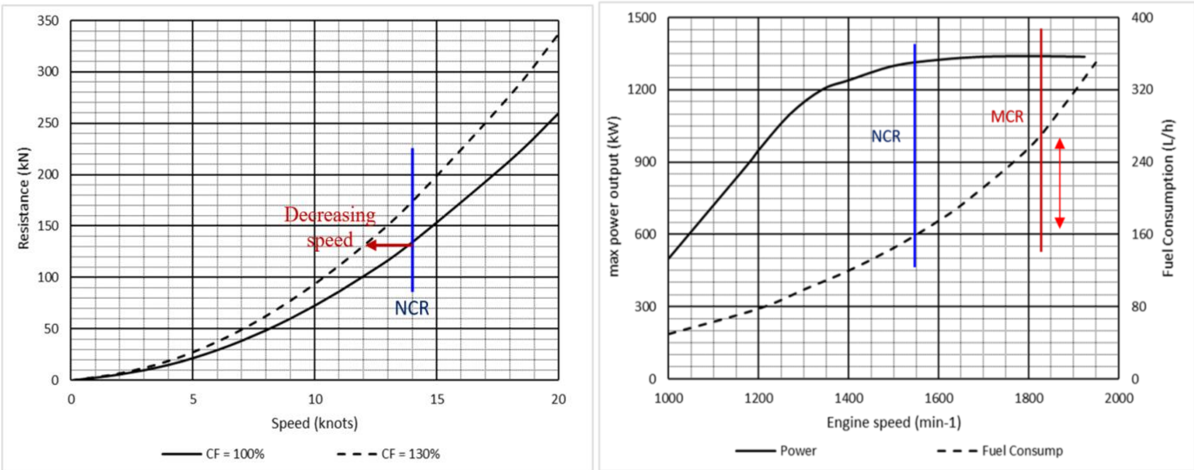
$$R_F(V) = \frac{1}{2} \times \rho \times S \times V^2 \times C_F(V) \tag{5}$$

$$C_F(V) = \frac{0.075}{(\mathrm{LOG}_{10}\,\mathrm{Re(V)} - 2)^2} \tag{6}$$

$$\mathrm{Re}(V) = \frac{\rho \times L \times V}{\mu} \tag{7}$$

Where V is ship speed, ρ is the density of seawater, S is the wetted surface area of ship hull, L is ship length and μ is the dynamic viscosity of seawater.

If the ship operator chooses to increase the engine power from NCR to Maximum Continuous Rating (MCR) to increase its speed again, as shown in Figure 3 (b) [15] as a characteristic graph of a marine engine [37], then the fuel consumption will increase drastically. From the curves, the increase in RPM from 1550 to 1825 will increase fuel consumption from 160 L/h to be 260 L/h, which is an increase of 100 L/h or 62.5%. Figure 4 shows the relationship of biofouling growth to total resistance [20]. Here ship resistance increases with biofouling growth and then decreases due to cleaning during dry docking, however, the effect of shot blasting also causes the hull to become rougher.




(a) (b)

**Figure 3.** (a) Resistance curve due to increase of $C_F$ [15],
(b) Engine characteristic of YANMAR 12AYM-WGT-L rating [37]

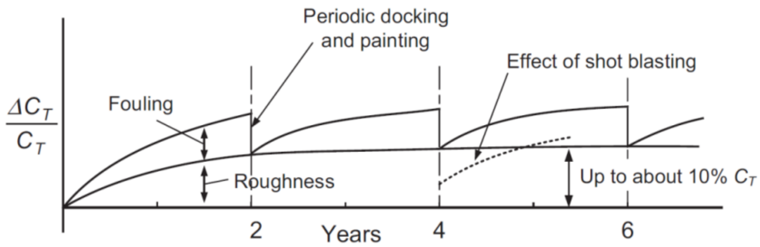



**Figure 4**. Growth of roughness and fouling [20]

## 5. Prevention of Biofouling on Ship

Biofouling has been a problem in shipping activities since about 1500 BC. Historical stories about the development of anti-fouling are described in Table 1 [38] that was rewritten by Demirel [39]. In its development, TBT (Tributyltin) anti-fouling paint was the most effective paint to prevent the attachment of biofouling in the 1960s to 2000s. However it turns out that TBT causes aquatic animals to experience reproductive failure and pollute the waters as toxic [40, 41, 42]. Thus, IMO banned the use of antifouling paints containing TBT in 2003 and entered into force in 2008 [19].

