The challenges and opportunities of anti-fouling systems: investigating of future demand and identifying the potential of energy saved

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THE CHALLENGES AND OPPORTUNITIES OF ANTI-FOULING SYSTEMS

Investigating of future demand and identifying the potential of energy saved

By

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A dissertation submitted to the World Maritime University in partial fulfillment of the requirements for the award of the degree of

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DECLARATION

I certify that all the material in this dissertation that is not my own work has been identified, and that no material included for which a degree has previously been conferred on me.

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ABSTRACT

Title of Dissertation  The Challenges and the Opportunities of Anti-Fouling Systems

Degree:  Master of Science

The dissertation examines two main key issues related to climate change and biological pollution. The need of new innovative antifouling systems to fulfill future demand and the impact of biofouling on the ship’s hull from both economic benefit and the environment benefit. The study of literature reviews shows the varieties of anti-fouling paints under two main mechanisms namely, SPCs and FRCs which are developed after TBT ban in 2001, put more pressure on shipping companies while looking for the most efficient anti-fouling systems as well pressure on paint manufacturers to develop an efficient alternative to TBT-based paint.

The author intended to answer the research question by identify the gap between the current anti-fouling system and optimum anti fouling systems through SWOT analysis the result of this analysis gives the required characteristics for future solution. Moreover, the author investigates the potential of saving energy through anti-fouling system by adopting Monte Carlo methodology and process the data through crystal ball the result shows that the antifouling system is a key element and is a part of an integrated system for maximizing energy efficiency. The author also introduces a methodology to guide the shipping company on the selection of the most efficient anti fouling systems among different systems through cost and benefit analysis the result shows the increased of operating cost due fouling.

Although there are several types of anti-fouling paints and hull cleaning practices as result of AFS convention there is gap between current antifouling systems and optimum anti-
fouling systems, which require all stakeholders namely; IMO, shipping companies and paint manufacturer to share their goals and objectives to achieve a sustainable anti-fouling systems solution, maximizing energy efficiency and reducing of GHG as a part of marine industry commitments towards initial GHG strategy adopted recently by IMO in April 2018.

**KEYWORDS:** GHG, Ant-Fouling Systems, Future Demand, AFS Convention, Maximizing Energy Efficiency, Economic Benefit, Environment Benefit, Sustainable Anti- Fouling Systems
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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AC foul</td>
<td>Extra cost due to fouling</td>
</tr>
<tr>
<td>APEC</td>
<td>Asia Pacific Economic Cooperation forum</td>
</tr>
<tr>
<td>AFS</td>
<td>International Convention on the Control of Harmful Anti-Fouling Systems on Ships</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon Dioxide</td>
</tr>
<tr>
<td>CDB</td>
<td>Convention on Biological Diversity</td>
</tr>
<tr>
<td>CMP</td>
<td>Chugoku Marine Paints</td>
</tr>
<tr>
<td>CDP</td>
<td>Copolymer Depletion Paint</td>
</tr>
<tr>
<td>Csp</td>
<td>Cost due to speed reduction</td>
</tr>
<tr>
<td>Cfc</td>
<td>Cost due to increase in fuel consumption</td>
</tr>
<tr>
<td>Cdd</td>
<td>Cost due to dry-docking</td>
</tr>
<tr>
<td>DNVGL</td>
<td>Det Norske Veritas &amp; Germanischer Lloyd</td>
</tr>
<tr>
<td>DOC</td>
<td>Daily Operating Cost</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>EPS</td>
<td>Extracellular Polymeric Adhesive Substances</td>
</tr>
<tr>
<td>Edd</td>
<td>Expenses due to dry-docking</td>
</tr>
<tr>
<td>FRCs</td>
<td>Fouling Release Coatings</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse gases</td>
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<tr>
<td>IMO</td>
<td>International Maritime Organization</td>
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</table>
ITCP  Integrated Technical Co-operation Programme
LPf   Loss of Profit due to fouling
LPsp  Loss of Profit due to reduced speed
LPdd  Loss of Profit due to dry-docking
MEPC  Marine Environmental Protection Committee
ONR   Office of Naval Research
PARCOM Paris Commission
PPG   Pittsburgh Plate Glass paint company
RINA  Registro Italiano Navale
RoPax Roll/On-Roll/off Passenger ships
SPERP Secretariat of the Pacific Region Environment Programme
SWOT  Strength Weaknesses Opportunities Threats Analysis
TBT-SPC Tributyltin Self-Polishing Copolymer
TBT   Tributyltin
UNEP  United Nation Environmental Programme
UK    United Kingdom
USA   United State of America
UNCED United Nation Conference on Environmental and Development
Chapter 1

Introduction

1.1 Background

In 2016, a total volume of seaborne trade expanded to reach 10.3 billion tons; this was predicted to increase to 10.6 million in 2017. Furthermore, the annual prediction between 2017 and 2022 was estimated to be a 3.2 percent annual growth rate (UNICTADE, 2017). Recognizing that ships are the most cost-effective mode of transport in terms of moving large shipments, therefore, sea transport is indispensable. Ships have been identified as a significant source of pollution for both air and water. According to the third IMO GHG study (2014), shipping accounted for 3.1 percent of the annual global CO2 emissions for the 2007-2014 period and based on the outlook of the seaborne trade expansion, shipping GHG’s emissions share is expected to significantly increase to the range between 50 to 250 percent by 2050 in the case of business as usual. Ships are also sources of water pollution. Although, there are several types of water pollution caused by ships, this study will focus on the biological pollution caused by the outer ship’s hull, which has been identified as the movement of living organisms accidentally travelling to a new marine environment (biofouling).

According to IMO (2018) unwanted organisms, which are attached to the ship’s hull and introduced to the new environment, may survive, reproduce and become invasive species endangering the ocean and biological conservation. The volume of invasive species moved by ship’s hulls is expected to increase, due to the expanded seaborne trade. The quantitative data that shows the number of new ecosystems being invaded is increasing, and those invasive species have been recognized for several decades and identified to cause a significant threat to ecological system, including human health. Moreover,
tourism, fisheries and all other industries, which rely on the coastal and marine environment will be impacted. Not only IMO, but other international organizations and regional collaborations have recognized the potential of introducing invasive species to a new environment by biofouling from the ship’s hull. These include the Convention on Biological Diversity (CBD), UNEP Regional Seas Conventions (Barcelona Convention for the Protection of the Mediterranean Sea Against Pollution), the Asia Pacific Economic Cooperation forum (APEC) and the Secretariat of the Pacific Region Environment Programme (SPREP).

In 2001, IMO adopted an international convention on anti-fouling systems (AFS Convention) that addresses anti-fouling systems on ships, and establishes a mandatory international regime to control the use of harmful substances, such as organotin compounds in anti-fouling coat components, to stop the adverse impacts on the marine ecosystem rather than to stop the transfer of invasive species. Consequently, IMO in 2007 authorized the MEPC to control the transfer of invasive species from biofouling. The outcome of MEPC led IMO to adopt in 2011 the first guidelines that mainly focus on the management of ships' biofouling to minimize the transfer of invasive aquatic species. As a result of scientific and technological developments, the guidelines have been improved to increase the awareness of biofouling impacts such as those involving the port states, coastal states, and flag states who play a role in minimizing the risks of transferring invasive species. IMO, to support the implementation of the guidelines, started a technical cooperation activity under its Integrated Technical Co-operation Programme (ITCP). Moreover, in 2017, IMO began a project called Glo Fouling Partnerships, which targets developing countries by building capacity to implement biofouling guidelines and safeguard the marine ecosystem. Since the mid-1980s several countries control and regulate the use of TBT in antifouling systems after the recognition of its adverse impact on the environment.
After the IMO AFS Convention came into force in 2008, it called for the international community to ban the use of TBT to prevent adverse effects on the ecosystem; this was a driving force for the marine painting industry to focus on the development of new technology to meet IMO requirements. Since then, the competitiveness generated among marine painting companies has resulted in a variety of antifouling paints, which create uncertainty for shipping companies that decide to select the most suitable antifouling systems for their fleet. One of the objectives of this thesis is to analyze the current types of antifouling systems and determine the pros and cons of each type. The outcomes of this research should then assist decision makers in shipping companies in selecting the most cost-effective anti-fouling system from the shipping companies. At the same time, the fuel oil consumption of ships should be reduced. Moreover, it should also assist in identifying the gap for the need of a new anti-fouling system to fulfil the future demand.

Seaborne transportation is consuming about 300 million tons of fuel per year, and ship air emissions are expected to range between 38 percent and 72 percent by 2020, if no new measures are introduced to mitigate these emissions (FOUL-X-SPEL, 2013). This has led the shipping companies and research organizations to focus on energy saving. A ship's hull roughness plays crucial role in terms of increased hull resistance. One of the important factors that has a direct impact on the resistance is biofouling; therefore, the application of an appropriate antifouling system can easily reduce ships to resist and improve a ship’s power curve and maximize the energy saving potential, consequently reducing fuel oil consumption and air emissions, especially GHG, and ultimately reducing the operational costs.

1.2 The dissertation

**Research question:** Do we need innovative anti-fouling system to fulfill the future demand?

The results of this research highlight the important roles of an antifouling system from the environmental impact and economic interest (cost –effectiveness).
From environmental impact such as minimizing the risk of transferring aquatic invasive species to a new ecosystem, using an environmentally friendly component in an anti-fouling system, reducing the ship roughness, and consequently reducing the fuel oil consumption and GHG emissions.

From economic interest (cost–effectiveness) such as the capital and operational costs of the anti-fouling system, lifetime cycle, easily cleaned, not harming the hull construction and last but not least less maintenance.

Moreover, the author identifies the gap for future demand to develop a new anti-fouling system to fulfil this demand, and to maximize energy efficiency by selecting optimum anti-fouling systems.

1.3 The dissertation’s objectives

1. Develop a reference guide for shipping companies about a recently used antifouling system, which supports the decision maker to identify the most suitable system for the fleet.
2. Answer the research question, which is the need for a new anti-fouling system to fulfil future demand.
3. Identify the gap between current antifouling systems and the need for new technology to produce a new anti-fouling system that will drive the research and development department at the big paint manufacturers to look for new technology.
4. Design a model that can estimate the potential savings of applying a specific antifouling system by using the historical data of a RoPax ship.
5. Build a decision-making framework for maximizing energy efficiency by selecting an optimum anti-fouling system.
6. Examine the cost and benefit analysis for anti-fouling systems.
1.4 Research methodology

To fulfil the research objectives, namely objectives one, two and three, a SWOT analysis was done to assess and identify the pros and cons of the selected anti-fouling system, the boundary of the selection of anti-fouling system based on the currently applied types and commonly used by shipping companies, shipyards, types produced from painting manufacturers, types recommended by classification societies and ship-owners associations. The obtained data, through the questionnaires, interviews, desk research and personal contacts, has been processed by qualitative analysis and coded under different categories. They are namely:

1. Biocidal paint
2. Fouling release paint
3. Biomimetic coating
4. Active technology
5. Hull Bug (grooming device)
6. Cleaning device (boat washer)

1.5 Dataset

There are two types of data that have been collected, qualitatively and quantitatively, through questionnaires, interviews, desk research and personal contacts. The data was received from different maritime sectors, namely:

1. Shipping companies such as Maersk line, Wallenius Marine AB, Stena shipping company, Team tanker international and Stolet tankers;
2. Shipyards such as Meyer Turku shipyard and Dalian COSCO KHI Shipyard;
3. Engineering paint manufacturers such as Jotun, Hempel, Chugoku Marine Paints and PPG paint;
4. Ship-owners associations such as Bimco, Asian ship-owners association and European Ship owner associations;
5. Classification societies such as Lloyds register, DNVGL, ABS and RINA. All of the above sources provide the qualitative data for this study.

The quantitative data obtained is from one source, namely RINA. In particular, the soft wear developer department, and the data provided by RINA, was detailed data for one RoPax ship for two different periods; the first period being before dry dock and accounted for 6 months while the second period after the dry docking accounted for 6 months. Although the given data by RINA was for a short period, due to their confidential legal commitments to their client, the data was sufficient to build an ideal model under specified conditions.

