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Dissertation

"Managing the Operational Impact of Hull Maintenance on Vessel Performance"

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“Thank God and my future wife...for their exceptional patience”

Abstract

Hull pollution due to accumulation of marine plant and sea animal organisms upon ship's surface of hull and propulsive mechanisms (i.e. propellers and shafts) is a phenomenon that is responsible for an increase of fuel oil consumption. This is due to the increase of total resistance of the ship, resulting gradually in the deterioration of the ship's performance, according to relevant studies upon the biofouling impact on vessel performance for merchant types of ships (containerships, general cargo, VLCC). In the current study, the examined ships are of naval types (frigates, gunboats, patrol boats, landing ships, general support vessels). For these types of naval ships, the examined period was five years, beginning from the undocking of the vessel after a full hull cleaning and the renewal of their hull coating paints performed. Taking into account the average speeds, hours travelled and excessive fuel consumptions, for three conditions of hull fouling (zero, soft and hard) and comparing them with the corresponding values of ship's designed characteristics, the result showed an extra fuel consumption for each type of ship. This excess of fuel consumed, is then calculated in respect of each type's operating profile and the outcome was the associated yearly cost of the biofouling impact for the examined period. For this economic impact, a risk assessment is attempted, in order to evaluate the potential of an excessive fuel cost, with the use of a Risk Matrix. The assessment of the results underlines the importance of the continuous monitoring of ship's hull condition and the profit of an optimised hull maintenance schedule, in order to manage the associated costs that derive from operating ships with a fouled hull.

Key – Words

Hull - maintenance/ bio-fouling/ coating/ paintings

Underwater/ Submerged surface/ appendage

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Abbreviations

BFMP	Bio-fouling Management Plan
C_B	the ship's hull shape coefficient
DD	Dry Docking
FOC	Fuel Oil Consumption
FR	Fouling Rating
GSV	General Support Vessel
IMO	International Maritime Organization
Kp	roughness of propeller blades' surface
Ks	roughness of submerged hull surface in terms of the equivalent sand roughness height
MARPOL	International Convention for the Prevention of Pollution from Ships
MEPC	Marine Environment Protection Committee
NSTM	Naval Ships' Technical Manual
PDR	Paint Deterioration Rating
SOLAS	Safety Of Life At Sea

1. Introduction

The management of hull pollution of the ships, due to accumulation of marine plant and sea animal organisms, is one of the most important measures taken by shipowners in order to comply with the current regulations (MARPOL, MEPC, SOLAS etc.). The performing of cost-effective hull maintenance programs on ships already in operation, lead to a large number of analyses and numerous reports on the economic impact of biofouling on vessel's performance. Some of the measures, which are adopted and imposed by the International Maritime Organization (MEPC,2019), address the pollution of ships' hulls, both because of the direct effect it has on the speed of the ship and also of the consequent need for dry-docking (with the corresponding cost) that this phenomenon ultimately brings.

Biofouling is a phenomenon that is responsible for the increase of fuel consumption by up to 6% as well as the increase of the total resistance of the ship up to 50% (depending on the type of vessel, but is rarely measured less than 40%) according to Dinis Reis Oliveira et al. (2022) [1]. It is worth mentioning that shipping companies endorse, within their policies, many effective measures for confronting the biofouling impact on their ships' performance, in order to raise their annual savings (Mohammud Hanif Dewan et al., 2024).

Regarding the hull maintenance policies, a common practice adopted globally refers to the Naval Ships' Technical Manual [2] for the hull's fouling rate (FR) and the paint deterioration rate (PDR) criteria, which both suggest the appropriate points in time for the cleaning or repainting tasks to be performed. Another similar approach has been implemented by the International Maritime Organization (IMO) by publishing guidelines for a typical Bio-Fouling Management Plan (RESOLUTION MEPC.378/80, 2023) [3], which aims to minimizing ship's biofouling. Both of these guidelines comprise of periods of inspections, proactive and reactive cleaning procedures, as part of an existing contingency action plan of any company or organization that manages active ships.

With reference to the causal factors of the phenomenon, the hull biofouling gradually results in an increasing deformation of the steel underwater surface of ships. Eventually, the total resistance of the ship towards the sea water, together with the fuel consumption, increases. By monitoring this excessive fuel consumption due to biofouling, an assessment of the economic impact can be performed and this is the scope of this study. In addition, from the perspective of the operational impact and the necessity of a BFMP, a risk assessment of the economic impact is attempted for 10 different types of naval ships.

Despite the significance of the gradual increase of microorganisms on ships' hulls and its consequent economic impact, there are fewer studies on the subject concerning naval ships. This is probably due to the confidentiality that surrounds military matters and affairs, or maybe because of the significantly minor associated costs in naval ships compared to the costs of merchant type ships. Besides, naval ships constitute only a small percentage of the global fleet, regarding the deadweight, so the cost of the excessive fuel consumption is generally more affordable and easier to manage.

2. Literature Review

2.1 Economic Impacts of Biofouling

A recent study [4] showed that even more ship operators seem to embrace efficient measures, in order to reduce or minimize the operational costs that derive from hull fouling. Accordingly, from these measures, the hull maintenance is among the highest considerations of most ship operators, in a percentage higher than 80% of the maritime operating companies (Mohammud Hanif Dewan et al., 2024).

Regarding the economic impact in subject, this can generally be divided into environmental costs and energy penalties (Shukui Liu's et al., 2023) [5]. Focusing on the energy costs, due to increased fuel consumption that derives from hull's biofouling, in the same study [6], there has been a calculation of the impact in the reserve power as a result of hull and propeller's biofouling condition (Ks, Kp parameters). The results were used in the examination of a VLCC travelling in rough weather conditions (Shukui Liu's et al., 2023). The outcome was an increase in fuel consumption, together with the associated cost, by 39% for specific fouling conditions (equals to Ks=500μm and Kp=300μm) (Shukui Liu's et al., 2023).

According to another study [7] upon the energy potential savings of cleaning the biofilm in two types of containerships (representative of their kind in marine industry), the result was 64M $ and 66,6M $ impact per year (Andrea Farkas et al., 2022), which is rather significant and cannot be ignored. Although, investigating other types of ships the economic impact may differ a lot, it remains a negative economic factor in ship's operational management.

Generally, it is worth mentioning that an appropriate schedule of hull periodical cleaning, full and partial circumstantially, can contribute to fuel savings of more than 15%, (NSTM, 2006). In regards to naval ships, a study upon the total cost, involving biofouling of an Arleigh Burke, resulted in $56M yearly and $1B after 15 years, for a whole class of this type of vessel (Michael P.Scultz, 2010)[8]. Similarly, regarding the merchant types, an optimized cleaning schedule of hull and propeller can reach a 30% energy potential (Andrea Farkas et al., 2022).

Although the studies upon the impact of biofouling on ship's performance are numerous and continuous, the current study is relevant to the biofouling impact in naval instead of maritime operations, where the relevant studies are less.

2.2 Assessing the Operational Impacts of Biofouling

Typically, all kinds of ships while in-service, for the purpose of completing their missions and achieving to operate on time, within a given operational timeline, try to maintain a constant speed, which is usually predetermined for their route. Whilst operating, the fouling condition of the hull worsens gradually and this will lead to an increase of fuel consumption, in order to provide the excess of power needed to maintain the ordered operational speed. The technical explanation of this increased demand for power is given in a previous study [9]. The calculation of this excess power was made in combination with a potential of adverse weather conditions, which inevitably raised the risk of extra costs that derive from the useless waste of fuel, while the ship's propulsive machinery is striving to maintain the ordered shaft revolutions and overcome the ship's total resistance (Shukui Liu et al.,2023). In a similar study that included naval ships, the results of Schultz (2007) for a vessel, similar to the patrol boats of the current study, were an increasing resistance and excessive power due to hard fouling, which both together led to a power penalty up to 86% while travelling in cruising speed (Michael P.Schultz, 2007).