Anti-fouling paint is classified into two categories based on composition, namely: biocidal and non-biocidal. Biocidal consists of CDP (Controlled Depletion Polymer), SPC (Self-Polishing Copolymer) and Hybrid SPC, while non-biocides are foul-release coatings (FR). CDP removes biofouling by releasing biocidal compounds into the marine environment leading these organisms not able to attach on the hull. These biocidal compounds are usually copper compounds or other heavy metals compounds. The differences between biocidal and non-biocidal are explained in Table 2 [43]. Based on the explanation in the table about the effects on the environment, it is necessary to develop new anti-fouling technology to be truly environmentally friendly, for example with the electrolytic system method, ultrasonic system, and electro-chlorination [44].

**Table 1.** Historical development of the antifouling strategies [38] [39]

| Timeline | Major events |
|---|---|
| 1500-300 BC | Use of lead and copper sheets on wooden vessels |
| 1800-1900s | Heavy metals (copper, arsenic, mercury) incorporated into coatings |
| 1800s-present | Continued use of copper in AF coatings |
| 1960s | Development of TBT conventional coatings |
| 1974 | Oyster farmers report abnormal shell growth |
| 1977 | First foul release AF patent |
| 1980s | Development of TBT SPC coatings allowed control of biocide release rates |
| 1980s | TBT linked to shell abnormalities in oysters (Crassostrea gigas) and imposex in dogwhelks (Nucella lapillus) |
| 1987-90 | TBT coatings prohibited on vessels <25 m in France, UK, USA, Canada, Australia,<br>EU, NZ and Japan |
| 1990s–present | Copper release rate restrictions introduced in Denmark and considered elsewhere e.g. California, USA |
| 2000s | Research into environmentally friendly AF alternatives increases |
| 2001 | International Maritime Organisation (IMO) adopts''AFS Convention'' to eliminate<br>TBT from AF coatings from vessels through:<br>2003 – prohibition of further application of TBT<br>2008 – prohibition of active TBT presence |
| 2008 | IMO ''AFS Convention'' entered-into-force |

**Table 2.** Properties of the existing hull coatings [43]

| | Protection and longevity | Fuel saving properties and conditions | Need to drydock for repainting | Environmental concerns |
|---|---|---|---|---|
| **Typical antifouling coatings (SPC)** | Soft coating. Fairly easily damaged. 3-5 years before AF coating needs to be replaced. Full recoating down to bare steel 2 or 3 times in 25 years. Not suitable for aluminum hulls. | Unfouled hull roughness from AF coating gives 2-4% fuel penalty. Usually, sails with slime = up to 20% fuel penalty. Effectively reduces higher fuel penalties. Coating degradation increases fuel penalty over time. | 5 - 8 drydockings required for paint alone during ship's service life including 1-3 full blasting and repainting. Multiple coats and length curing times can mean 2-3 weeks in drydock for a full repaint. | Contaminates marine environment with toxic biocides, harming marine life, the food chain and humans. Pulse release of biocides if cleaned in-water. High VOC content when applied. Limits fuel consumption and GHG emissions from effects of heavy fouling. Prevent some NIS but further others. |
| **Typical FR coating system** | Soft coating. Easily damaged. 3-5 years before FR coat needs repair/reapplication. Full recoating required 1-3 times in 25 years. | Smoothest tested surface when unfouled. Usually sails with slime = up to 20% fuel penalty. Can foul badly if vessel has long lay-ups. Coating degradation increases fuel penalty over time. | 5 - 8 drydockings required for paint alone during ship's service life including 1-3 full blasting and repainting. Multiple coats and length curing times can mean as much as 2 – 3 weeks in drydock for a full repaint. | Does not contain biocides but leaches potentially harmful oils, alters enzymes in barnacle glue; some silicones catalyzed by highly toxic dibutyltin dilaurate. Medium VOC. Some reduction in fuel consumption/GHG. Can help limit spread of NIS. |

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## 6. Measurement of Fuel Consumption in a Ship

This section describes the measurement of fuel usage data on an operating ship from November 2015 to September 2017. Here the ship experienced drydocking at the end of August 2016 until the beginning of October 2016 as shown in Figure 5. The data is measured based on how much fuel is needed to carry out one regular. When the ship experienced dry docking, the fouling-hull of the ship was cleaned by blasting and then repainted with a higher quality of anti-fouling paint. Hence the first period (red line) used ordinary quality coating, while the second period (blue line) used a higher quality of the anti-fouling coating.

The data is raw without statistical treatment, hence the fluctuations. The fluctuation is due to the variation in the ship's cargo. As we know if the displacement changes, then the draft of the ship also changes, thus it will affect to the magnitude of the ship's resistance, so at the end, it affects the amount of fuel consumption. Beyond the influence of inconsistent cargo, other uncertainties such as weather, waves, engine degradation, and aging components of the ship can also affect the reading.