1.6 Dissertation outline

Chapter 2

Legal developments of the Anti-Fouling System

1.6.1 Review the legal developments of the anti-fouling system

This chapter shows and describes the adopted regulations and resolutions by IMO and international communities to address and prevent the use of harmful substances in antifouling system components. The chapter also explains the adopted guidelines of MEPC and IMO to prevent the transfer of invasive species through ships’ biofouling. Moreover, the chapter describes the regional agreements among neighboring countries and national policies to reduce the risk of transferring invasive species to new ecosystems. The importance of this chapter is that regulations have been the driving force for the marine coating industry to develop a new anti-fouling system/ technology to establish, and then maintain, the balance between environmental impact and economic interest.
Chapter 3

The development of anti-fouling system types

1.6.2 Review of the development of anti-fouling system types/ potential of energy saving from antifouling systems

In this chapter, the author studies and reviews in detail the biofouling process, formation and types, which will help this author to identify the different categories for antifouling systems. Moreover, it builds a base for the data analysis chapter. Also in this chapter, the author has identified several AF systems and solutions inspired by nature.

In addition, the study reviews the potential energy saved through the introduction of anti-fouling systems.

Chapter 4

Current and future solutions of anti-fouling systems

1.6.3 Dataset and data analysis, findings and discussion (SWOT analysis)

Data obtained by the questionnaire, interviews, personal contacts and desk research were analyzed using a SWOT analysis. Qualitative data was collected from different maritime sectors as mentioned above in the research methodology. The obtained data was categorized and coded to identify the pros and cons of the selected anti-fouling systems. The results demonstrate the future need for new innovative antifouling systems to satisfy both the environmental and economic benefits.
Chapter 5

1.6.4 Dataset and data analysis, findings and discussion (case to study analysis)

The analysis was undertaken by utilizing the Monte Carlo methodology through Crystal-ball software, based on data obtained from RINA to build a model utilized for calculating fuel oil consumption before and after dry dock to evaluate the approximate value of the biofouling impacts on hull roughness, power penalties and GHG emissions. Moreover, the methodology for calculating and measuring the anti-fouling system performance, through cost-benefit analysis, resulted in conclusions which will hopefully aid decision makers in shipping companies to select an efficient anti-fouling system, and to decide the right time for hull cleaning.

After the analysis, the results confirm that:

1. There are various anti-fouling systems and the shipping companies challenging in choosing the most suitable system for their fleet to satisfy their economic interests.
2. The decision-making framework assists shipping companies in maximizing the energy efficiency by selecting the optimum antifouling system.
3. The application of anti-fouling systems is unique by ship types and seagoing areas.
4. The need for implementation and adoption of anti-fouling management system by shipping companies.
5. The need for developing new technology to balance between environmental impacts and economic interests.
6. Use of the model is helps to identify the effect of biofouling on fuel oil consumption.
7. Possible future anti-fouling systems may advance the reduction of biofouling and empower ship energy efficiency.

Chapter 6

1.6.5 Conclusion and recommendation
Chapter 2

The legal developments of the Anti-Fouling System

2.1 Review of the legal developments of the anti-fouling system

This chapter is intended to review the regulation, resolution, guidelines and agreement at the international and national levels which were undertaken to reduce and control the risk of the use of harmful substances in an antifouling system. After 1960, the use of metal compounds in the painting industry has been developed, such as the use of organotin compound which is known as TBT based paint. The first phase of that product was free association paint. However, this type of paint has a problematic issue. That is, the rate of the leaching is uncontrolled and the lifetime of the paint is from twenty-four to thirty months. In the late 1960’s, and at the beginning of 1970, a sudden improvement in the paint industry noted and resulted in producing the second phase of TBT-based paint was named a self-polishing copolymer system with an advantage of the controlled rate of leaching and with an expected lifetime of 60 months. TBT-based paint is based on the biocides principal, which is organotin. In 1970, the self-polishing copolymer TBT-based paint became dominant and by the end of the 1970s, most shipping companies had used this product as hull coating due to its promising efficiency in reducing biofouling and its extended life time which for about five years.

According to Yebra, Kiil, & Dam-Johansen (2004) TBT was proven to be a strong Ecotoxicity. The first negative impacts were detected in France, where along France’s west coast it was reported that the high concentration of TBT leached from boats; this leading to the increase of the death rate of oyster larvae in the 1970s. Moreover, it caused the deformation of the shell of adults so that they became unsaleable. In the 1980s a reduction of the dog whelk population, had been noted in the United Kingdom due to
poisoning episodes from TBT (Santos, Ten Hallers-Tjabbes, Santos & Vieira, 2002; Strand & Asmund, 2003).

In the 1980s, high concentrations of TBT were reported from several coastal countries and areas such as the Mediterranean Sea, Atlantic coast of France, Bahrain, North Sea Off United Kingdom, Canada, United States, Australia and New Zealand. This urged many countries to regulate and limit the use of TBT as the example of France in 1982, where the use of TBT-based paint on small boats of less than 25 meter in length was prohibited. In 1990, Japan also prohibited the use of TBT-based paint in anti-fouling systems. In 1997s Japan also prohibited the production of all paints containing TBT compounds (IMO, 2018b). In 1988, the Paris Commission (PARCOM), an international organization concerned in the prevention of marine pollution at the northeast of Atlantic Ocean, requested that IMO develop an instrument to restrict the use of TBT-based paint in anti-fouling systems. By this time there was a preponderance of evidence that used TBT compounds and was damaging marine organisms and the food chain. This led many countries to establish measures under the national and regional levels, however, the need to develop international measures to regulate the use of TBT was crucial, and in 1990 the result from the Third International Organotin Conference declared that IMO was the appropriate organization to develop these measures. In 1990, IMO adopted a resolution on measures to control the use of organotin compounds in anti-fouling systems. Moreover, the resolution recommended that states should take action to prohibit the use of TBT-based paint on non-aluminum ships less than 25/meter in length, and to prohibit the use of TBT-based paint, which had a leaching rate of more than four micrograms of TBT per cm2 per day. These recommendations served as a transitional phase setup to ban the use of TBT-based paint in anti-fouling systems for ships. According to IMO (2018b), the result of the Rio Conference emphasized the needs to develop an international measure by IMO to control the risk of used TBT-based paint. In 1996, MEPC established a correspondence group for investigating TBT issues. In 1998, the correspondence group
came forward with conclusive advice that stressed the urgent need for developing mandatory international measures for anti-fouling systems and the prohibition of the use of organotin compounds in anti-fouling systems.

In 1998, IMO assigned a working group to draft a mandatory instrument to ban the use of any toxic compounds in anti-fouling systems such as TBT. In late 1998, IMO approved the draft resolution which stipulated a deadline for banning the use of organotin compounds by 2008. In 1996, although there was sufficient evidence for harmful effects caused by the introduced TBT to marine environment, there were some concerns about the existence of appropriate alternatives (TBT free paint). These concerns generated claims and debates, and consequently a consensus among IMO members was achieved. The response from the MEPC to these claims was as follows:

2.2 The issues and concerns that emerged among IMO member states after the announcement of the adoption of an international instrument to ban the use of organotin compounds in anti-fouling systems. According to IMO (2018b)

1. Insufficient efficient alternative products existing in the market
Response: there are already existing available TBT free paint products. In 1990, after the use of TBT was banned for small boats, the Japanese paint industry was encouraged to develop new TBT free antifouling paint. Further, a global ban of the use of TBT-based paint was established in 1990 for vessels less than 25/meters in length, which gives more opportunities to develop new products, such as seawater soluble matrices containing tin-free biologically active components.

2. Uncontrollable hull fouling leads to potential corrosion and safety hazards
Response: Available alternatives of anti-fouling systems are already controlled, and shipping companies which have appropriate dry-dock schedules will not face any corrosion and safety problems. Moreover, the anti-corrosive paint can be used in conjunction with new alternative anti-fouling systems.
3. **Increased dry-docking for ocean-going vessels.**
Response: Some of the available alternatives claim for an effective potential equal to the TBT-based paint in terms of dry-dock intervals every five years, however, many types of ships are regulated by SOLAS every 2.5 years for dry-docking, namely tanker ships and bulk carrier ships, and every one year for RoPax ships. In terms of the extra cost that would be added due to the increase of dry-dock intervals, some states proposed to impose fines on the polluting vessels.

4. **Unknown environmental risks due to the increased use of alternative biocides and their metabolites.**
Response: The environmental impacts were considered by MEPC while regulating the alternatives biocides.

5. **The accumulation potential of organic biocides may become more severe.**
Response: This is not expected to happen if the alternative selected under the criteria aims for protecting environmental risk. Some delegations argued that if the alternatives contain copper, it will lead to the same impact as organotin-based paints. However, some studies had already concluded that the hazards caused by copper are thousands of times less than the hazard created by organotin, so in this case there is no other alternative antifouling system; the use of copper still can benefit the environment.

6. **The acceleration of greenhouse and acid rain effects due to higher heavy oil consumption.**
Response: A study shows the worst case would increase the emission by 0.03 percent if the TBT free paint was used. The accumulation of biofouling will occur if the shipping companies do not take appropriate action on hull cleaning. Therefore, it would increase fuel oil consumption and operational costs. This scenario is unfavorable for any business. Moreover, the IMO environmental working group argues that it is not justifiable to allow the leaching of chemical compounds into the marine environment to reduce air emissions.
7. European shipyards claim that unilateral measures could result in the loss of business and possible closures of certain shipyards.

Response: The developed instrument includes the application of the banned TBT-based paint which will be global meaning when it comes into force there is no market distortion. During the year 2000 the MEPC working group was working on developing the draft of the convention. In April 2001 MEPC at the 45th meeting had tabled the revised draft convention. In October 2001, IMO held a diplomatic conference to adopt the AFS convention, and the convention under the name of International Convention on the Control of Harmful Anti-Fouling Systems on Ships (AFS Convention) was adopted. In 2003, a prohibition was applied against the application of any organotin compounds acting as biocides in an anti-fouling system. In 2008, the convention entered into force, which meant the complete prohibition of the use of organotin compounds as biocides in anti-fouling systems.

2.3 After the AFS Convention came into force (2008)

1. Ships were not allowed to carry any organotin compound on their hull or;
2. They can coat the unwanted paint with other materials to prevent the TBT from leaching.

The convention required each ship 400gt and above involved in international voyages (other than fixed or floating platforms) to carry out an initial survey before putting into service or before obtaining the anti-fouling system certificate for the first time. In addition, a survey was required in case the ship’s owner intended to change or replace the antifouling system.

2.4 Resolutions and Guidelines: According to IMO (2018a)

Resolution 1: By this resolution, member states are bound to stop an application for selling and/ or producing any substances as listed in Annex 1 in the Convention.
Resolution 2: Under this resolution, the International Maritime Organization is required to prepare a set of guidelines. The guidelines were developed and adopted as follows:
1. Guidelines for survey and certification of anti-fouling systems on ships - adopted by Resolution MEPC.102(48), superseded by Resolution MEPC.195(61);
2. Guidelines for brief sampling of anti-fouling systems on ships - adopted by Resolution MEPC.104(49);

Resolution 3: All States are required to have appropriate systems for the approval, registering and licensing of any anti-fouling systems that are used in their territories. Furthermore, this resolution urges states to participate in international forums which, pertain to the harmonization of the testing methods and performance standards of anti-fouling systems.

Resolution 4: IMO, by this resolution, supports the technical cooperation. IMO requests member states to cooperate with any competent entities or international and regional organizations or industry programs to provide technical support, especially for developing countries which are asking for assistance. Furthermore, IMO supports the cooperation for scientific and technical research on the effects of anti-fouling systems.
2.5 Summary of the national /international regulations and or agreements pertaining to the antifouling system:

Table 1: Summary of national /international regulations and or agreements.