Andrea Farkas et al. (2020) [10] proved the increase of fuel consumption and the decrease of the ship's speed due to biofouling accumulation on the propulsive machinery of the ship. In a review[11] of the evaluating methods on hull's fouling condition, including that of Farkas et al.(2020), the performance indicators, which most of the times suggest a need for cleaning, are: the reduction of standard ship's speed, the increase of the amount of fuel required so as to preserve the ordered speed (assuming that all the propulsive gear of the machinery plant is working properly and in optimum efficiency), the increase of total resistance, an increase of the excess of power needed and a potential propeller’s changed behavior[1] (Iliya Valchev et al., 2022).

Shukui Liu et al. (2023) and Andrea Farkas et al. (2022) used algorithms and equations of Schultz [12] (2007) together with the similarity law scaling method of Granville (1958[13], 1987[14]), to calculate the ship’s total resistance, as the most serious factor of the ship’s fuel consumption increase. The authors of another study [15], also proved the increase of the total resistance due to biofouling, though with a different and more practical predictive model. Fitting the data of the computational fluid dynamics’ (CFD) model of Yigit Kemal Demirel et al. (2017) [16] and comparing the results to experimental measurements, the calculations of the increased ship’s resistance due to fouling were very similar (M.L. Hakim et al., 2023). In his abstract [17], another author, reports the prediction of an increase in total resistance of a frigate by up to 23%, due to an FR 40-60 of biofouling accumulation in hull’s surface (J.P. Monty et al., 2016).

In addition, Yigit Kemal Demirel (2019) in the context of his study [18], calculated the effect of biofouling on the ship’s added reserve power, producing diagrams of the added resistance due to different fouling rates. This added resistance is then used to calculate the reduction of the ship’s speed, for 6 different merchant types of vessels.

Consequently, the monitoring of the above ship’s performance indicators between the drydocking periods can provide a good estimation of the ship’s performance. For the purpose of the present study, the fouling rate (FR)[2] is the reference number which describes the hull’s surface roughness condition. It is used in order to compare the operating parameters of the ships between their drydocking maintenance periods and the consequent impact on fuel consumption due to the gradual concentration of microorganisms upon their hulls’ surface.

2.3 Review of Hull Maintenance Management

The importance of the monitoring of biofouling and the hull’s maintenance is thoroughly explained and proved by NSTM (2006) and IMO (MEPC 378/80, 2023), for naval ships and merchant types respectively. For that reason, the procedures and tasks

[1] This could mean i.e. an increase in the shaft revolutions per minute needed, in order for the ship to attain the ordered speed

[2] The correlation to other coefficients such as Rt50 (roughness according to Reynolds), Ks, Kp and IMO’s from-0-to-5 scale is given in the table of ANNEX ‘A’

associated to the maintenance itself are not of concern herein and, do not contribute to the calculations made. Anyway, the costs of maintenance are part of other studies and therefore are either taken for granted or exempted deliberately.

The management of preventive and corrective measures and the risk assessment of hull's biofouling evolvement can be performed by following the recommended guidelines of either NSTM's or IMO's publications, regarding the ship's hull maintenance management system. Thus, simply monitoring the impact of biofouling on fuel consumption, can be a useful tool of evaluation and risk assessment as well as a corrective assistant in managing ship's performance.

Regarding the biofouling monitoring, a previous review categorized the methods in physical, data-driven and hybrid models, depending on the quality of data used to calculate and evaluate the potential impact of biofouling (Iliya Valchev etal.,2022). Concerning the naval ships of the current study, a simple mathematical model is used in order to evaluate the impact of biofouling in the fuel consumption.

The authors of another study, in order to validate their introduced software, calculated three different maintenance scenarios for a 10.000 deadweight general cargo vessel (Dinis Reis Oliveira et al., 2022). In that way, they represented the marginal costs of two different kinds of hull coatings used along specific routes through the Baltic Sea. The purpose was to restrain the economic impact of biofouling, which derives from the various power penalties due to increase of hull roughness, by choosing the appropriate hull coatings and corresponding maintenance schedule.

The prediction of the fouling rate and the determination of the life cycle of protective coatings (Demirel, 2018) [19] depend on the quality of paint materials used in relevance to the type of the ship and the variable environmental conditions of its operating profile. In regards, Dinis Reis Oliveira et al. (2022) using MATLAB, presented multiple and different assumptions relative to the examined sea area, ship type and operating profile. They also produced a very useful tool for shipowners merchandising through the Baltic Sea, that can help them evaluate their hull maintenance plans in order to achieve a more profitable performance of their ships.

Undoubtedly, regardless of the value of any other predictive method, model or application, the real ship's data recording, analysis and assessment are the most essential evaluating tools. As an example, the authors of a study [20] experimented on the economic benefit of extending DD periods upon optimising hull's maintenance schedule by choosing a composite type of hull coating paints on a 42,276 DWT ship against conventional materials. Using data of a 7-year operating period, they calculated the fuel savings simply by using a linear regression model between speed and fuel consumption (Dragan Bebic et al.,2018).

An experimental study of Mogeke et al. (2023) [21], with the use of strain gauges upon a light-weight patrol boat of the Royal Australian Navy, materialized a virtual hull monitoring system for the prediction of hull’s structural fatigue through time of operational life-cycle of the ship. This method is based on data retrieved in real weather and sea state conditions, thus can provide accurate results under specific circumstances with the correct parameters used.

The previous study analysed the fatigue of the hull’s structure. However, the same technology, using strain gauges, can be performed in general hull’s monitoring for other measurements, yet still not including the biofouling measurements in real time occurrence. Heretofore, the technological research has provided numerous and real time metrics upon the hull’s condition underneath the sea waterline, thus a future review on real time hull’s biofouling monitoring would be an interesting case study.

3. Methodology

3.1 Description of Hull’s Surface Condition

The hull surface monitoring of the examined vessels in this study is exempted and so are the aforementioned underwater inspections and cleaning tasks, which are performed periodically within the five-year period. In regards of the naval ships examined, the hull surface conditions taken into account are three: the typical no-foul, the soft and the hard fouled hull state.

For the naval ships of this study, the examined period begins immediately from the day after the vessel’s undocking. After a full hull cleaning and the renewal of their coating paints performed, the hull’s surface condition starting point is at ‘0’ (no-foul). Usually, it is observed that the concentration of microorganisms towards the formation of soft biofouling condition starts to appear after six months from undocking, whereas the formation of what is called hard fouling begins after about a year from undocking.

For the purpose of this study the NSTM’s scale ratings of fouling is used. In order to express the soft and hard fouled condition of the hull’s surface, the soft condition equals to values between 10-30 FR whereas the hard fouling equals to values between 40-60 FR. This applies to various percentages of the total underwater surface of the ships, but in no way over 40% as this would suggest performing a drydocking maintenance.

3.2 Types of Naval Ships

In the field of this study, the calculation of the impact on fuel consumption is done using the statistics from ten different types of ships, which in turn correspond to five categories, in respect of their deadweight and operating profile.

