ERDENİZ EROL

M.Sc. THESIS

2019

IMPACT OF FOULING ON VESSEL ENERGY EFFICIENCY

ERDENİZ EROL

PİRİ REİS UNIVERSITY

2019

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by

Erdeniz, EROL

B. S., Electrical Electronics Engineering, Middle East Technical University, 2007

Submitted to the Institute for Graduate Studies in Science and Engineering in partial fulfillment of the requirements for the degree of Master of Science

2019

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APPROVED BY

Assoc. Prof. Dr. Elif ÖZEN CANSOY ....

(Thesis Supervisor)

Asst. Prof. Dr. Orhan Özgür AYBAR ....

(Thesis Co-Supervisor)

Prof. Dr. Uğur ÇELTEKLİGİL ....

Assoc. Prof. Dr. Derya Y. İMER ....

Asst. Prof. Dr. Bora ÇEKYAY ....

DATE OF APPROVAL: 02.07.2019

ACKNOWLEDGMENTS

I would like to express my sincere gratitude for my company Elkon Elektrik Sanayi Ticaret A.S for their technical support and providing vessel automation data. I would like to also thank to all my colleagues about their helpfulness about log data extraction and data analysis.

I wish to thank to my thesis supervisors Assoc. Prof. Dr. Elif ÖZEN CANSOY and Asst. Prof. Dr. Orhan Özgür AYBAR for their support and encouragement on this thesis preparation.

I am grateful to the members of my thesis committee, Prof. Dr. Uğur ÇELTEKLİGİL, Assoc. Prof. Dr. Derya Y. İMER and Asst. Prof. Dr. Bora ÇEKYAY for their valuable comments and contribution.

I would like to thank to my dear wife Tülay, my daughter Zeren that we recently feel her kicks, my parents who raised me and my brother for all their support and patience during all my education period.

ABSTRACT

IMPACT OF FOULING ON VESSEL ENERGY EFFICIENCY

Shipbuilding and shipping areas are highly technically dependent to each other since shipping is the end user of shipbuilding industry that are suppliers of them. We can call these two as maritime business as a whole. One of the biggest specific challenge of maritime arrived as regulations about emission has begun to spread all over the world. Approximately 90% of the cargo carried in world trade is based on waterborne transport, and the volume of international waterborne trade is rapidly increasing day by day. Taking into account the pollutant (emission) values carried by the vessels, cargo and the distance, it is the cleanest way to transport by sea, compared to land and air transport. However, the emission values per vessel are quite high. Generally, NO_x, SO_x, CO_2 and other pollutants are emitted in the exhaust gases from vessels driven by diesel engines. These pollutants have an adverse impact on the environment due to acid rain, thinning of the ozone layer and health problems. For example, the annual emission value of the world's 15 largest container ships is equal to the emission value of all cars on the world, approximately 760 million cars.

Maritime industry has enormous potential in terms of decline in energy usage and emission supervision with respect to existing ships especially. The specific challenges are to introduce energy efficiency and minimize emissions; to make research on alternative energy sources; to conduct vessel electrification, where sailing displacements and infrastructures permit it; and to optimize the basic performance of vessels. Two of these challenges will be addressed in this work via one design and one operational improvement methods. These are vessel electrification in other words ship electric propulsion design and the other one is impact of fouling or opposite hull cleaning which enables efficiency and increase the performance of vessel.

In this study, a battery hybrid electric ship automation data are analyzed using Curve Fitting and Detrended Fluctuation Analysis in order to interpret the impact of fouling on ship energy performance degradation and efficiency by continuous monitoring.

Keywords: Ship Energy Efficiency, Fouling, Curve Fitting, Detrended Fluctuation Analysis.