<table>
<thead>
<tr>
<th>Country name</th>
<th>Date</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>France</td>
<td>1982</td>
<td>First ban use of TBT based paint for boat &lt; 25m at France west cost / regulate retail sale of antifouling paint</td>
</tr>
<tr>
<td>UK</td>
<td>1986</td>
<td>Regulate the retail sale of antifouling paint</td>
</tr>
<tr>
<td>Sweden, Belgium, Denmark, France, Netherlands, UK, Germany, Norway and Japan</td>
<td>1988</td>
<td>Jointly proposed to IMO as member states for the intentional ban for using the TBT in antifouling systems.</td>
</tr>
<tr>
<td>USA</td>
<td>1988</td>
<td>The federal organotin antifouling paint control was signed</td>
</tr>
<tr>
<td>Japan</td>
<td>1990</td>
<td>Comprehensive restriction of the use of TBT paint</td>
</tr>
<tr>
<td>UNCED</td>
<td>1992</td>
<td>At the Rio conference decision taken to urge IMO to work for adopting measures to prohibit the use of harmful substances used in antifouling systems</td>
</tr>
<tr>
<td>Sweden</td>
<td>2002</td>
<td>Use of copper in anti-fouling systems banned for recreational boats and smaller ships on the east coast of Sweden</td>
</tr>
<tr>
<td>Denmark</td>
<td>2003</td>
<td>Denmark followed Sweden by banning the use of copper</td>
</tr>
<tr>
<td>EU</td>
<td>2003</td>
<td>EU regulation (EC No782/2003) prohibition of the use of all organotin compounds in antifouling paints</td>
</tr>
</tbody>
</table>

(Source: Dekinesh, 2018)
**In conclusion,** it is noted that several states and organizations had banned the use of organotin compounds in anti-fouling systems as a forerunner of IMO, which created a concern about competitive advantage. Therefore, these states, namely Sweden, Belgium, Denmark, France, Netherlands, UK, Germany, Norway and Japan introduced a joint proposal to IMO for the international ban of the use of organotin compounds in anti-fouling systems. The AFS Convention came into force, through the efforts from IMO and its member states through:

1. The implementation,
2. Technical cooperation,
3. Survey and certification, and
4. The enforcement through port state control inspections.

There were many concerns generated in the marine industry; for example, whether the alternative paints would be effective as TB-based paint from both aspects of the environmental impact and the economic interest. From the environmental impact the concern was if the efficiency of alternatives would be able to prevent the hull fouling; for example, as a consequence of the control of the transfer of invasive species to new ecosystems. Additionally, from an economic interest the perspective shipping companies are concerned about the efficiency of the alternatives in terms of the paint cost and the prevention of fouling, which is linked to fuel oil consumption, dry-dock intervals, off hired period at dry dock, and the lifetime of the paint. Based on all the above evidence this is a driving force for the paint industry to produce several alternatives to cope with both the aspects, which create the challenges and uncertainties for shipping companies while selecting the most optimum anti-fouling system for their fleets among these various types.
Therefore, the next chapter investigates and reviews:

1. The biofouling formation and process.
2. The currently available antifouling systems.
3. The potential energy saved from anti-fouling systems.
The development of anti-fouling system types

3.1 Review of the development of anti-fouling system types/ potential of energy saving through antifouling systems

In order to have a clear view and understand the antifouling systems, it is important first to define “fouling”, the types, particularly focus on the bio-fouling formation mechanism of settlement, attachment and how a biofilm that is an obstacle for marine shipping can be developed on a ship’s hull.

3.2 Biofouling definitions

Wilson and Hansson (2015) defined fouling generally as the “undesired deposition of material on submerged structures, which reduce the efficiency and functionality of the fouled surface and/or the device”.

In particulate biofouling is defined as a process in which living organisms attach and colonize hard surfaces. Fouler are classified into three different categories namely, non-living natural substrate, living organism and man-made structure. (Durr et al., 2010).

Wahl and Lafargue (1990) stated that living organisms to reproduce and fulfill their life cycle need to settle on submerged marine structures therefore, a ship’s hull is an appropriate structure for bio foulers.

3.3 Types of fouling

There are two main types for fouling known as non-biological and biological.

Pugh, Hewitt, & Müller-Steinhagen (2005) stated that there are three types of non-biological fouling is divided as follows:
1. Particulate fouling occurs when sea water particles such as silt, sand, mud and other fines particles attach to surfaces mostly as a heat exchanger and act as an insulating layer.

2. Crystallization fouling means the sedimentation of sea water salts on surfaces, mainly heat exchanger.

3. Corrosion fouling mainly occurs on tubes when the metals are oxidized.

Biological fouling (biofouling) as stated by Junter, Coquet, Vilain, and Jouenne (2002) is a terminology used to describe all types of living organisms including bacterial cells, animal’s cells and plants in biofilm process. More than 4000 marine organisms may contribute to biofilm formation on substrate such as bacteria, algal, diatom, barnacles, mussels and tubeworms (Yebra et al., 2011).

Biofouling in terms of its formed unit size has been divided to micro-biofouling and macro- biofouling; unicellular organisms are found in a multitude in the ocean, such as bacteria and protozoa build micro-fouling, which can be thin or thick according to its thickness, while macro visible organisms such as mussels and oysters build macro-fouling.

Although the number of macro-foulers are less than the number of micro-foulers the adverse effects of macro-foulers on frictional resistance on ship’s hull is greater than micro-foulers due to their enormous size when compared to micro-foulers (Wilson & Hansson, 2015).

**3.4 Biofouling formation**

Biofouling formation is a cascade process, which consists of two main stages. The first stage is the result of a micro fouler generation, which is considered a very important basic for macro biofouling formations, therefore, preventing the first stage that will prevent the next stages (Wilson & Hansson, 2015).
According to Railkin (2003); Massanisso (2014) biofouling cascades can be illustrated in detail as follows:

1) Surface adsorption of organic materials (molecular fouling).
2) Micro-foulers settlement.
3) Micro-foulers attachment.
4) Production of extracellular Polymeric adhesive substances (EPS) by the prokaryotic micro fouler.
5) Micro-foulers proliferation (micro-biofouling).
6) Macro-foulers settlement and reproduction (macro-biofouling).
7) Attachment of randomly spread detritus.

**3.4.1 Factors influencing biofouling**

Biofouling is a complex process that is controlled by various physical and chemical aspects. These factors can be illustrated as follows: the pre-conditioning of the substratum, interface properties, biofoulers cell surface characteristics, EPS secretion ability, interspecies interactions, cellular transport, medium composition, nutrient availability, presence of inorganic material and the hydrodynamic conditions, and finally the presence of antifouling agents (Kim & Han, 2014; Davies et al., 1998; Donlan, 2002; Donlan and Costerton, 2002; Chmielewski and Frank, 2003; Gieseke et al., 2003; Huggett et al., 2009 & Hadfield, 2011).

Once the clean structure is submerged into seawater, it begins to attach with a molecular film of mostly organic substances found in the surrounding environment (Callow and Callow, 2011), then the micro and macro-biofoulers may settle and attach forming biofouling structures which inhabit the ship’s hull.
3.5 Essence of biofouling

3.5.1 Settlement

One of the most important steps for a biofouler organism is to find and attach a suitable surface (Wilson & Hansson, 2015). Settlement is the process of finding an appropriate surface, exploration, evaluation and begins to contact with that surface (Durr, 2010). Settlement is the weakest step in the biofilm formation cascade, therefore it is a point of concern to get rid of the biofouling in its initial stages (Dargahi, Hosseinidoust, Tufenkji, & Omanovic, 2014).

According to Allison (2003); Amann et al. (1998); Roberts et al. (1991) after a few hours of surface immersion in the sea water, the surface becomes covered by micro and macro biofouling, whereas micro fouling is a foundation for macro-fouling. Micro-biofilm formation might be faster according to the micro-biofouler lifecycle, and a shorter lifecycle results in a rapid and thick biofilm (Wilson & Hansson, 2015). Bacteria are the primary colonizers of the biofilm substrata, where they proliferate and excrete their attachment slimy matrix, hence, it can establish a stable resistant micro-biofilm community (Dobretsov & Qian, 2002).

The types of the colonized biofoulers rely on the organisms existing surroundings. Biofouling formation mainly begins with micro-foulers, such as bacterial cells, and ends up with a macro fouler settlement, such as barnacles (Barranguet et al., 2005; Battin et al., 2007; Besemer, 2012&2007& Antunes, 2010).

The competing on the necessities of life such as nutrients, aerobic condition, space and light are control the diversity of the organisms within the biofilm (Pippo et al., 2013). As biofoulers grow and reproduce, the competition for life needs such items such as nutrients, aerobic condition, space, and light, select biofoulers species, which are extremely competitive for the available limiting resources. For an explanation, the utilization of oxygen and carbon dioxide during the photosynthesis process results in a steep vertical
redox that stratifies the biofilm community cells, restricting aerobics to the upper layer of the biofilm and the an-aerobics to the lower layers (Manzo & Massanisso, 2014).

3.5.2 Extra polymeric substance EPS deposition

The EPS matrix is a slimy, highly hydrated, and mostly composed of polysaccharides associated with a mixture of glycoproteins, proteins, nucleic acids, humic substances, phospholipids and glycolipids (Costerton et al., 1999; Daims & Wagner, 2007; Donlan, 2002; Fazi et al., 2005). The produced extracellular matrix “slime” plays the main role in the biofilm bacterium connection and functionality (Fazi, Pizzetti, & Di Pippo, 2014).

Fazi et al. (2008); Flemming & Wingender (2010) added that EPS apparently is a hydrogel-like structure, which determines the whole biofilm’s properties.

The EPS texture nature enfolds and gathers the microorganisms forming the biofilm, which permits the proliferated colonies to be stable that allows cells to metabolize, replicate and interconnect with each other more efficiently producing a functional stable microbial community with a minimum use of its stored energy (Amann, Ludwig, & Schleifer, 1995).

Moreover, EPS provides protection against heavy metals, toxic substances and predators grazing. Finally, biofilms can be defined as an interconnected matrix-enclosed microbial community that inhabits a ship’s hull and devices, developing a highly distinguished architecture which seems like ripples, mushrooms, and ridges (Manzo & Massanisso, 2014).

3.5.3 Attachment

Rationally, an attachment will become more stable on rougher hydrophobic surfaces that are pre-conditioned with a molecular film (Simões & Simões, 2010). The surrounding environmental condition of the water temperature, flow velocity, even nutrient concentration can also affect the attachment’s strength (Donlan, 2002; Simões et
After settlement on a surface, microorganisms start to secrete EPS so that it ensures their stability, growth so they proliferate, resulting in a completed biofilm formation (Landoulsi, 2011). Hence, a hull adsorption of chemical organics first, like glycoproteins, proteoglycans and polysaccharides that occur naturally (molecular film deposition) is not necessary for the adhesion and settlement of biofoulers (Cooksey, 1995). Biofoulers cell surface properties, extracellular appendages and the micro-organism ability to produce the adhesive EPS provides a competitive advantage among the microorganisms found in a mixed community (Donlan, 2002; Simões et al., 2007b). Ultra-smooth surfaces are unsuitable for a microorganism to settle (Ralston, 2011). The main surface properties influencing a micro-organism attachment are surface energy and texture. One of the reasons why the problem with marine fouling is so complex, is the surface energy. For more explanation, bryozoans and barnacles prefer to attach the surface with different energy, where, diatoms and the green algal Ulva have opposite adhesion strengths depending on the surfaces wettability (Wilson & Hansson, 2015).

In addition, the attachment point theory explains that firm attachment is increased when there is enough and suitable attachment points on both of the microorganism and the surface. On the micro-scale level, if the organism attachment points are larger than the micro texture scale they will have a reduced adhesion, but if the organisms have attachment points smaller than the scale of micro texture, the adhesion strength will be promoted (Scardino, 2006, 2008).

### 3.6 History of anti-fouling systems

In the literature the data for anti-fouling systems has been recorded for a long time. According to some literature, it has been claimed that the impacts of biofouling have been addressed more than 2000 years ago, where copper layers, asphalt and tar oil were used on a ship’s bottom in the ancient era such as the Phoenicians and Carthaginians (Callow, 1990; WHOI, 1952).
However, this study will focus on the time that TBT began to be used, as this is more relevant to this study’s focus. Furthermore, TBT was a driving force for IMO to adopt new measures for controlling fouling hazards, as well as for paint manufacturers to focus their research to find optimum alternatives.