The types of ships examined are as below:

a. Frigate type 1, 2 cruising gas turbines/2 main gas turbines
b. Frigate type 2, 2 cruising diesel engines/2 main gas turbines
c. Patrol boat type 1, 4 main diesel engines
d. Patrol boat type 2, 4 main diesel engines
e. Gunboat type 1, 2 main diesel engines
f. Gunboat type 2, 2 main diesel engines
g. Gunboat type 3, 2 main diesel engines
h. Landing ship, 2 main diesel engines
i. General support ship Type 1, 2 main diesel engines
j. General support vessel Type 2, 2 main diesel engines

The above types are significantly different between each other concerning their deadweight, so there is a variety of hull surface shapes and magnitudes in respect of the ships' structure. The impacts examined herein are analogously similar to each other, which is within the scope of the current study in order to evaluate the impact of biofouling in as many types of naval ships as possible.

3.3 Assumptions

For the scope of the current study, the following assumptions are made:

a. the fouling rating (FR) is a physically increasing number for a specific ship and can be reduced only by means of human intervention.

b. the operating profile of the ships, meaning the hours travelled per year as in **Table 1** below, remain constant for every year of the time period examined.

c. other parameters, such as weather conditions and sea state, which have an additive impact on the FOC and operational costs of a ship, are not examined, as they only worsen the various impact scenarios.

d. the fouling condition remains ‘0’ for the 1st six months after undocking.

e. after the first year, and for the next four years until next drydocking, the hull’s surface roughness follows a regression between soft and hard fouling state respectively. This is due to the interim and periodic underwater cleanings performed in regards of maintenance schedule, which is taken into account[3].

f. a potential maintenance management plan, according to which hull drydocking maintenance is scheduled to take place almost every five years and not earlier. Consequently, drydocking tasks, which may have been performed as part of contingency actions or extraordinary repairs, have not been taken into account.

g. the price of fuel (0,54€/lt) is considered as an average within the examined period of five years, excluding the fluctuations due to Covid-19, the geopolitical changes of the last three years since 2019 and the inflation heretofore.

h. all ships are painted with similar conventional antifouling painting systems, with a similar degradation rate (PDR) towards seawater’s salinity.

3.4 Parameters

Fouling rating: the FR parameters, according to NSTM, are defined by the personnel of the technical department of a naval base, who is responsible for gathering and evaluating the hull inspections’ results. The conditions of the hull’s surface fouling used are the three most common conditions; zero, soft and hard condition (see **Table 4** in ANNEX ‘A’).

Speed: another essential parameter used is the ships’ speed for the three hull surface conditions examined herein. Specifically, taking under consideration the fact that bacteria’s and micro-organisms’ accumulation is thoroughly enhanced when the ship is not moving, it is observed that the same also happens for low speeds under 7-8 knots, although in a smaller pace. For the examined types of naval ships, in conjunction with their operational characteristics, this low-speed scale is seven-to-nine knots. Another significant value is the

[3] An increase of the FR number over 30 and 40 for the propeller and shaft respectively suggests underwater cleaning.

economic speed, in terms of the identical speed under which the maximum endurance is achieved by a ship. Last but not least, the third speed value is that of the higher speed, depending on the maximum designed limit of each type.

Hours travelled: in order to distribute the operating profile of the ships, for the examined period of five years between drydocking, the hours travelled yearly in the corresponding average speeds are shown in **Table 1**.

FOC: the fuel oil consumption is the most critical parameter. For a zero FR condition the ships are considered to have a theoretical consumption in litres/hour, while travelling with all engines running (two or four depending the ship's type). Comparing the measured consumption of each ship to its theoretical value, for each of the three examined hull conditions, the outcome corresponds to a marginal cost. This is a result of the excess of power used in order to maintain the constant speed examined under the existing conditions from time to time.

3.5 Operating Profiles of Naval Ships

The aforementioned types of ships follow different operating profiles, relatively to their missions and capabilities. The main statistical characteristics used for the purpose of this study are shown in **Table 1** and concern the hours yearly travelled and the relative speeds for the 5-year period examined.

The periods of docking and an insignificant number of hours in low-speed running, since being under unspecified conditions, are excluded. Though, even if they were taken into account, the results regarding the impact would only be worse.

***Table 1** Operating profiles of naval ships*

A/A	Ship type	SPEED	Hours travelled (annualy)	SPEED	Hours travelled (annualy)	SPEED	Hours travelled (annualy)	Total hours travelled (annualy)	Average Travel	Average Murage	Average Fuel impact due to Soft or no FR	Average Fuel impact due to Hard FR
1	Frigate 1	7	720	15	720	25	60	1500	17.12%	82.88%	28.61%	71.39%
2	Frigate 2	7	720	15	720	25	60	1500	17.12%	82.88%	28.55%	71.45%
3	Patrol boat 1	8	850	17-18	390	25	60	1300	14.84%	85.16%	27.92%	72.08%
4	Patrol boat 2	8	70	17-18	400	25	70	670	7.65%	92.35%	28.97%	71.03%
	Patrol boat 2	-	-	12	130	-	-					
5	Gunboat 1	7	500	10-12	260	18	150	1100	12.56%	87.44%	29.00%	71.00%
	Gunboat 1	-	-	15-16	190	-	-					
6	Gunboat 2	7	465	10-12	230	18	90	950	10.84%	89.16%	28.94%	71.06%
	Gunboat 2	-	-	15-16	165	-	-					
7	Gunboat 3	7	700	10-11	300	15	100	1100	12.56%	87.44%	29.25%	70.75%
8	Landing ship	7	480	10-11	520	12	50	1050	11.99%	88.01%	27.86%	72.14%
9	GSV 1	7	610	10-11	1100	16	300	2310	26.37%	73.63%	29.26%	70.74%
	GSV 1	-	-	14-15	300	-	-					
10	GSV 2	9	380	11-12	400	14	60	840	9.59%	90.41%	29.25%	70.75%

Source: Author

4. Results

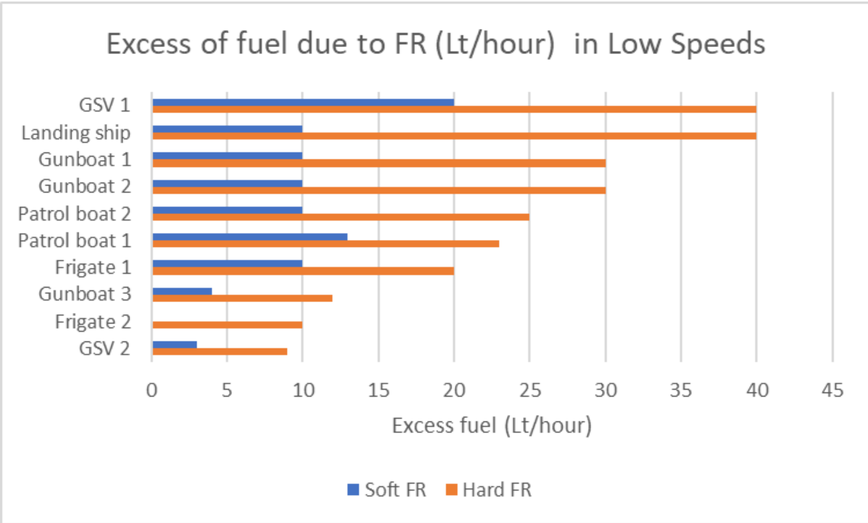
4.1 Calculative results

Taking into account each type's operating profile, as in **Table 1**, according to a 5-year cycle of hull's maintenance schedule between drydocking, it is obvious that almost 70% of operations are performed under hard fouling conditions (meaning 40-60 FR according to ANNEX "A"). Consequently, the remaining 30% impact is due to 'no' or 'soft' fouling (meaning 0-30 FR according to ANNEX "A"), which is considered as the minimum excessive fuel consumption due to a moderate operational use of the ships.