ÖZET

TORTUNUN GEMİ ENERJİ VERİMLİLİĞİNE ETKİSİ

Gemi inşa ve lojistik alanları gemi inşa endüstrisinin son kullanıcısı olduğu için birbirine bağımlıdır. Bu ikisi bir bütün olarak denizcilik sektörü olarak adlandırılabilir. Emisyon ile ilgili düzenlemeler dünyanın dört bir yanına yayılmaya başlayarak, denizcilikle ilgili en büyük zorluklardan biri haline gelmiştir. Dünya ticaretinde taşınan yükün yaklaşık 90% oranı suyolları üzerinden taşınmakta ve dünyada su üstü taşımacılığında gerçekleştirilen uluslararası ticaret oranı giderek yükselmektedir. Kargo ve mesafe başına gemiler tarafından taşınan kirletici (emisyon) değerleri dikkate alındığında, kara ve hava taşımacılığına göre deniz yoluyla taşınma en temiz yoludur. Bununla birlikte, gemi başına emisyon değerleri oldukça yüksektir. Genel olarak dizel motorlarla çalışan gemilerden egzoz gazlarında NO_x, SO_x, CO_2 vb. kirleticiler asit yağmuruna, ozon tabakasının incelmesine ve sağlık sorunlarına bağlı olarak çevre üzerinde olumsuz bir etkiye sahiptir. Örneğin, dünyanın en büyük 15 konteyner gemisinin yıllık emisyon değeri, dünyadaki tüm otomobillerin, (yaklaşık 760 milyon araç) yaydığı emisyon değerine eşittir.

Denizcilik endüstrisi, özellikle mevcut gemilerle ilgili olarak enerji kullanımı azaltma ve emisyon kontrolü açısından büyük potansiyele sahiptir. Gemilerde enerji verimliliği ve emisyon azaltımlarının farkındalığı; gemilerde alternatif enerji kaynaklarının araştırılması; seyir mesafeleri ve altyapıları müsaade ettiği ölçüde gemi elektrifikasyonu yapmak; ve gemilerin temel performansını optimize etmek bu endüstrideki özellikli zorluklardır. Bu zorluklardan ikisi, bu çalışmada bir tasarım ve bir operasyonel iyileştirme yöntemi ile ele alınacaktır. Bunlar gemi elektriği tahrik sistemi tasarımıdır, diğeri ise, tortu birikiminin veya zıttı tekne temizliğinin enerji verimine ve geminin tortu birikimi ile düşen performansına olan etkisidir.

Bu çalışmada tortu birikiminin gemi enerji verimliliği üzerindeki etkisini sürekli izleme ile değerlendirebilmek için Eğri Uydurma ve Eğimden Arındırılmış Dalgalanma Analizi yöntemleri ile bataryalı hibrit bir geminin otomasyon verileri analiz edilmiştir.

Anahtar Kelimeler: Gemi Enerji Verimliliği, Kirlenme, Eğri Uydurma, Eğimden Arındırılmış Dalgalanma Analizi.

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LIST OF SYMBOLS/ABBREVIATIONS

AAKR	Auto Associative Kernel Regression
AC	Alternative Current
ACA	American Coatings Association
CFD	Computational Fluid Dynamics
C_F	Frictional resistance coefficient which depends on Reynolds number
DC	Direct Current
DFA	Detrended Fluctuation Analysis
DG	Diesel Generator
DNA	Deoxyribonucleic Acid
ECA	Emission Control Areas
ECG	Electrocardiogram
EEG	Electroencephalogram
EM	Expectation Maximization
FOC	Fuel Oil Consumption
FR	Foul Releasing
GMM	Gaussian mixture model
HVAC	Heating Ventilating and Air Conditioning
IMO	International Maritime Organization
kW	Kilowatt
LCA	Life Cycle Assessment
LNG	Liquefied Natural Gas
MDO	Marine Diesel Oil
MPC	Model Predictive Control
NaN	Not a Number
NaT	Not a Time
PCA	Principal Component Analysis
PDSMe	Polydimethylsiloxane elastomer
R&D	Research and Development
R_A	Air resistance

R_E	Eddy resistance
R_F	Frictional resistance
R_W	Wind resistance
ρ_w	Water density
S	Submerged area of a ship hull which is wetted under sea.
SFOC	Specific Fuel Oil Consumption
SPRT	Sequential probability Ratio Test
SSE	Sum of Squares due to Error
SSR	Sum of Squares of the Regression (SSR)
SST	Total sum of squares
TBT	Tributyltin
THD	Total Harmonic Distortion
VEGA	Vector Evaluated Genetic Algorithm
V_S	Ship Speed

1. INTRODUCTION

Economics, compliance and customer requirements affect shipping industry in terms of energy efficiency improvements. However, adaptation of technological and operational developments on world fleet is relatively slower. This slow adaptation is due to suspicion on integrity and accuracy of the data collected from shipping industry because of many effects like weather, trim, fouling and other physical factors like ocean currents. The aim of this thesis is first to understand how these effects can be considered on the design of ship propulsion according to ship operational energy efficiency and impact of fouling [1].