3.7 Inventory of risks and damages associated with biofouling accumulation on ship’s hull

1. Generation of hull roughness
   1.1. Increase of fractional resistance,
   1.2. Increase of ship’s weight,
   1.3. Reduction of ship’s speed,
   1.4. Increase of required propulsive power, (Il Koo et al., 2017).
   1.5. Increase of fuel oil consumption, which is estimated for 40 percent more than a cleaned hull (Champ, 2000). Furthermore, an increase in the total voyage costs up to 77 percent (Abbott, Abel, Arnold & Milne, 2000).
   1.6. Increase of air emissions in particular (GHG)

2. The increase of dry-dock frequencies results in a huge amount of toxic waste that can be generated in the docking area.

3. The coating layer is prone to corrosion and damage due to hull cleaning.

4. A great opportunity to introduce new invasive species to new ecosystems (Reise, Gollasch, & Wolff, 1999).

3.8 The developments of Types of anti-fouling systems

The result from reviewing the era before the AFS convention, shows the early record of fouling control, and several substances used as an anti-fouling system such as lead sheets, lime, arsenal, oil mixed with sulphur and copper (Stebbing, 1985; Clare, 1995; Ten Hallers-Tjabbes, 1997).
In the 1960s, after the development of the chemical industry, TBT became the dominant biocide used in the antifouling system due to its efficiency in releasing hull fouling, as well as being cost-effective (Evans, 1970).

3.8.1 Biocidal anti-fouling paints
These paints contain one or more active substances (biocides) such as copper which control or prevent the growth of organisms (EU, 1998). Copper was selected as an example because of its efficacy as an active substance for controlling several biofouling organisms. As an indicator figure, rather than an absolute, the required leaching rate of copper to prevent the barnacles fouling is 10 µg/cm²/day while, 20 µg/cm²/day required for preventing diatom fouling (Finnie & Williams, 2010).

3.8.1.1 Free association paint
TBT, when used as a biocide, is released by contact leaching, and will leach out from the coat when exposed to water; the rate of leaching is then uncontrolled resulting in the loss of the coating layer in a short time. As a result, the second phase TBT-based paint is developed. (Champ & Pugh, 1987).

3.8.1.2 Ablative or Copolymer depletion paint (CDP)
Uncontrolled leaching has led to developing this improved solubility mechanism of paint, which depends on the hydration or dissolution means of breaking bonds. It is also a soluble matrix paint, and over time the coating layer will become thinner and the lifetime of coating is estimated to be 36 months (Yebra, Kiil, & Dam-Johansen, 2004).
3.8.1.3 Tributyltin self-polishing copolymer (TBT-SPC paints)

In the 1970s, TBT-SPC paints were used in anti-fouling systems, and this new principle came with a controlled and constant leaching rate. Quite simply, as the waves contacted with the hull it released the biocides. This new principle resulted in an extended coating life time of about 60 months (Evans, 1970; Champ & Pugh, 1987; Callow, 1990).

There are more advantages for this self-polishing nature, for example:

1. Preventing biofouling formation in an early stage,
2. The hull surface is not ready to receive fouling for a long time due to unstable substrate,
3. Reducing fuel oil consumption (Ludgate, 1987; Clare, 1995).

3.8.1.4 TBT-free copolymer-based technologies /first anti-fouling system free of TBT

In the early 1990s, IMO adopted a resolution urging governments to ban TBT based paint as follows:

1. Eliminate the use of TBT based paint for non-aluminum vessels less than 25 meters in length.
2. Prohibit the use of any TBT based paint with a leaching rate of more than 4 micrograms of TBT per cm² per day.

By this resolution, the need for alternatives became crucial, and as a result in introducing nonstick coating for small vessels in the same time various tin free coating developed.

However, studies have shown that the use of large amounts of copper in antifouling systems can be toxic to marine organism (Abbasi, Shackley, & King, 1995; Anderson, Middaugh, Hunt, & Turpen, 1991; Katranitsas, Castritsi-Catharios, & Persoone, 2003). Copper-based paint replaced the TBT based paint in the 1990s.
As a result, the development of polymer-based tin free SPC technologies was approved. Two products were introduced with a high performance being metal acrylate copolymers and silyl acrylate copolymers.

Metal acrylate copolymer paint was developed by the Nippon paint company (NPC), where specifically metals were used (copper and zinc), then widely introduced by NPC and other international paint companies, which encouraged IMO to regulate the TBT based paint (Ohsugi, Matsuda, Eguchi, & Ishikura, 1989).

More painting companies, such as Kansai Paint and Chugoku Marine Paints (CMP) later developed related acrylate copolymer paint until it became commercially used (Yebra et al., 2004).

Although there are several products based on metal acrylate copolymer SPC technology, the most proven type shows the same efficiency equal to TBT-SPCs based paint that was a copper-SPC product.

For silyl acrylate copolymers SPCs; these have been developed and commercially introduced by (CMP) and Nippon. The principle of silyl acrylate copolymers is based on rosin and it can be classified under CDP, unlike the metal acrylate copolymers SPCs (Silverman & Aubart, 2006; Finnie & Williams, 2010).

The difference between those two types of acrylate copolymers, metal acrylate copolymers SPCs was claimed to be a high performance antifouling system, while silyl acrylate copolymers CDP claimed it to be cheaper and a low-performance antifouling system.

3.8.1.5 Other biocidal antifouling paint technologies

A new technology has been developed by mixing metal acrylate copolymers SPCs with rosin CDP, resulting in a new product named hybrid paints which, when combined, it had the characteristics of SPCs and CDP as well as a reasonable price along with a life time of between 3-5 years (Yebra, Kiil, Dam-Johansen, & Weinell, 2006).
3.8.1.6 Natural biocidal antifouling systems

Almeida, Diamantino, and de Souse (2007) stated that there are many researches in the area of natural product biocides, such as the research to use sponge, algae toads and trees.

Also, many studies have been done with natural product antifouling based biocides. According to De Nys et al. (1995) the halogenated furanones groups are the most widely of those that have been studied in natural product biocides.

Zosetric acid natural biocide is derived from the marine algae Zostera marina having been proven to be a good example for biofouling prevention. Moreover, it can be added to conventional and silicon paint but the problem is it has high water solubility and it is difficult to control the release rate (Todd, Zimmerman, Crews, & Alberte, 1993; Finnie & Williams, 2010).

Another natural category that has been studied is enzymes which has been investigated for over 20 years. Furthermore, a complete review by Olsen et al. completed by the assessment of the state of the art of enzymatic antifouling technology (Olsen, Pedersen, Laursen, Kiil, & Dam-Johansen, 2007).

Enzymes like proteases, can act in the antifouling process in different ways, direct and indirect. The direct way, has a biocidal effect, reducing the ability of an organism to attach. The indirect way is to produce biocides from the interaction with the coating or the surroundings (Bonaventura & Hooper, 1991).

It was concluded in the complete review by Olsen et al that there are technical and legal issues associated with enzymes; the duration of enzymes activity and the efficiency of different types of organisms, for example. For legal issues, the European Union classified the enzymes under biocides, therefore, they should pass all the legal requirements started from test procedures until the final registration, which means more time and cost for approval (Olsen et al, 2007).
3.8.2 Non biocidal coatings

Due to the increase of the environmental impact concerns, further development necessitated in antifouling system. New technology has been developed by reducing the ability of a surface for adhering and attaching organisms, which allows self-cleaning, either by the weight of the organisms or by the water flow (Candries & Anderson, 2003).

Despite the fact that this technology has been commercially introduced into the market in 1995, the mechanism for releasing the fouling from the surface is still not well recognized (Finnie & Williams, 2010).

3.8.2.1 Foul release surfaces

The principle of an anti-fouling concept (foul release surface) is to create a surface with minimum ability for adhesion to the adheresives created by marine organisms rather than an active substance (Fourche, 1995). Several studies have been done to study the relationship between surface properties and adhesion strength. Callow and Fletcher (1994) stated that you can achieve less adhesion strength for the surface by reducing the wetting of it and he claims that bio adhesion will occur when the critical surface tension reaches between 20 to 30 mN/m as force per unit length.

However, another study done by Newby, Chaudhury, and Brown (1995) stated that surface tension is not only the main factor commanding surface adhesion strength, also we need to consider fracture mechanics as a guide for breaking a marine surface adhesive connection. Moreover, they demonstrate a model. The result from the model shows that we cannot predict the surface adhesive strength if the surface is free of energy. Another study done by Brady (2000) confirmed the relationship between surface energy and elastic factors.

Kohl and Singer (1999) stated that there is adverse relationship between the releasing force of the surface and film thicknesses.
3.8.2.2 Foul release surface materials

Several materials have been tested for foul release properties and ranked according to barnacle’s adhesion strength. The result show that the polymer for two materials, namely silicones and fluoropolymers, passed the foul release requirements positively (Swain, 1999). Silicon was introduced first and was commercially a successful alternative. Until recently, fluoropolymer became dominant due to its proven high performance and cost effect (Candries & Anderson, 2003; Finnie & Williams, 2010).

3.8.3 Non biocidal coatings Types

3.8.3.1 Fluoropolymers

These are used as fouling release coatings (FRCs) and are defined by polymers containing the fluorinated group. Many fluoropolymers based materials have been studied, the first in 1976, namely for fluorinated polyurethane coatings based on fluorinated polyols (Finnie & Williams, 2010).

Furthermore, those fluorinated polyurethane coatings have been applied to two USA navy patrols, the result shows a limited success, and hand scrubbing was needed to clean fouled shell (Brady & Griffith, 1987).

A further study in 2005, focused on the improvement of released fouling by introducing fluoropolymer and polyethylene glycol amphiphilic networks. (Gudipati, Finlay, Callow, Callow, & Wooley, 2005). This improvement has been confirmed by international paint companies, introducing a product called Intersleek 900.

3.8.3.2 Silicones

Known also by polysiloxanes the nonstick properties which are obtained from the non-polar methyl organic side groups, make it an optimum candidate for FRCs. (Vincent & Bausch, 1997).
In 1955, silicones such as FRCs became known, however, there are many studies done to optimize the use of silicones. Almeida, et al. (2007) stated that first trial for silicon application showed negative results due to insufficient adhesion on the surface and was furthermore costly.

Milne (1975) stated that an improvement in silicon fouling release was obtained by adding phenylmethyl siloxanes. However, there are more studies and funds by the US Office of Naval Research (ONR) for improving the fouling release mechanism. The main factor for increasing the application of silicon was because of the improvement on adhesion properties on the surface (Webster, Chisholm, & Stafslien, 2007; Groenlund Scholten, Martin, Weinrich Thorlaksen, Oxfeldt Andrensen, & Nielsen, 2003; Hamilton, Green, & Williams, 1998). FRCs became commercially viable after the TBT-based banned drive painting companies, such as international paint and Sigma paint, to develop new products based on FRCs for covering a wide range of ships of different speeds. For example, the international paint introduced Fluoropolymers-based paint for ships with speeds greater than 10 knots. Moreover, replacing the use of tin free SPCs due to the cost reduction (Finnie & Williams, 2010). Furthermore, potential energy saving by FRCs, which reached a 10 percent saving in fuel consumption due to the reduction of hydrodynamics drag and the increasing of hull smoothness, drives shipping companies to use of FRCs technology (Candries, Altar, & Anderson, 2000; Westergaard, 2007).

3.8.4 Non-coating solutions

In the last fifty years, several technologies and approaches have been tested such as ultrasonic, biochemical heat, radiation and electrical (Kohn, 1998; Matsunaga et al., 1998), and low frequency sound waves (Branscomb & Rittschof, 1984). However, none of them have proven to be highly effective methods, while, furthermore, still far from being commercially viable.
Another approach being tested is namely those naturally produced compounds that have been derived from marine cnidarians (Standing, Hooper, & Costlow, 1984). Such deriving anti-fouling compounds from bacteria have been noted as promising approaches. The use of mechanical cleaning devices to clean a ship’s hull, also known as hull husbandry, have become viable. Finnie and Williams (2010) state that several companies are offering cleaning solutions for coated with silicones and glass epoxy.