The excess of fuel consumption in liters per hour due to soft and hard fouling is shown in **Figures** 1 to 3 and corresponds to three speed ranges (low, economic and high). Apparently, the excessive fuel consumed is higher in low speeds and becomes lower in high speeds, because the fuel consumption is higher itself due to the increased speed. Specifically, comparing the similar types of the 5 categories, Frigate 1 shows a constantly increasing impact on fuel consumption in all three operational speeds. On the other hand, Frigate 2 seems to be almost unaffected in low speeds with soft fouling condition and presents a moderate increase of fuel consumption with hard fouling for the same operational speeds accordingly.

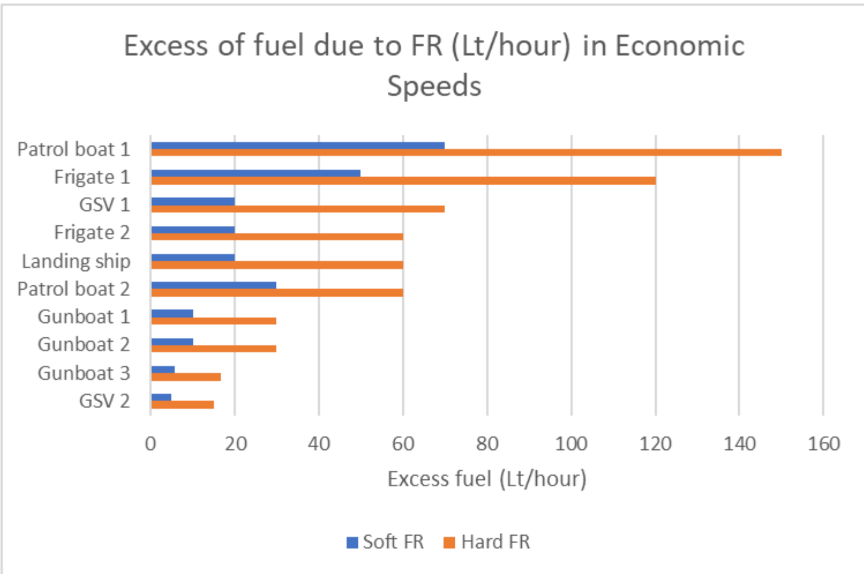
On the contrary, regarding the smaller types, the patrol boats and gunboats presented higher level of excessive fuel consumption generally in low speeds, compared to the economic speeds, and even lower in high speeds. Patrol boat 1 is an exception, since it had a disproportionately increased excess of fuel consumed in economic speeds, for both fouling conditions, soft and hard.

***Figure 1** Excess of fuel consumed (Lt/hour) due to FR in Low Speeds*



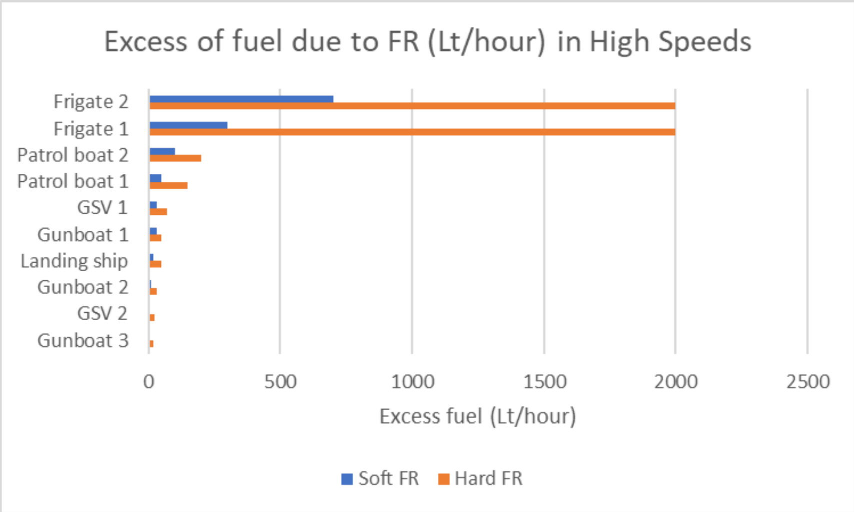
Source: Author

***Figure 2** Excess of fuel consumed (Lt/hour) due to FR in Economic Speeds*



Source: Author

Figure 3 *Excess of fuel consumed (Lt/hour) due to FR in High Speeds*

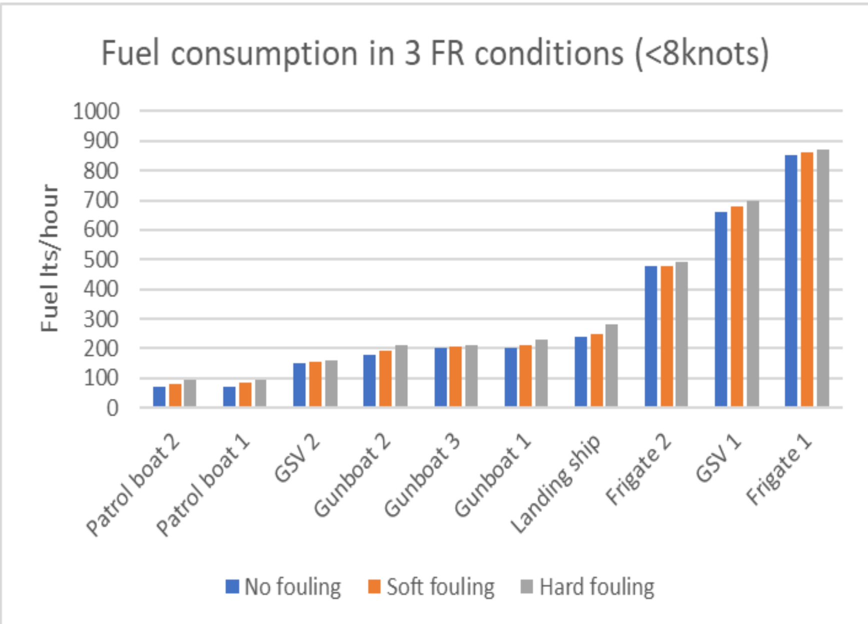


Source: Author

With regards to the three fouling conditions examined and in conjunction with the various operational speeds of **Table 1**, it seems that frigates running in high speeds are the most vulnerable in hard fouling. For the ongoing calculation, these excessive consumptions due to biofouling are used in correlation with the yearly operating hours of the ships, which are given in the same table.