Using linear regression, Figure 6 shows an increase in fuel consumption from how long the ship has left dry-docking. In the first year, from November 2015 to mid-August 2016 which is outlined with red lines, the ship hull is protected by a regular antifouling paint. The data shows that the fuel usage increased by approximately 20% at the end of the period. This period has a slope factor value of around 0.275% per trip. In the second year, from the beginning of October 2016 to mid-September 2017 as drawn in blue line, the ship hull is protected by a higher quality antifouling paint. The fuel consumption was increased by only 5% at the end of the period, with the slope value of around 0.0758% per trip. From these results, it can be concluded that biofouling increases fuel consumption over a period of time after the ship has experienced drydocking. However, by using a higher quality antifouling paint, the biofouling attachment becomes less and lead to a lower fuel usage.

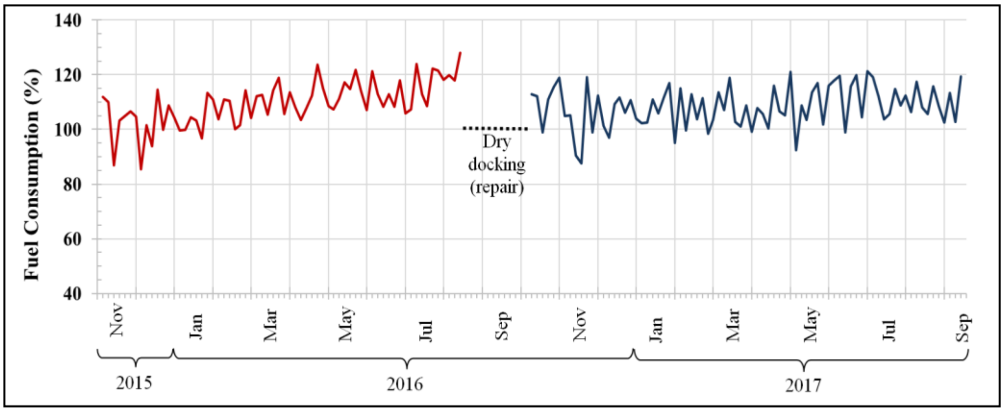


**Figure 5.** Rough data of the fuel consumption per trip for 2 years

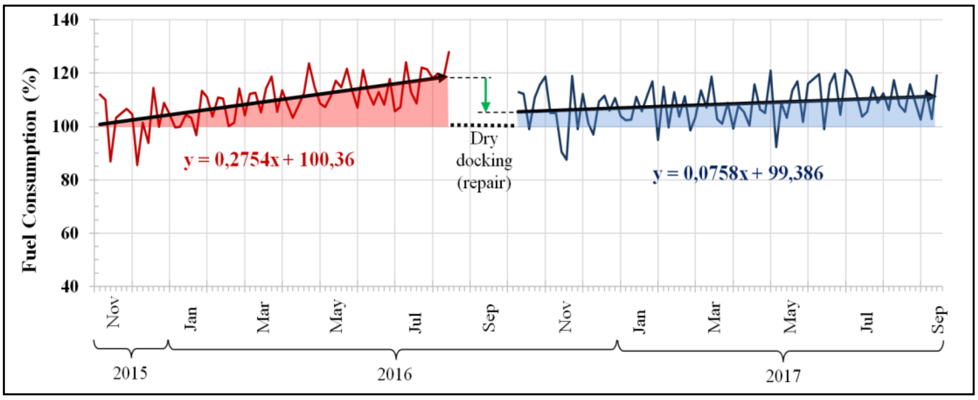


**Figure 6.** Linear regression on fuel consumption for 2 years

Then when observed during dry docking, there was a decrease in fuel consumption from approximately 120% to be 105%, with the other meaning is not fully returning to new condition, but an increase of 5% from the initial hull condition. This happened because, the ship's hull which was previously attached by biofouling then became clean again, but because of the cleaning process through blasting, the hull also experienced an increase in roughness, as stated by Utama [14].

## 7. Conclusion

Biofouling causes many problems in maritime activities around the world, such as damage to environmental ecosystems through invasive species and harmful anti-fouling. Beyond this, the roughness due to biofouling growth can increase ship resistance that would lead to the increase of power and fuel requirements of ships. The data analysis from ship fuel consumption indicates that biofouling growth can increase fuel usage, and then dry docking efforts can normalize the performance of the ship, albeit not entirely as a new ship. Finally, the application of anti-fouling paint with better quality can reduce the increase in fuel consumption**.**

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