**In conclusion**

The harmful consequences of fouling on a ship’s hull has been addressed for millennia, and is associated with low speed, more power required to maintain same speed, and the increase of maintenance. Paint and coating technology have been used to minimize those consequences and several developments of coatings and paint have been recorded under different categories:

1. Biocidal paint based on an active toxic substance that prohibits the settlement of organisms on the ship’s hull.
2. Biocidal free paint FRCs mechanisms based on the creation of unstable surfaces which protect an early growth of organisms and further easily removal these organisms through the water flow

Biocidal paint, which has been commercially promising, was classified as follows:

1. Control leaching
2. Soluble matrix (CDP, SPC)
3. Hybrid antifouling paint

Competitive advantages between painting companies drive them to develop, improve and create long-term anti-fouling system technologies. In addition, the increase of the legislation trends to ban and restrict the use of any harmful substances used in anti-fouling systems are significant.
As a legal requirement, painting companies are required to demonstrate that the used substances in any biocide-based paints are environmentally friendly; one needs to pass a test under intensive procedures which consider to be time consuming and costly. Furthermore, painting companies still need to prove that even if the source of biocides is neutrally, it still means no difference in the legal requirements between synthetic biocides and natural biocides.

Based on this, the painting companies have worked towards research in other areas to develop other technologies based on biocidal free control fouling, to satisfy both the environmental needs and shipping companies need.

3.9 Review of energy saving potential through anti-fouling systems

Biofouling is defined as unwanted organisms attached and settled to submerged man-made structures, such as ship’s hull. The consequences of this attachment is the increase of hull roughness and frictional resistance which leads to an increase of power to maintain the required speed therefore the fuel oil consumption increases.

It is crucial for shipping companies to understand the relationship between the antifouling systems and the amount of fuel oil that is possible to save from an economic benefit point of view and reduce GHG emissions from the environmental impact point of view. It has been noted that 50 percent of the operating costs are because of the high fuel bills.

Champ and Lowenstein (1987) stated for a ship, with a hull roughness of 10µm, it is expected that an increase of fuel consumption with an average 0.5 percent and the ship with a fouled hull for 5 percent expected to give an increase of fuel consumption of an average of 7.5 percent.

Ludgate (1987) stated that when a ship’s hull is fouled with 33 percent it will result in an increase of fuel cost by 50 percent. This fouling will increase the dry-dock frequencies and periods consequently, reducing the profits.
Inglis, Floerl, and Woods (2012) stated that fuel efficiency, and a ship’s speed are important key issues for commercial and passenger ships while they may fulfill their obligations.

A ship’s performance in terms of speed and fuel efficiency is pertinent to the appropriate selection of antifouling systems, which differs from one ship to another depending on the ships operating profile and types (Edyvean, 2010).

A heavily fouled ship results in an increased power to greater than 80 percent, while a slime fouled ship increases the required power to about 20 percent (Bressy & Lejars, 2014).

Based on all above statements that necessitate the adoption of anti-fouling management systems for shipping companies to select the most efficient anti-fouling system for their fleets from both aspects, the economic benefits and the environmental concerns.
Chapter 4

Current and future solutions of anti-fouling systems

4.1 Methods

The research primarily explores the perspectives of the current and earlier antifouling systems, from different anti-fouling systems, to hull cleaning mechanisms, regarding the relationship between biofouling accumulation and fuel oil consumption.

An extensive literature review was conducted throughout the research on the legal aspects, biofouling formation and process, and antifouling systems including hull coatings.

This study is based on data from different sources pertinent to marine industries, such as paint manufacturers, shipping companies, dry-docks, classification societies, ship-owner associations, data collected through questionnaires, interviews, desk research and personal communications.

The questions have been formulated and organized accordingly; the author determined the needs to accomplish the six objectives:

1. Analyze the current anti-fouling systems implemented by shipping companies such as Maersk and Stolt tanker companies.
2. Investigate current antifouling paints/coats produced by big/medium paint manufacturers such as Sigma paint (PPG) and Chugoku Paint.
3. Investigate the different antifouling systems applied through shipbuilders such as China, South Korea, and the Myer Turku shipyards. China and South Korea have been selected because of the last three decades where they have been recognized as having a large shipbuilder capacity, while for Turku it is a pioneer shipyard in Europe and a specialist in passenger ships since 200 years ago.
4. Determine effective cleaning intervals by asking questions to shipping companies about their hull cleaning schedules, fuel oil consumptions and running distances for a certain period post and prior to hull cleaning.

5. Identify how biofouling accumulation affects ship performance (fuel consumption, ship’s speed).

6. Design a decision-making framework for maximizing energy efficiency by identifying the main contributing categories that influence the optimum selection of antifouling performances.

A SWOT analysis was used to better understand the strengths, weaknesses, opportunities and threats for the collected data by literature and questionnaire regarding anti-fouling systems and hull cleaning mechanisms.

A qualitative data analysis has been applied in this study to code the data under specific categories; a quantitative data analysis has been applied to examine the cost and benefits from the quantitative excel datasheet obtained from RINA classification society for calculating fuel oil consumption before and after hull cleaning (in-water or out-water cleaning).

4.2 Data analysis

4.2.1 Qualitative analysis has been applied through a SWOT analysis for assessing the current anti-fouling systems in use. The collected data was coded by the author under the following categories:

1. Biocidal paint
   a. Antifouling biocides
   b. Soluble matrix paints
   c. Contact leaching paints
   d. Ablative paints
   e. Self-polishing copolymer paints
2. Non-toxic coatings
   a. Fouling release coatings
   b. Deterrent surfaces
   c. Biomimetic coating
   d. Hull Bug (grooming device)
   e. Cleaning device (boat washer)

A SWOT analysis

Table 2: SWOT analysis

<table>
<thead>
<tr>
<th>Anti-fouling category</th>
<th>Strengths</th>
<th>Weaknesses</th>
<th>Opportunities</th>
<th>Threats</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anti-fouling biocide</td>
<td>- Effective anti-fouling agents</td>
<td>- Short list in terms of accepted compound</td>
<td>- Use of Copper compound as less hazard than TBT</td>
<td>- Regulation for controlling and restricting the use of biocides</td>
</tr>
<tr>
<td>Soluble matrix paint</td>
<td>- Mixed with matrix/binder/resin</td>
<td>- Continuously released at the paint Surface</td>
<td>- Based on the natural product wood rosin</td>
<td>- Regulations for controlling and restricting use of biocides</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Lifetime between 18-24 months</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contact leaching paint</td>
<td>- Insoluble matrix</td>
<td>- Continuous biocide release</td>
<td>- Less hazard biocides</td>
<td>- Regulations for controlling and restricting use of biocides</td>
</tr>
<tr>
<td></td>
<td>- Hard racing</td>
<td>- Life time mostly not exceeding 18 months</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Low cost</td>
<td>- Out water application</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Adverse environmental impact</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Improvement in biocides release system such as (CDP, SPC)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Another solution not using biocides</td>
<td></td>
</tr>
<tr>
<td><strong>Ablative paint Or (CDP)</strong></td>
<td>Soluble matrix /control depletion polymer -low cost -Presently used</td>
<td>Mechanism hydration &amp; dissolution -use stronger biocides when compared with SPC, Hybrid systems -adverse effects on environment -possible release of biocides during hull cleaning -possible hull roughness because of leaching mechanism -possible to oxidize while exposed to air</td>
<td>Life time up to 36 months -cost is a key factor on selecting anti-fouling system - Regulations for controlling and restricting use of biocides - Another solution not using biocides</td>
<td></td>
</tr>
<tr>
<td>---------------------------</td>
<td>-------------------------------------------------</td>
<td>--------------------------------------------------------------------------------</td>
<td>--------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td><strong>Self-polishing copolymer paint (SPC)</strong></td>
<td>Copylomer act as paint matrix &amp; biocides - Copolymer coat varies to work for different ship speed profile</td>
<td>As biocides still environmental impact -High price - Possible release of biocides</td>
<td>Improve ships performance in case an increased fuel price will be very effective -Possible advanced - Regulation for controlling and restricting use of biocides - Another solution not using biocides</td>
<td></td>
</tr>
</tbody>
</table>
| **Hybrid (SPC +CDP)** | - Controlled release rate  
  - Reasonable price but higher than CDP | - As biocides still environmental impact  
  - Possible release of biocides while cleaning hull | - Effective in medium biofouling areas  
  - Use of new biocides | - Regulation for controlling and restricting use of biocides  
  - Another solutions not using biocides |
|-----------------------|---------------------------------------------|--------------------------------|--------------------------------|---------------------------------|
| **Fouling release coatings (FRCs)** | - Is no use for active substances as biocides  
  - Environmentally friendly  
  - Effective for long time | - Ship should move in the water for activity  
  - Soft and fragile  
  - More relevant to high speed ship  
  - Ship should be at dry-dock during application  
  - High cost  
  - Less efficiency than SPC  
  - Not easy to apply; needs professional drive for more research and development  
  - Became an alternative solution to biocides  
  - More restriction of regulations concerning environmental impact of use of biocides | - No solution for biofilm  
  - Not working while ship in static state  
  - Less efficiency in law speed  
  - Use of environmentally friendly biocides |
### Deterrent surface
- Use of chemical & physical process
- Environmentally friendly alternative
- Natural product is under research
- Chance for electric conductive coating

### Biomimetic coating
- Natural solution
- Mimic the skin of ocean creatures
- Environmentally friendly
- Prevent the initial stage of biofilm formation (settlement)
- Under research state
- Not yet tested for large surface
- More restrictions by regulations concerning environmental impacts of use of biocides
- Appropriate solution due to increase of environmental awareness
- Needs further research for commercial use
- Unknown price

### Ultra Sonic Transducer
- Environmentally friendly
- Free of biocides
- Under water noise
- Currently used in small private boats
- More restrictions by regulations concerned environmental impacts of use of biocides
- Drive force for research and development of anti-fouling systems
- Regulations to control under water noise

### Grooming device (Cleaning device)
- In water or out of water cleaning process
- Ship off hire - divers cost - while cleaning
- Cleaning schedule to better
- Environmental impact due to cleaning residual
<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short time needed cleaning</td>
<td>maybe chance for releasing biocides result in less antifouling performance</td>
</tr>
<tr>
<td>Not damaging coating layer</td>
<td>- can’t replace antifouling system</td>
</tr>
<tr>
<td>Cleaning micro-biofilm layer</td>
<td>- used for cleaning micro-biofilm rather than macro-biofilm</td>
</tr>
<tr>
<td>Preventing macro-fouling formation for longer time</td>
<td>antifouling performance - Nylon brush for sensitive hulls</td>
</tr>
<tr>
<td>Reduces ship’s drag fuel consumption</td>
<td>- regulations due to biological pollution</td>
</tr>
</tbody>
</table>

(Source: Dekinesh, 2018)

**Summary of SWOT analysis**

It has been noted from the above table that there are two dominant mechanisms for combating biofouling; the antifouling mechanism and the fouling release mechanism. What is the different between them and do they fulfill the future demands from both aspects; the environment requirement and the economic benefit.

Firstly, the author will answer the first question. The antifouling mechanism is a mechanism used to kill the organism by active substances which are one or group of heavy metals called biocides. In contrast to this, fouling releases no biocides, nor heavy metals, but is based on the non-stick mechanism.

Both mechanisms do not give a zero result for biofouling on a ship’s hull; rather they reduce the fouling thickness, or in other words, they need to integrate it with the hull cleaning operation.

Secondly, in answer to the second question, both mechanisms have drawbacks; biocides have a high performance but use active substances which harm the marine environment. As opposed to FRCs, there is virtually no impact on the marine environment, but it does
have a low performance in the idle ship and slow steaming mode. This was an opportunity to develop more environmentally friendly mechanisms, which are the fouling release mechanisms of FRCs. Moreover, the prediction of more regulations to restrict the use of biocides as defined in the AFS Convention (specifically annex 1) which results in the limitation of antifouling using the biocides which would challenge the improvement of antifouling performances. However, as stated by a PPG paint company (personal contact, 2018) the use of antifouling mechanisms (biocides-SPCs) will be extended for more time, due to the inefficiency of FRCs mechanisms, particularly when the ship is underway at a low speed or staying at anchor for a long time. Which is considered to be one of the key factors, to be more dependent on antifouling mechanism (biocides-SPCs) rather than FRCs. When it comes to hull cleaning it is not a standalone solution, or in other words, it is used in conjunction with two other mechanisms, which result in additional cost and time.