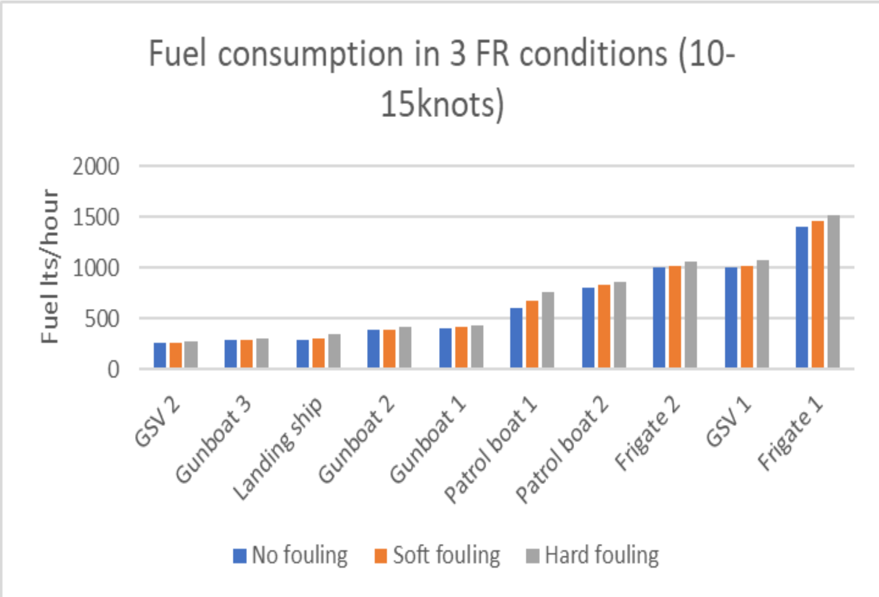
According to the parameters described so far, it is clear that the excessive fuel consumption due to a fouled ship's hull follows an increasing rate in all three conditions of hull's surface roughness examined for the 10 types of ships, as shown in **Figures** 4 to 6.

Figure 4 *Fuel consumption in low speeds (<8knots) for three hull surface conditions (No fouling – Soft fouling – Hard fouling)*



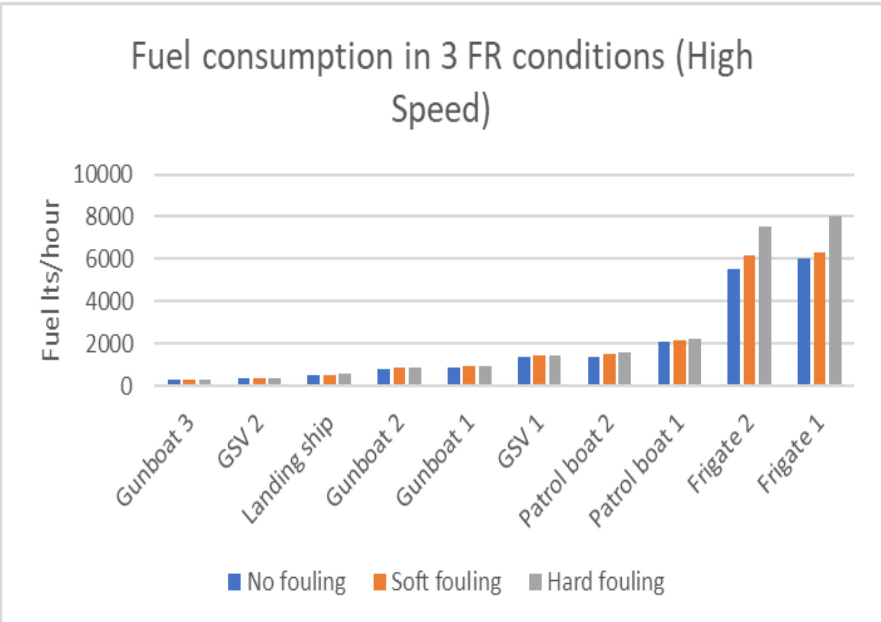
Source: Author

Figure 5 *Fuel consumption in economic speeds (maximum endurance in distance travel) for three hull surface conditions (No fouling – Soft fouling – Hard fouling)*



Source: Author

Figure 6 *Fuel consumption in high speeds (depending on the ship type) for three hull surface conditions (No fouling – Soft fouling – Hard fouling)*

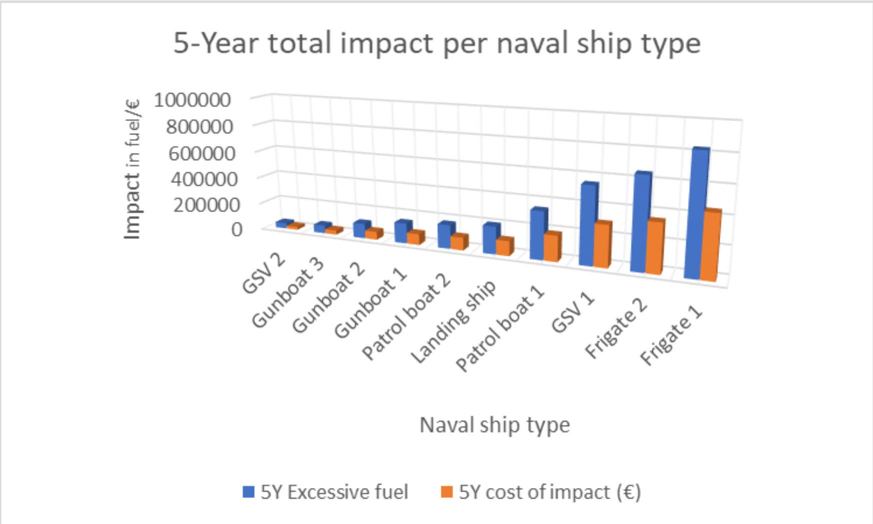


Source: Author

Even though frigates, as presaid, presented the higher impact cumulatively for the 5-year period, the general support vessel GSV 1 is also more affected by hard fouling while travelling in low speeds compared to high speeds. This is due to the contribution of Cb and the ship's operational speed to the effect of biofouling on the fuel consumption, which is explained in the studies of Shukui Liu et al. (2023) and Andrea Farkas et al. (2022).

Accordingly, this impact on fuel consumption is proven relative to the ship's hull shape factor (coefficient Cb) and the regarding deadweight, as both are critical factors of the ship's relevant total resistance. Similarly to these studies, the impact in ways of excessive fuel consumption, seems to differentiate between different types of naval ships. The hull's fouling impact on fuel consumption of the examined types of naval ships for a 5-year period, depicts similar results as shown in **Figure 7**. It represents the total amount in cash expenses per naval ship type, as a cumulative cost due to excessive fuel consumption through these five years.

***Figure** 7 5-year total impact in euro and liters of fuel per naval ship type*



Source: Author

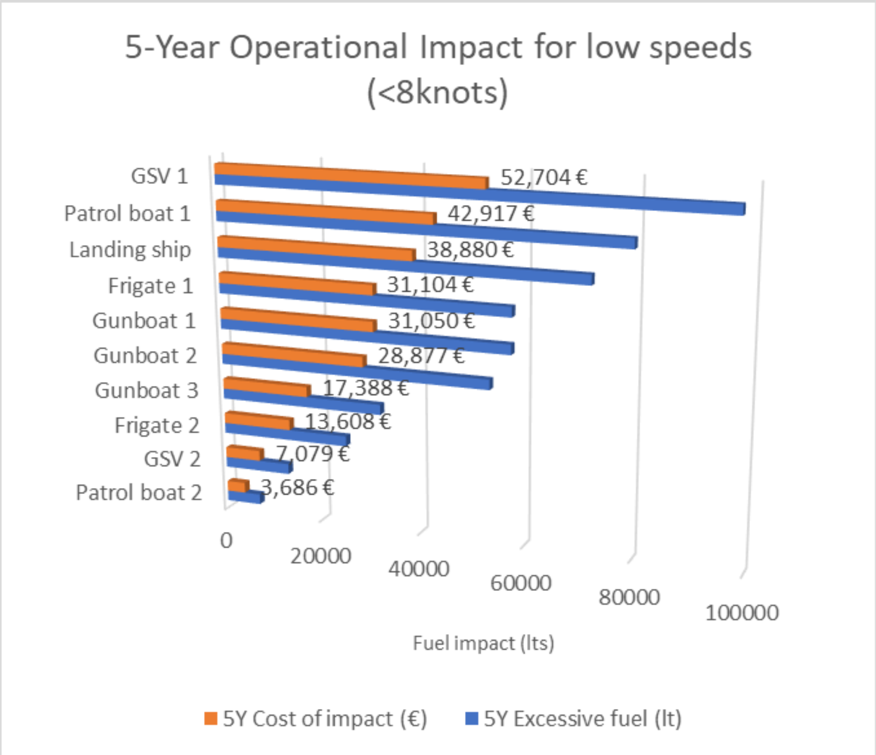
Consequently, the ships with a combination of high Cb value and maximum designed speed, seem to present the highest total 5-year cumulative cost. First in the row are the two types of frigates with a total cumulative cost of 450.360€ and 352.512€ respectively. Third in the row stands the larger type, in deadweight and Cb coefficient, General Support Vessel GSV 1 with a 5-year cumulative cost equal to 299.214€. This is much different from the smaller similar type GSV 2, which in turn is less affected by the fouling rate of the hull's surface regarding the fuel consumption. GSV 2 had a rather insignificant amount of 5-year economic impact equal to 22.480€. This is an example of the contribution of hull's form coefficient to the total resistance of the ship, as also calculated by Shukui Liu et. Al (2023) [22]. Similarly in the current study, bigger ships may confront a higher economic impact despite of operating in lower speeds, due to the significantly larger hull form coefficient (i.e. comparatively to a similar type of naval ship).

Considering the variability of the naval ships, due to their designed characteristics and the different operating profiles, the results of the 5-year cost of impact, which is considered as the total excess of fuel consumed due to biofouling, for the speed ranges of **Table 1**, are depicted in **Figures** 8-10.

The three figures have many differences amongst, due to the variability of the parameters associated to hull shape and speed characteristics, as analyzed previously. When comparing the first three types of naval ships with the highest impact in all three figures, these are not the same. Other than that, each type of naval ship, while operating within different speed ranges, presents a completely different impact from biofouling.

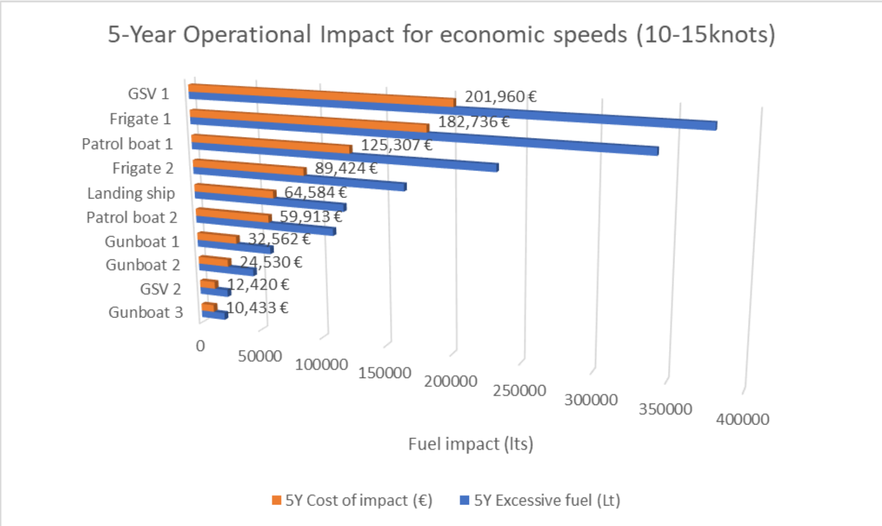
In addition, regarding the total economic impact of the types reviewed, it is also valuable to look separately into each type's total impact within the 5-year period per speed range, as in ANNEX 'B'.

Figure 8 *5-year Operational impact of biofouling in euro and liters per naval ship type, while travelling in low speeds (<8knots)*



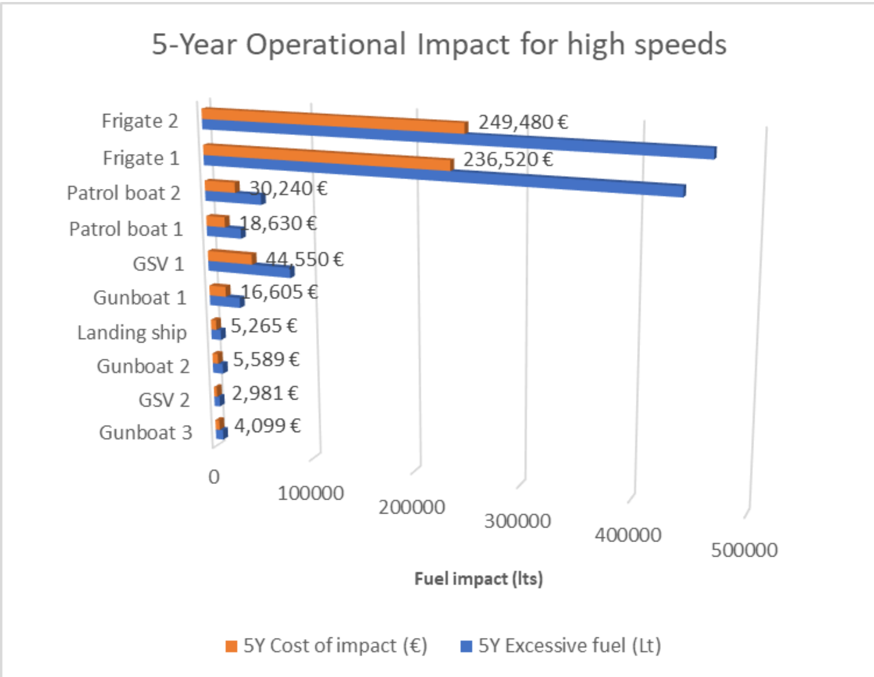
Source: Author

Figure 9 *5-year Operational impact of biofouling in euro and liters per naval ship type, while travelling in economic speeds*



Source: Author

Figure 10 *5-year Operational impact of biofouling in euro and liters per naval ship type, while travelling in high speeds*



Source: Author

4.2 Biofouling Impact Risk Assessment

Using the above results, a risk assessment is performed upon the basis of the biofouling's impact on ship's performance in relation only to the excessive fuel consumption. The risk assessment is performed by following a common practice, well presented by Guevara (2024) [23]. For the scenario of the current study, the impact is considered as a “higher than usual” fuel consumption with the corresponding probability to happen in a 5-year period.