From the SWOT analysis, it seems to be that current solutions (mechanisms) are far from satisfying both the high performances and the environmental impacts.

Figure 1 illustrates the concept of the antifouling mechanism more specifically (self-polishing co-polymer mechanism) which has been chosen due to its domination of the current market as per data collected through questionnaires (Dalian COSCO KHI shipyard & PPG paint company, 2018). While Figure 2 illustrates the concept of the fouling release coatings mechanism (FRCs)
Figure 1: Self-polishing binder system

(Source: adopted from PPG August, 2018)
Figure 2 Illustrated the concept of foul release mechanisms

(Source: adopted from PPG August, 2018)

As aforementioned, the anti-fouling mechanism was dominant, however, to maintain high performance (antifouling efficiency and fuel saving) it is required to have a consistent biocide delivery plus the controlled polishing, which has an environmental impact so that it is concluded to be an inappropriate solution. Earlier, the author highlighted that the fouling release mechanism was an inappropriate solution due to its limitation for the low speed ship and idle ship.

4.3 Findings and discussions

Based on the above analysis there is a gap between the current solutions and the optimum solutions. First the author had identified the optimum solution through the study of Dr. Geoff Swain of Florida Institute of Technology. He had a specific study on the effects of biofouling accumulation and control. Dr. Swain has published many articles and this article “Can Biomimicry and Bioinspiration Provide Solutions for Fouling Control?”
Ralston and Swain (2011) had identified the optimum antifouling solution. Based on that article, and the data analysis by the author, the optimum solutions have been identified as follows:

4.3.1 Characteristics of optimum solutions

1. **Cost-effectiveness**: it is a crucial factor for the solution; it is all about business from the shipping company’s point of view, so that the optimum antifouling solution has a low initial cost, moreover, it has an effective reduction on the ship’s drag which directly influences the fuel bill.

2. **Prevent the formation and the growth of all types of fouling**: micro-fouling and macro fouling are very important factors as well, because the soft flours are mostly a base for hard fouler, which increase the fuel consumption.

3. **Maintain and improve the ship’s smoothness**: in order to avoid hull roughness, the solution should support and optimize the ship’s hydrodynamic profile, which directly affects the fuel consumption.

4. **Life time antifouling systems**: it is also a shipping company’s point of view; the optimum solution has to be for a ship’s life cycle, or at least an extended life time.

5. **Compliance with laws and regulations**: as IMO regulates the shipping industry it is predicted there will be more restrictions and regulations to protect marine life; the optimum solution has to be environmental friendly rather than in the past and current solution.

6. **Prevent the transfer of invasive species**: which have a negative impact on the marine ecosystem, therefore the optimum solution has to stop the introduction of invasive species of a new marine ecosystem.

7. **Less maintenance and easy to apply**: the ship is made for business so when the ship is under repair or maintenance it is very important to minimize the off-hire time there for, the optimum solution has to be easy in application and maintenance operations.
8. **Be compatible with the ship’s hull and ship’s recycle:** not to cause damage or corrosion to the ship’s hull and marine environment; has to pass through an appropriate test procedure before application.

Now we do have more ideas about better solutions in other words optimum solutions. The next step is to compare the currently used systems and potential optimum solutions by completing this comparison we would be able to identify the gap between today’s solutions and optimum solutions.

**Table 3: Comparison between today’s solutions and optimum solutions**

<table>
<thead>
<tr>
<th>Optimum solution (1)</th>
<th>Cost –effectiveness should be presented by optimum solution</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Current mechanisms</strong></td>
<td>We have seen from literature that hard fouled hull can cause 80% of increased power while soft fouled ship increased to 20% which, increased fuel bill, very important to select an effective (high-performance) anti-fouling system, so shipping company should investigate sailing area as fouling intensity differs from low to medium or heavy fouling, many factors should be consider such as sea water temperature.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Optimum solution (2)</th>
<th>Prevent the formation and the growth of all types of fouling</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Current mechanisms</strong></td>
<td>Not yet achieved by current solutions unless the ship exposed to hull cleaning which put, extra cost, more delay and is not acceptable operation by many ports. Moreover, hull cleaning is not preventing fouling formation rather dealing with it. However today solutions can prevent the formation of macro fouling and recently micro fouling is...</td>
</tr>
</tbody>
</table>
under research with some improvement to prevent bio film formation.

<table>
<thead>
<tr>
<th>Optimum solution (3)</th>
<th>Maintain and improve the ship’s smoothness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current mechanisms</td>
<td>Ship’s smoothness is indicated by ship’s drag today solutions is proven good result in reduction of ship’s drag due to application of foul release coatings FRCs however, shipping companies looking for optimization of fuel consumption by more reduction on ship’s drag</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Optimum solution (4)</th>
<th>Life time of antifouling systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current mechanisms</td>
<td>Today solutions are only can be for maximum five years which achieved by FRCs, on the other hand for SPCs mechanism the prudent management in shipping companies can control the paint life time through the selection of leaching layer thickness as an example for tanker ship it should visit the dry-dock once every 30 months as per Safety of Life at Sea regulation (SOLAS) and it can be the same time for repainting to avoid off hiring the ship. Furthermore, the cost of paint will be less due to less thickness leaching layer as adjusted for 30 months instead of applying of more thickness and by cleaning the hull at dry-dock result in damage to the paint and losing of money.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Optimum solution (5)</th>
<th>Compliance with laws and regulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current mechanisms</td>
<td>It is a driver for any solution to gets its approval, today solutions for FRCs it is environmentally friendly however it is not appropriate for slow speed ship and idle ship. For SPCs solution is still use of biocides and we never know what is future regulation, which permit the use of the substance</td>
</tr>
</tbody>
</table>
today and might be restricted in the future. Moreover, the regulation for testing and getting approval for new substances even it is created by natural substances should follow same test and approval procedures, putting more pressure on paint manufacturers.

<table>
<thead>
<tr>
<th>Optimum solution (6)</th>
<th>Prevent the transfer of invasive species</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current mechanisms</td>
<td>Today solutions be able to prevent the transfer of macro fouling which is considered very good achievement. However, for micro fouling further development is needed to completely prevent the transfer of invasive species to new ecosystem (biological pollution)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Optimum solution (7)</th>
<th>Less maintenance and easy to apply</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current mechanisms</td>
<td>Although painting is an easy task but some types of paint need professional. Any paint or even spot maintenance for antifouling paint need the ship to be at dry dock. regarding to hull grooming it can be in –water or out-water but is needed professional operators due to that the paint coat can easily damage ,furthermore ship need to be at zero speed and also there is a risk of national regulation which restrict the cleaning operation in their territorial water.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Optimum solution (8)</th>
<th>Be compatible with ship’s hull and ship’s recycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current mechanisms</td>
<td>Today solutions are compatible with hull construction and ship recycling, unless we have a more future restrictions on ship recycling which still at the infancy stage.</td>
</tr>
</tbody>
</table>

(Source Dekinesh, 2018)
4.3.2 Recommendations

1. Further research is needed for many aspects of the antifouling systems such as the performance standard for paint manufacturers at the time of testing the efficiency of antifouling. As a result of an absence of this standard, uncertainty of the selection between different antifouling systems would be encountered.

2. The researcher also needs to focus on how to prevent the formation of biofouling rather than releasing the organism after the settlement and the formation of the biofilm, which will make it harder.

3. The researcher should put more focus on the new solutions, which at least should have two characteristics; non-biocidal and high performance.

4. From the environmental impact perspective, the new solutions should consider many factors such as the no use of toxic substances that harm marine life and extend to the food chain, prohibit the transfer of invasive species to new ecosystems, maintain the smoothness of the outer hull surface to ensure less fuel consumption then, less GHG emissions.

5. New solutions have to be more comprehensive in terms of the uses and maintenance; for example, in water maintenance particularly while the ship is at anchor waiting for berthing instructions, as well as while the ship is at berth for cargo operations in case the solutions do not cause hazards or endanger the safe handling of the cargo. These solutions will be more favorable for the shipping companies.

6. As today’s solutions have already two existing anti fouling mechanisms (SPC and FRCs) which are integrated with hull cleaning for a better performance, it is a good idea to work on developing these mechanisms to achieve a better performance and less environmental impact. As stated by the research and development manager at I-tech AB biocides company founded in the year 2000 (Lena Martensson-personnel communication, 2018) it is not easy to find substances to fulfill all the criteria such as an effective and environmentally safe.
She stated that the EU in 2012 had approved new materials called Medetomidine (bioactive substance) which are commercially sold under the brand named selektope. In the same context the author got conformation from the two shipping companies, and one shipyard in Europe, the data have been collected through personnel meeting in 2018 from July to August. As stated by (Mr. Sami Kouvonen –head of ship design in Meyer Turku shipyard, 2018), (Mr. Jesper logstorm-head of innovation and performance in Wallenius Marine AB, 2018), (Mr. Mikael Laurin-chief executive officer in Laurin Marine), that the trend of the selektope application has dramatically increased since 2014 in Europe.

7. The law and regulations are dynamic in nature, so the researcher needed to investigate the changing of antifouling requirements while searching and developing new solutions, as well as while improving an existing mechanism.

4.3.3 Recent developments in the antifouling paint market using new biocide technology:

All data have been collected through personal communications with Mr. Marc van Eekelen-Chugoku Paints, (2018)

1. **GRANDPRIX 880HS plus**: have proven a solution to barnacles suitable for seagoing vessels with an extended life time of 90 months and can protect barnacles SE fouling up to 45 days while the ship is at idle.

2. **SEAFIO NEO Z**: fuel efficiency hydrolysis anti fouling paint uses new technology named low fractional technology coating, which results in the reduction of resistant frictional from 7.9 percent to 1.6 percent, which is equal to a 3-5 percent reduction on fuel oil consumption, as illustrated in Figure 3.
3. **SEAFLO NEO CF PREMIUM**: Barnacle & slime antifouling solution based on a combination between CMP’s zinc acrylate polymer technology and new biocide Selektope. Has been applied to some ships but the company is waiting for customs (shipping companies’ feedback).

**In conclusion**, after the aforementioned analysis and discussions it is an obvious that today’s solutions, and the recent developments in the anti-fouling market still more depend on biocides (self polishing copolymer) which has proven high performance in terms of fuel saving and the lifetime cycle of anti-fouling systems. But has an adverse impact on the marine environment. So the author sees that in order to achieve sustainable
development in anti-fouling systems, we have to consider all the elements from the enivromental aspect, human aspect, and economic aspect, which may be achieved by Gathering all the new or innovative solutions and aspects.
Finally it is not easy and takes time from researcher to study and test such technology. However, at least we highlight the gap between today’s mechanisms and the optimum solutions as well as the key role of the researcher to fill this gap by developing new sustainable antifouling technology.
Chapter 5

The potential of energy saving by anti-fouling systems

5.1 Potential energy saved through anti-fouling systems

In the literature review, specifically chapter three, the author examined biofouling and well understood the consequences of the biofouling attachment and settlement on the ship’s hull. The relationship between biofouling and a ship’s drag, which increases the required power to maintain the required speed, was scrutinized and explained.

In other words, we call power penalties, which can range between 80%-20% due to the amount and types of fouling; hard fouling and soft fouling. Accordingly, the use of an anti-fouling system is a very important key element to overcome power penalties and GHG emissions. By using antifouling systems, the hull surface acquires more smoothness and less drag force on the hull. Since the 1960s, the use of the organotin in antifouling systems was an efficient substance for killing invasive organisms until numerous amounts of evidence proved that the organotin is toxic and damaging not only to biofoulers but also to marine life in the ocean.

IMO adopted a convention to ban the use of TBT-based paint in anti-fouling systems. This action drove the paint industry to search for alternatives. However, there were none of these alternatives with the same TBT-based paint efficiency, and therefore it has been very important to shipping companies to understand how to calculate the efficiency of anti-fouling systems, which will help them to choose efficient anti-fouling systems.
In view of this situation, the author has collected data through questionnaires gathered from different sectors in the marine industry to introduce the potential of energy saved by antifouling systems in the first part of the analysis. In the second part of the analysis the author investigated the life cycle cost of anti-fouling systems, with the analysis based on the data received from RINA through a case study, with the results potentially assisting shipping companies in selecting the most efficient anti-fouling systems.