***Table 2** Risk assessment Matrix for the evaluation of the impact of biofouling on fuel consumption*

		Impact	Insignificant	Minor	Significant	Major	Severe
Ship type	**Probability**	**Scale**	1	2	3	4	5
GSV 2	0.01	1	1	2	3	4	5
Gunboat 3	0.01	2	2	4	6	8	10
Gunboat 2	0.02	3	3	6	9	12	15
Patrol boat 2	0.03	4	4	8	12	16	20
Gunboat 1	0.04	5	5	10	15	20	25
Landing ship	0.04	6	6	12	18	24	30
Patrol boat 1	0.09	7	7	14	21	28	35
Frigate 2	0.21	8	8	16	24	32	40
Frigate 1	0.26	9	9	18	27	36	45
GSV 1	0.28	10	10	20	30	40	50

Very Low	Low	Medium	High	Very High
1-10	10-20	20-30	30-40	40-50

Source: Author

The calculation of the risk levels resulted in the risk Matrix of **Table 2**, according to the equation:

$$\text{Probability x Impact} = \text{Risk Level} \qquad [1]$$

The probability is calculated for each ship type as a 5-year amount of excessive fuel towards the summing of all types’ total 5-year amount of excessive fuel, for the examined period, using the following equation:

$$probability = \frac{Average\ hours\ travelled\ per\ year * 5year\ fuel\ consumption}{total\ 5year\ fuel\ consumption\ for\ all\ ships} \qquad [2]$$

Respectively, in order to evaluate the risk, the probabilities are scaled from 1 to 10, according to the produced values of equation [2], in which each ship’s average hours travelled yearly for the period examined, derived from the following equation:

$$Average\ hours\ travelled\ per\ year = \frac{hours\ travelled\ per\ year}{total\ hours\ of\ year} \quad [3]$$

Finally, a factor for the potential fuel impact is conceived and ranked from 1 to 5 according to Guevara's (2024) method. The outcome of the risk assessment for the 10 different naval ship types examined, are explained in **Table 3**.

Table 3 *Risk assessment Matrix-Logical Procedure Explanation*

Probability x Impact = Risk Level	
Level	**Probability**
9-10	**Almost certain** – sure to happen and/or have major consequences
7-8	**Likely** – almost sure to happen and/or to have major consequences
5-6	**Moderate** – likely to happen and/or to have serious consequences
3-4	**Unlikely** – possible to happen and/or to have moderate consequences
1-2	**Rare** – unlikely to happen and/or have minor or negligible consequences
	Impact
1	**Insignificant** – won't cause serious problems
2	**Minor** – can cause problems managing the cost or paint defects, only to a mild extent
3	**Significant** – can cause extra cost or paint defects that may require attention but limited actions
4	**Major** – can cause irreversible cost or paint defects that require constant attention and urgent actions
5	**Severe** – can result in extreme or major situation, even immediate DD
	Risk level (Colours)
1-19:	**Acceptable** – no further action may be needed and maintaining control measures is encouraged
20-29:	**Adequate** – may be considered for further analysis
30-39:	**Tolerable** – must be reviewed in a timely manner to carry out improvement strategies
40-50:	**Unacceptable** – must implement cease in activities and endorse for immediate action

Source: Author

Reviewing the results of the matrix (**Table 2)**, the risk measured regarding the minimum cost of the fuel consumed in operations, has to do with a potential of unjustified raise of the consumption due to the gradual accumulation of microorganisms in ship's hull. Thus, the depicted risk levels in **Table 2** in conjunction with **Table 3** show the importance of taking or not actions, e.g. either a reduction of operational hours of use or measures associated to the BFMP of the ships.

5. Conclusion

Following the results of the previous studies upon various types of vessels and the proof of how the hull's fouling impacts on any ship's performance, in this study there's been an evaluation of this impact for 10 different types of naval ships. The purpose was to evaluate the same impact, in terms of an excessive fuel consumption of naval ships, in relation to their various operating profiles, with different speed ranges and operating hours yearly. The results analysed above, derived from plausible operational scenarios of a 5-year period (before 2020) for the 5 categories of the most commonly used types of naval ships.

In comparison to relevant studies upon the impact on vessel performance for containerships of Andrea Farkas et al. (2022), for general cargo ships of Dinis Reis Oliveira et al. (2022) and for VLCC of Shukui Liu's et al. (2023), the current study examined types of naval ships (frigates, gunboats, patrol boats, landing ships and general support vessels). For these types of naval ships, the examined period was five years, beginning from the undocking of the vessel after a full hull cleaning and the renewal of their hull coating paints performed. Using average speeds, hours travelled and fuel consumptions, for three conditions of hull fouling (zero, soft and hard), a comparison was made with the corresponding values of ship's designed characteristics, which resulted in an extra fuel consumption for each type of ship.

Subsequently, this excess of fuel consumed, in respect to each type's operating profile, produced adequate graphs, depicting the results of the impact of biofouling on fuel consumption, similar to the aforementioned studies. Furthermore, the associated yearly cost for the examined period is being assessed from the perspective of the excess of fuel consumed due to hull's biofouling. Finally, a risk assessment of the impact of biofouling on the fuel consumption is attempted, in order to evaluate the potential impact of hull's maintenance schedule on vessel's performance, regarding the differences among the 10 types of naval ships.

Concerning the operational management of naval ships, a plan of operability taken into account when planning a maintenance schedule, can improve even more the operational availability and restrain the expenditures of the drydocking tasks. It is said that even in case of an upcoming drydocking, the on time underwater interim cleaning of the hull should not be avoided or postponed, as this could raise the extra costs of the already expensive drydocking cleaning tasks. This opinion agrees with Dragan Bebic et al. (2018), considering the flexibility of an optimized maintenance schedule, which can contribute to the balancing of the maintenance tasks' costs. For example, even if it is sometimes unavoidable, the necessary postponement of a drydocking when it comes to a frigate, will result in greater losses than for a smaller type of vessel or the GSV 2, as resulted in the Risk Matrix (**Table 2**).

According to the produced Risk Matrix of **Table 2** when a ship is in low risk level, it means that the impact on fuel consumption remains in low levels. In such a case, an extension of a DD, as in Dragan Bebic et al. (2018), may be affordable, so the cost within the extension period will be only due to periodic inspections and underwater cleanings, which is significantly lower than the cost of a scheduled DD.

Concerning naval ships, the operational availability is a main factor when a maintenance plan is being scheduled. The results showed that for all types of vessels their different operating parameters, the variability of hull's condition and the hours travelled, when monitored in conjunction, can be used effectively in order to manage the impact of biofouling on ship's operability.

Using an optimized BFMP could aid the balancing between the operating hours travelled under hard and soft fouling, in terms of decreasing the first and increasing the latter, respectively. An optimised maintenance plan can better fit into different operational schedules and vice versa, thus, the operators can perform the ships' missions by managing the operational impact of hull maintenance on vessel performance. Regarding the optimization of a BFMP, the operational costs of biofouling could be analysed relatively to the maintenance costs of ship's hull as a case for a future study upon the subject.

In the future more data will be available due to technological evolution, e.g. with the use of underwater inner hull gauges. The number and quality of data could provide even more accurate calculations, in order to better evaluate and validate the heretofore models, which are already plenty and useful. In addition, using more available data of ship's real performance, could contribute to an even better optimization of a hull maintenance plan. Such a field of future research stands mostly for the merchant types of ships, as, regarding the naval ships, the number of accessible data is limited due to confidentiality. Nevertheless, taking into account the similarities in the impact of biofouling on ship's performance as analysed in the current study, still the outcome would be valuable.