5.2 Part one of the Case study

Based on the data received from the classification society REGISTRO ITALIANO NAVALE (RINA) RINA has also extended their business by developing software programs for monitoring the efficiency performance of ships.

5.2.1 Data:

The detailed data is for RoPax ships which use the fouling release coatings FRCs mechanism, particularly the silicon coat. *International Paint Intersleek 1100, annual dry-dock as per SOLAS requirement. For RoPax ship.*

Table 4: Ship’s particulars

<table>
<thead>
<tr>
<th>Ships particular</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Unknown for confidentiality</td>
</tr>
<tr>
<td>Gross tonnage</td>
<td>49257 T</td>
</tr>
<tr>
<td>Dead weight</td>
<td>9720 T</td>
</tr>
<tr>
<td>Length overall</td>
<td>211.5 m</td>
</tr>
<tr>
<td>Breadth</td>
<td>30.5 m</td>
</tr>
<tr>
<td>Depth</td>
<td>7.40 m</td>
</tr>
<tr>
<td>Designed speed</td>
<td>25.0 knots</td>
</tr>
</tbody>
</table>
The received data were for two different periods for the ship during sailing time:

1) Before dry-dock for 6 months (fouled ship by 30%)
2) After dry dock for 6 months (zero fouled ship)

Main data parameters:

1) Ship’s speed [Knots]
2) Wind Speed [Knots]
3) Wind Direction [deg]
4) Sailed Distance [nm]
5) Propulsive Power [Kw]
6) Forecast Sea State [Beau]
7) Displacement [t]
8) Main engine consumption per hour [t/h]
9) Main engine per Mile consumption [t/nm]
10) Specific fuel oil consumption SFOC [g/kWh]
11) Trim [m]
12) Optimum Trim [m]
13) DG Average Power [kW]
14) DG Consumption [t]

5.2.2 Data analysis:

The above data has been processed using the Monte Carlo methodology through the Crystal Ball software at two different stages: before dry docking and after dry docking, then finally a comparison between the two periods was made with a particular focus on the required power and speed.
5.2.2.1 First stage result: before dry docking for a 6-month period

Figure 4: The required power Vs speed

![Before Dry Dock](image)

\( y = 6.3635x^3 - 200x^2 + 2246.9x \)

\( R^2 = 0.9119 \)

(Dekinesh, 2018)

Figure 5: Main engine consumption regression 6t/nm
Figure 6: Average propulsion power 27378 [Kw]

(Dekinesh, 2018)
Figure 7: Sensitivity Chart

(Dekinesh, 2018)
5.2.2.2 Second stage result: after dry docking for a 6-month period

Figure 8: The required power Vs speed

(Dekinesh, 2018)

Figure 9: Maine engine consumption regression 5.46 t/nm
(Dekinesh, 2018)

Figure 10: Average propulsion power 24810 [Kw]
Figure 11: Sensitivity chart

Table 5: Results of the analysis of comparison before and after dry-docking (required power versus different speed)

<table>
<thead>
<tr>
<th>Speed</th>
<th>Before power</th>
<th>After power</th>
<th>After cubic</th>
<th>Power %</th>
<th>Cub %</th>
<th>Best %</th>
<th>Final best power</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.0</td>
<td>20390</td>
<td>18618</td>
<td>23547</td>
<td>8.69</td>
<td>-15.48</td>
<td>8.69</td>
<td>18618</td>
</tr>
<tr>
<td>22.5</td>
<td>21789</td>
<td>19907</td>
<td>23169</td>
<td>8.64</td>
<td>-6.33</td>
<td>8.64</td>
<td>19907</td>
</tr>
<tr>
<td>23.0</td>
<td>23303</td>
<td>21254</td>
<td>23127</td>
<td>8.80</td>
<td>0.76</td>
<td>8.80</td>
<td>21254</td>
</tr>
<tr>
<td>23.5</td>
<td>24937</td>
<td>22660</td>
<td>23445</td>
<td>9.13</td>
<td>5.98</td>
<td>9.13</td>
<td>22660</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------------------------</td>
<td>-----------------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24.0</td>
<td>26695</td>
<td>24148</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24.5</td>
<td>28581</td>
<td>25654</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25.0</td>
<td>30602</td>
<td>27245</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25.5</td>
<td>32762</td>
<td>28900</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26.0</td>
<td>35064</td>
<td>31298</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26.5</td>
<td>37515</td>
<td>34293</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27.0</td>
<td>40119</td>
<td>37819</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Dekinesh, 2018)

Figure 12: Speed versus propulsive power before and after dry docking

(Dekinesh, 2018)

5.2.2.3 Findings of the analysis

From the above analysis, the result shows that after the dry dock the ship’s propulsive power performance has been improved by 9.35 percent.
From this case study it is noted that the importance of an antifouling system for better energy performance is approximately a 10 percent reduction in power; also there is a reduction in the fuel oil consumption and a subsequent reduction in GHG emissions.

5.3.0 Part two of the case study

The second part of the case study highlights the calculation of the efficiency of antifouling systems based on an assessment of their cost and benefit analysis. The result of this part would help shipping companies to select an efficient antifouling system for their fleet.

In order to easily understand the cost and benefit analysis, the author will separate here the two elements of the study into fouling and antifouling systems. Therefore, we need to determine:

1) The cost of fouling.
2) The cost of antifouling systems.
3) The benefit of antifouling systems.

Then the results from the cost and benefit analysis of antifouling systems will be compared with the cost of fouling. The final result of this comparison would help the shipping companies to select the most efficient antifouling system. In other words, the cost is defined as a negative figure, and the shipping companies are intending to reduce the negative figure by selecting a lower cost for the antifouling system, which means more efficient systems after calculating the cost of the various antifouling systems.

5.3.1 Data:

The aforementioned data was received from the different marine industry sectors through questionnaires, interviews and desk research, such as shipping companies, shipyards, paint manufactures and software developers; particularly NAPA and RINA.
In particular, RINA, recently developed a performance and monitoring program which tracks and monitors the ships energy performance online and feedbacks it to the ship.

The data was collected from RINA for RoPax ships as mentioned at the beginning of this chapter, in addition to:

1) Types of antifouling system: *FRCs International Paint Intersleek 1100.*
2) Dry- dock interval: *annually as per SOLAS requirements.*
3) Hull cleaning interval: *annually at dry-dock.*
4) Cost of hull cleaning *10,000. U$*
5) Repainting interval: *every 5 years as the life time of paint permit.*
6) Cost of anti-fouling system: *120,000. U$*
7) Fuel oil consumption without fouling (after dry dock): *132.4 t/day*
8) Fuel oil consumption with fouling (before dry dock): *149.7 t/day*
9) Daily operation cost DOC between: *(16000-18000) U$*

5.3.2 Methodology to calculate cost:

The author adopted the methodology followed by Abbott et al. (2000) with a little adaption for our case.

Total costs of fouling = cost of fouled ship - cost of zero fouled ship.

Total costs related to fouling can be separated to:

1) Increase in fuel consumption
2) Operational cost result from reduced speed (delay)
3) Operating cost while ship at dry-dock
4) Expenses of anti-fouling painting
5) Operating expenses during painting
In addition to the three main parameters, these were calculated in order to compare the cost of a fouled ship and the cost of a zero fouled ship namely; fuel oil consumption, dry-docking cost and daily operating cost.

5.3.2.1 Daily operating cost (DOC)

As stated by Abbott et al. (2000) DOC consists of:

   a) Crew salaries
   b) Food rate (provisions)
   c) Maintenance
   d) Use of spare parts
   e) External inspections and survey such as periodical survey
   f) Administration costs
   g) Insurance
   h) Sundries

5.3.2.2 Extra operational costs as a result of fouling

Additional cost will be included due to the decrease of the ship’s speed, hence the increased fuel consumption (because of longer voyage).

Designed formula, \( AC_{(foul)} = C_{(sp)} + C_{(fc)} \) where \( AC \) foul is the extra cost due to fouling, \( C_{sp} \) is the increase in cost due to reduced speed, \( C_{fc} \) the increase in cost due to the increase of fuel oil consumption.

   a) \( C_{sp} = DOC \times \frac{\text{(number of hours /24h)}}{24} \)
   b) \( C_{fc} = \text{additional amount of fuel consumed} \times \text{current fuel oil price} \)

5.3.2.3 Cost of dry-docking

An additional dry dock period is predicted due to the hull fouling, the cost of dry-docking to clean this foul can be the sum of actual expenses incurred while the ship is at dry-dock and the daily operations cost at dry-dock. These are illustrated in the following formula:
\[ C_{dd} = E_{dd} + (DOC_{dd} \times \text{number of hours} / 24h) \] where \( C_{dd} \) is the total cost of the dry dock, \( E_{dd} \) is the actual expenses for dry-docking the ship, \( DOC_{dd} \) is the daily operation cost at the dry-dock and the number of hours the ship is required at the dry-dock for cleaning the fouling.

5.3.2.4 Loss of profit as a result of fouling:

Loss of profit consists of two elements; the first element is because of the reduced speed, while the second element is the period which the ship has spent at dry-dock. This is illustrated in the following formula:

\[ LP_f = LP_{sp} + LP_{dd} \]

where \( LP_f \) is the total loss of profit due to fouling, \( LP_{sp} \) is the loss of profit due to reduced speed, \( LP_{dd} \) is the loss of profit due to the time spent at dry-dock.

a) \( LP_{sp} = FR \times \left( \frac{\text{number of hours}}{24} \right) \) where \( FR \) is the daily freight rates of the ship, number of hours and extra hours added to the voyage due to the reduced speed.

b) \( LP_{dd} = FR \times \left( \frac{\text{number of hours}}{24h} \right) \) where \( FR \) is the daily freight rates of the ship, and the number of hours is the total hours which the ship is spent at dry dock.

5.3.2.5 Additional cost of fouling

Now we have all the parameters that relate to the cost of fouling, thus we are able to calculate the total cost of fouling as follows:

Additional cost of fouling \((AC_{(fouling)}) = C_{sp} + C_{fc} + C_{dd} + LP_f\), and from the above formulas it can be demonstrated as follows:

\[
\text{Additional cost of fouling} = \left[ DOC \times \left( \frac{\text{number of hours}}{24h} \right) + C_{fc} + E_{dd} + (DOC_{dd} \times \text{number of hours} / 24h) + FR \times \left( \frac{\text{number of hours added to the voyage due to reduced speed}}{24} \right) + FR \times \left( \frac{\text{number of hours added to the voyage due to time spent at dry-dock}}{24} \right) \right].
\]
5.3.3 Data analysis

Application of method to our vessel:

All calculations made for one-month voyage.

5.3.3.1 Calculating of the DOC for zero fouled ship, is the sum of the data mentioned in paragraph 5.3.2.1

Hence, DOC is estimated to be 17,000. U$/day (RINA,2018).

5.3.3.2 Extra operational costs as result of fouling

\[ AC_{(foul)} = C_{(sp)} + C_{(fc)}. \]

Table 6: Increased in cost due to reduced speed \((C_{sp}) = DOC \times \text{(number of hours /24h)}\)

<table>
<thead>
<tr>
<th>Daily Operating cost for zero-fouled ship (U$)</th>
<th>Speed after dry-dock (zero-fouled) (Knots)</th>
<th>Speed before dry dock (fouled ship30%) (Knots)</th>
<th>Reduction in speed due to fouling (Knots)</th>
<th>Increase in the number of days of voyage (day)*</th>
<th>Increase in cost due to reduced speed (U$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17,000</td>
<td>24.0</td>
<td>22.3</td>
<td>1.7</td>
<td>2.2</td>
<td>37,400</td>
</tr>
</tbody>
</table>

*increase of voyage days=1.7kts x 24hrs x 30days voyage assumption /24kts= 2.2 days (Dekinesh, 2018)
Table 7: Increased in cost due to increased fuel consumption \((C_{fc}) = \text{additional amount of fuel consumed} \times \text{current fuel oil price}\).

<table>
<thead>
<tr>
<th>Fuel oil consumption after dry-dock (zero-fouled) (Ton/day)</th>
<th>Fuel oil consumption before dry dock (fouled ship30%) (Ton/day)</th>
<th>Increase of fuel oil consumption due to fouling * (Ton)</th>
<th>Increase in cost due to increase in fuel oil consumption ** (U$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>132.4</td>
<td>149.7</td>
<td>38.06</td>
<td><strong>20,933</strong></td>
</tr>
</tbody>
</table>

*number of extra days because of fouling = 2.2 days, increase of fuel = \((149.7 - 132.4) \times 2.2 \text{ day}\)

** price of fuel is 550/ton average current price for low Sulphur fuel which is used by the ship, so cost of fuel due to foul = 38.06 \times 550\$ (Dekinesh, 2018).

Current fuel price as per (Ship & Bunker,2018).

5.3.3.3 Cost of dry-docking  \(C_{(dd)} = E_{dd} + (\text{DOC}_{dd} \times \text{number of hours / 24h})\)

Table 8: Increased in cost due to dry dock (Dalian COSCO KHI Shipyards, 2018)

<table>
<thead>
<tr>
<th>Paint cost (U$)</th>
<th>Total Rent for painting during dry dock for 3 days * (U$)</th>
<th>Expenses at dry dock (Edd) for period 3 days (U$)</th>
<th>Daily operating dock-cost (DOCdd)** (U$)</th>
<th>Total operating cost for dry dock period 3 days (U$)</th>
<th>Total cost of dry dock (Cdd)*** (U$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120,000</td>
<td>450</td>
<td>120,450</td>
<td>13,000</td>
<td>39,000</td>
<td><strong>159,000</strong></td>
</tr>
</tbody>
</table>

*Total rent for paining = per/day rent for dry-dock paint x 3 days=150x3 days

** DOCdd is the operating cost due to painting operation only

***\((C_{dd}) = E_{dd} + \text{DOC}_{dd} \times 3 \text{days} = 120.450 + 13.000 \times 3 = 159,000\)

(Dekinesh, 2018)
5.3.3.4 Loss of profit as result of fouling \[ LP_f = LP_{sp} + LP_{dd}. \]

Table 9: Loss of profit due to reduced speed \( (LP_{sp}) = FR \times \text{(number of hours /24)} \).

<table>
<thead>
<tr>
<th>Speed after dry-dock (zero-fouled) (Knots)</th>
<th>Speed before dry dock (fouled ship30%) (Knots)</th>
<th>Reduction in speed due to fouling (Knots)</th>
<th>Increase in the number of days of voyage (day)</th>
<th>Loss of profit due to reduced speed ( LP_{sp} \times ) (U$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24.0</td>
<td>22.3</td>
<td>1.7</td>
<td>2.2</td>
<td>88,000</td>
</tr>
</tbody>
</table>

*Loss of profit for 2.2 days = 40.000$/profit per day x 2.2 = 88,000 $ (Dekinesh, 2018)

Note profit per day has been calculated from a feasibility study in the European market for the utilization of 65% of the vessel per year, which was estimated at 14,333,000$ (SKEMA, 2009).

Table 10: Loss of profit due to time spent at dry-dock \( (LP_{dd}) = FR \times \text{(number of hours /24)} \).

<table>
<thead>
<tr>
<th>Number of days’ ship at dry dock for painting (Day)</th>
<th>One-day profit for RoPax (U$)</th>
<th>Loss of profit due to time spent at dry-dock ( LP_{dd} ) (U$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>40,000</td>
<td>120,000</td>
</tr>
</tbody>
</table>

(Dekinesh, 2018)

Additional cost of fouling \( (AC_{(fouling)}) = C_{sp} + C_{fc} + C_{dd} + LP_{sp} + LP_{dd} \): Additional cost of fouling \( (AC_{(fouling)}) = 37,400 + 20,933 + 159,000 + 88,000 + 120,000 = 425,333 \) U$
5.3.3.5 Findings of the analysis

Table 11: Comparison between Zero fouled ship and (fouled ship 30%) for the running cost for 30 days’ assumption.

<table>
<thead>
<tr>
<th>Voyage period (day)</th>
<th>DOC For voyage period (U$)</th>
<th>Total cost (U$)</th>
<th>Total cost</th>
<th>Voyage period (day)</th>
<th>Csp (U$)</th>
<th>Cfc (U$)</th>
<th>Cdd (U$)</th>
<th>LPsp (U$)</th>
<th>LPdd (U$)</th>
<th>Additional cost due to fouling (U$)</th>
<th>Total cost (U$)</th>
<th>Increase in cost (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>510,000</td>
<td>510,000</td>
<td>32.2</td>
<td>37,400</td>
<td>20,933</td>
<td>159,000</td>
<td>88,000</td>
<td>120,000</td>
<td>425,333</td>
<td>935,333</td>
<td>83</td>
<td>83</td>
</tr>
</tbody>
</table>

(Dekinesh, 2018)

*Total increased in cost due to fouling = additional cost due to fouling / total operating cost for zero fouled ship X 100%. = 425,333/510,000x100= 83%

From Table 11, it has been noted that there was an increase of 83 percent of the total cost of the ship because of the fouled hull which necessitated the shipping companies to have an efficient anti fouling system.

In conclusion, this chapter has discussed and analyzed the potential savings of energy through anti- fouling systems. The author has analyzed the data received from RINA in two parts; in the first part of the case study, by using the Monte Carlo methodology through the crystal ball software at the World Maritime University lab, the results show after 5000 trials that the potential for saved energy through the use of silicon paint as an anti-fouling system, was 10 percent. In the second part of the case, the study utilized a cost and benefit analysis for the anti-fouling system based on the methodology used by Abbott et al. (2000). The result of the cost and benefit analysis shows that an increase of the cost of the ship operation is 83%, due to fouling.
Based on the above results, it is crucial for shipping companies to select the most efficient anti-fouling system, and to apply the same method for the cost and benefit analysis for different anti fouling systems. In the same context, the environment will benefit from the reduction of GHG, due to the reduction of fuel oil consumption.
Chapter 6

Conclusions and recommendations

6.1 Conclusions

Biofouling has been defined as the attachment and settlement of marine organisms to a ship’s hull forming fouling layers on the underwater hull surface of the ship; thus fouling is a tremendous problem to the efficient operation of a ship’s activities. The use of biocides to combat the fouling problem was prominent for a considerable period. Biocides poison any organism that is in contact with the surface of the hull and its impact extends to marine life in the surrounding areas and persists for a long time. Since the 1970s, TBT was utilized as a means of controlling fouling, but, unfortunately, TBT had a deleterious effect on the environment. This created a dilemma for the shipping industry because once applied, and there are some very good commercial coatings, none provide the same performance as organotin paint. Thus, the need for research and the development of alternative coatings that are environmentally acceptable and have the function of maintaining a ship’s hull, smooth and free of fouling. In this respect, the shipping industry is a huge challenge, with an estimated 100,000 ships that transport between 80 to 90 percent of the world trade by volume. Shipping has also been estimated to consume over 333-million-tons of fuel.

So, from the global perspective, there is a great need to improve the efficiency of shipping and at the same time reduce the environmental impact of shipping, particularly GHG emissions, and also reduce the deleterious impact of biocides used in anti-fouling systems. The global awareness towards organotin issues led the IMO to adopt the AFS Convention in 2001, which came into force in 2008, and was associated with the concerns in shipping companies to find efficient alternatives of an anti-fouling system free of biocides. Since then paint manufacturers have focused on research to develop tin free biocides based on
copper. Further developments result in new generation copper free anti-fouling systems. The author’s research shows that two current systems commercially dominate the market, which are self-polishing co-polymer (SPCs) and fouling release coatings (FRCs), based on the two current main anti-fouling systems that the paint manufacturers have evolved and developed over time. The problem is that shipping companies are uncertain about selecting the most efficient anti-fouling systems, or paint types, among the many that exist. Added to this the absence of a pattern trade due to the open markets, particularly for tramp ships, (which means unknown cargo and route ships under order). This increases the challenges for selecting the most efficient types of anti-fouling systems even further. Such complexities have made this study of anti-fouling systems crucial for identifying the gap between today’s solutions and the optimum solutions.

The result shows that the future demand can be achieved by innovative solutions, particularly inspired by nature. And nontechnology might be one of those solutions, and in order to fulfil future needs, more effort is needed from the paint manufacturers to research and test those new technologies and make them commercially available.

The author also highlights the importance of the potential energy saved through anti-fouling systems. By analyzing the data provided by RINA, the result indicates a 10 percent power saving by using silicon paint on RoPax ships. Moreover, a cost and benefit analysis for anti-fouling systems has demonstrated that the additional cost of fouling, in this case, is increased by 83 percent due to ship operations. Thus, it is crucial for shipping companies first to calculate the additional cost incurred from fouling, then select the most efficient anti-fouling system, which provides less cost.

Furthermore, the end users (shipping companies) play a tremendous role in supporting the development of anti-fouling systems that are of high-performance and associated with both economic and environmental benefits.
6.2 Recommendations

1. Shipping companies

It has been illustrated through the research in this thesis, that anti-fouling systems are highly complicated systems with many factors involved in their performances. To support this claim, a personal communication by Mrs. Pekka (NAPA, Aug 2018), who states that in the worst cases regarding the paints studied, certain paints start falling off just a few months after the vessel’s delivery and soon the vessel has burned ~30% more fuel than under normal conditions. NAPA is a leading maritime software, services and data analysis provider to the shipping industry.

Therefore, shipping companies in order to successfully select the most efficient antifouling system, need first to understand the antifouling system as a management system such as the PLAN-DO-CHECK-ACT cycle as a systematic approach, which is an ongoing process. Although IMO has developed guidelines for anti-fouling system management, there is no effective result gained due to the lack of implementation and enforcement, such that shipping companies need to focus more on the anti-fouling system as the whole system, starting from a cost-benefit analysis and before selecting the antifouling system during the planning stage. This can then be followed by the implementation, monitoring and feedback of the system.

As the author has mentioned above, the trade pattern of the ships is unknown for tramp ships, so the check and feedback stage is very important, since after a time the ship may expect to encounter heavy fouling. Therefore, it is possible to use the key performance indicators to ensure that corrective actions are taken in time, such as applying a fouling rating scale. Ranging the scale for example from 0 (no fouling) to 100 (full fouling) this, of course, will build up a routine inspection mechanism. Therefore, trained people are essential to operate manual underwater cameras for that purpose.
Another key performance indicator might be used, such as fuel oil consumption as fouled ships consume more fuel to maintain their required speed such that the consumption may increases by up to 20 percent (for example), which means the ship may require to practice hull cleaning.

Another solution also can be approached by signing a contract with a consultant party for monitoring the performance of an anti-fouling system, or even to extend the monitoring to the ship’s energy efficiency performance. As the author mentioned above that RINA and NAPA providing this service

2. **IMO and regulations**

IMO through its regulations and laws could adopt a mandatory periodic inspection system for inspecting the underwater hull surface of ships.

Port State Control, as a key element for enforcement by the inspection of the antifouling systems on board a foreign vessel.

3. **Paint manufacturers**

As per the research result, the future demand for new technology might require the paint manufacturers to invest more in evolving and developing a new innovative solution for biofouling particularly based on a concept inspired by nature. In order to make it commercially viable the technology must be tested, not only inside the lab but also in towing tank facilities. This will create a competitive advantage for paint manufacturers.

Last but not least, the energy saved through an anti-fouling system is a part of a fully integrated system of energy performance operations of the ship; shared goals and objectives among stakeholders are required to enable the realization of improvements and maximize energy efficiency.
6.3 Future research:

It is recommended that future research could focus on different anti-fouling systems applied on different types of ships to enable designing decision support systems (DSS) models.

This study was limited due to the narrow data sources collected primarily from RINA and NAPA that was limited to RoPax ships coated with silicon, which should be expanded in future studies to gain more accurate results from more types of paints and ships. This was not possible in the time frame allocated for this dissertation.
Reference list


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