ANNEX A: " Correlation table between IMO's MEPC.378(80) & NSTM Ch081"

Table 4 *The correlation of NSTM's Fouling Rates to other coefficients such as Rt50 (roughness according to Reynolds), Ks, Kp and IMO's from-0-to-5 scale*

IMO/ RESOLUTION MEPC.378(80)				**NSTM Ch081**			**Roughness**	
Rating	**Description**	**Macrofouling cover of aera inspected (visual estimate)**	**Recommended cleaning**	**Type**	**Fouling Rating (FR)**	**Description**	**Ks (μm)**	**Rt50 (μm)**
0	**No fouling -** Surface entirely clean. No visible biofouling on surfaces	-	-	Soft	**0**	A clean, foul-free surface; red and/or black AF paint or a bare metal surface.	30	150
1	**Microfouling -** Submerged areas partially or entirely covered in microfouling. Metal and painted surface may be visible beneath the fouling	-	Proactive cleaning may be recommended as further specified in paragraph 9.4	Soft	**10**	Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling.	100	300
				Soft	**20**	Slime as dark green patches with yellow or brown colored areas (advanced slime). Bare metal and painted surfaces may by obscured by the fouling.	100	300

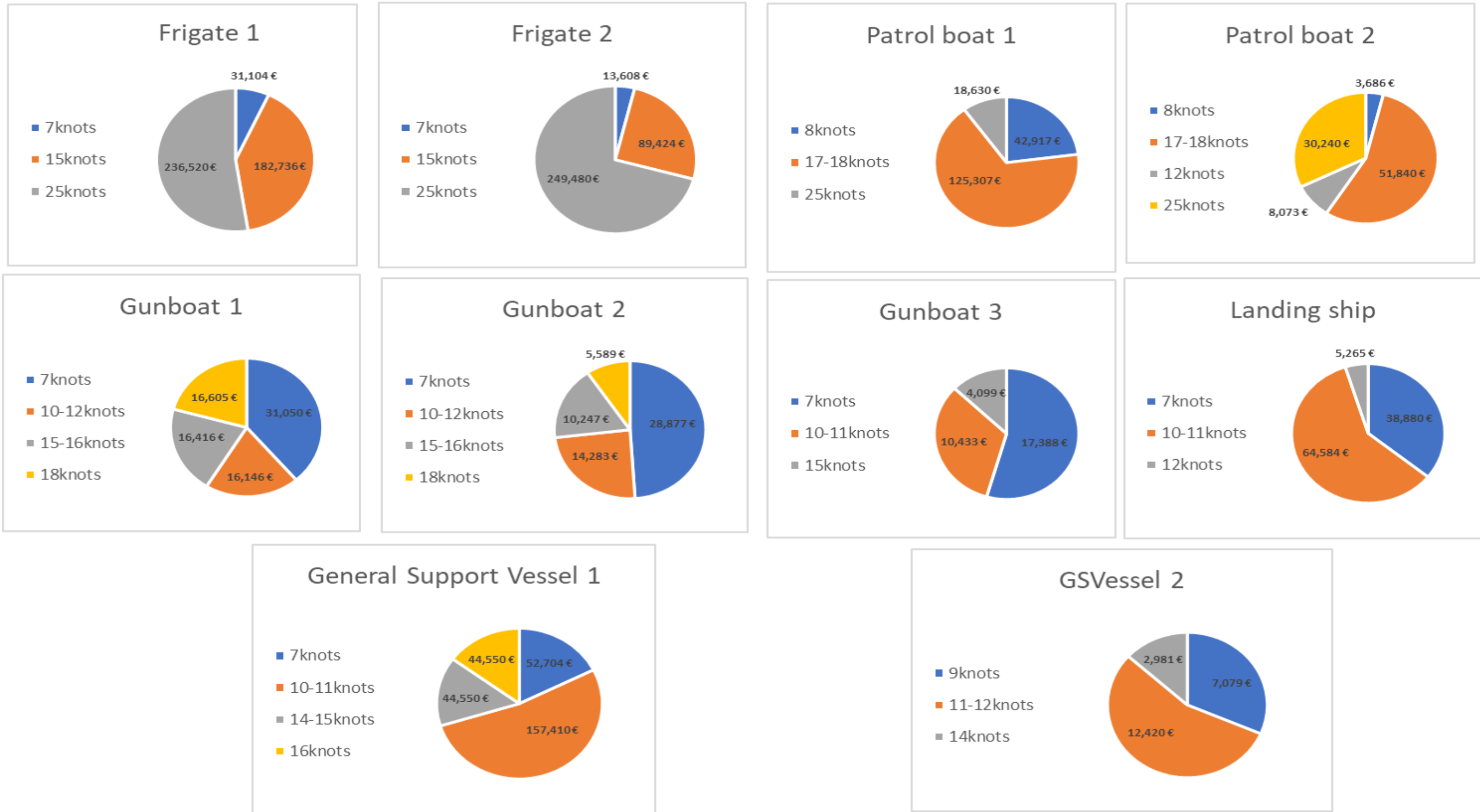
IMO/ RESOLUTION MEPC.378(80)				NSTM Ch081			Roughness	
Rating	**Description**	**Macrofouling cover of aera inspected (visual estimate)**	**Recommended cleaning**	**Type**	**Fouling Rating (FR)**	**Description**	**Ks (μm)**	**Rt50 (μm)**
				Soft	**30**	Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in color; or soft non calcareous fouling, such as sea cucumbers, sea grapes, or sea squirts projecting up to up to 1/4 inch (6.4 mm) in height. The fouling cannot be easily wiped off by hand.	300	600
2	**Light macrofouling -** Presence of microfouling and multiple macrofouling patches. Fouling species cannot be easily wiped off by hand.	1-15% of surface	Cleaning with capture is recommended as further specified in paragraph 9.9.	Hard	**40**	Calcareous fouling in the form of tubeworms less than ¼ inch in diameter or height.	1000	1000
				Hard	**50**	Calcareous fouling in the form of barnacles less than ¼ inch in diameter or height.	1000	1000

IMO/ RESOLUTION MEPC.378(80)				NSTM Ch081			Roughness	
Rating	Description	Macrofouling cover of aera inspected (visual estimate)	Recommended cleaning	Type	Fouling Rating (FR)	Description	Ks (μm)	Rt50 (μm)
				Hard	60	Combination of tubeworms and barnacles, less than ¼ inch (6.4mm) in diameter or height.	1000	1000
3	**Medium macrofouling** - Presence of microfouling and multiple macrofouling patches.	16-40% of surface	It is recommended to shorten the interval until the next inspection. If the AFS is significantly deteriorated, dry-docking with maintenance and reapplication of the AFS is recommended.	Hard	70	Combination of tubeworms and barnacles, greater than ¼ inch in diameter or height.	3000	3000
				Hard	80	Tubeworms closely packed together and growing upright away from surface. Barnacles growing one on top of another, ¼ inch or less in height. Calcareous shells appear clean or white in color.	3000	3000

IMO/ RESOLUTION MEPC.378(80)				NSTM Ch081			Roughness	
Rating	Description	Macrofouling cover of aera inspected (visual estimate)	Recommended cleaning	Type	Fouling Rating (FR)	Description	Ks (μm)	Rt50 (μm)
4	**Heavy macrofouling -** Large patches or submerged areas entirely covered in macrofouling.	41-100% of surface	It is recommended to shorten the interval until the next inspection. If the AFS is significantly deteriorated, dry-docking with maintenance and reapplication of the AFS is recommended.	Hard	**90**	Dense growth of tubeworms with barnacles, ¼ inch or greater in height; Calcareous shells brown in color (oysters and mussels); or with slime or grass overlay.	10000	10000
				Composite	**100**	All forms of fouling present, Soft and Hard, particularly soft sedentary animals without calcareous covering (tunicates) growing over various forms of hard growth.	10000	10000

Source: IMO (2023), NSTM (2006), Shukui Liu et al. (2023)

ANNEX B: “Economic impact in euro (for fuel price 0,54€/lt) in a 5-year period, for each type of naval ships and for different average travelling operational speeds”



Source: Author

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