In order to maintain efficient ship operations, one of the first method is to automatize operations as good as possible. First step of vessel automation in history aims introduction to remedy the shortage of seamen in early 1960s. Japanese Ship Kinkasan Maru was most probably the first of automated vessel in the world. The aims of ship automation which indicated the main five points, which remain as a rule of thumb, are;

- Relieve the ship’s crew from physical and mental fatigue
- Collect data for the reliability and efficiency of instrumentation
- Prevent errors due to unqualified crew employment
- Shift the control from the engine to the bridge
- Prevent failures or shutdowns by means of remote check points [2].

Achievement of above aims bring overall efficiency of ship operation within main duties of ship crew by their competency and availability of data. In general, crew keep the record of fuel and ship operational data by filling up noon reports. Ship automation data and history trends will help operators onboard tracking current situation of ship. These records are stored also in log files in order to determine alarms and sensor data acquired. All these data will be able to identify many aspects of ship operational efficiency. Ship consumption data includes feedback data for the efficient operation of the propulsion system along with the ship's own operation, the status of its inventory (generator, engine, battery, drive and transfer bodies) and verification of the design of the propulsion system. These information can be accurately analyzed by taking into consideration the operational needs of the ship and the environmental (climate, current, fuel performance, priorities, etc.) factors of the vessel. Automation systems in ships hosts both electrical and physical structure and all historical data that will be analyzed according to the design of the ship, the use of personnel, the physical condition of the ship's hull, operational requirements and provide better performance and operational efficiency.

This thesis’ literature background is based on a collection of recent works on determination of ship energy efficiency in general and the factors that affect it. Second chapter helps to learn these factors. One of the important factors is marine fouling which that ships exposed to that effect in time. Until today, ship energy efficiency is measured by fuel consumption and speed of ship comparisons. In third chapter state of the art fouling prevention and antifouling methods and coating is descripted. Since electrification of ships enables much more efficient ship operation, in this study, an anonymous battery hybrid electric propulsion ship automation data are analyzed in order to commentate the impact of fouling on ship energy performance by continuous monitoring.

Data analysis of real ship energy consumption data as inputs and ship speed as an output are implemented in fourth chapter. On the other hand fouling is an adverse effect on energy efficiency of ship, it should be detected and cleaned for better operation. Fouling detection can be achieved by underwater camera or likewise as this thesis clarifies how its adverse effect on operational efficiency can be detected from log data records in automation system of a ship.

In this thesis, design aspect of ship energy efficiency and factors that affect it, is clarified before analyzing automation data analytics. This approach enables which data sources are worth to analyze. The articles about the ship energy efficiency are investigated and key findings on recent articles are compiled. Two different data sets from same vessel are collected in July 2017 and April 2018. Although periods of dry docking of vessels are more than 4 years, impact of fouling can be detected within 9 months by analyzing this new built electric propulsion ship log data using curve fitting and Detrended Fluctuation Analysis (DFA) for anomaly detection.

2. FACTORS THAT AFFECT SHIP ENERGY EFFICIENCY

2.1. Ship Energy Efficiency

In principle, vessel efficiency is maximum at Design Point if other factors like certain draft, trim, cargo intake, propeller and hull cleanness of vessels, in addition to sea/weather conditions cause deterioration of this design point. Optimization of all these factors and their control aim to reach this design point since it is the designer's optimum point to be decided at once according to ship design requirements as it is shown in Figure 2.1 [3]. Figure 2.2 shows which physical factors influence ship energy efficiency adversely as red items [4].

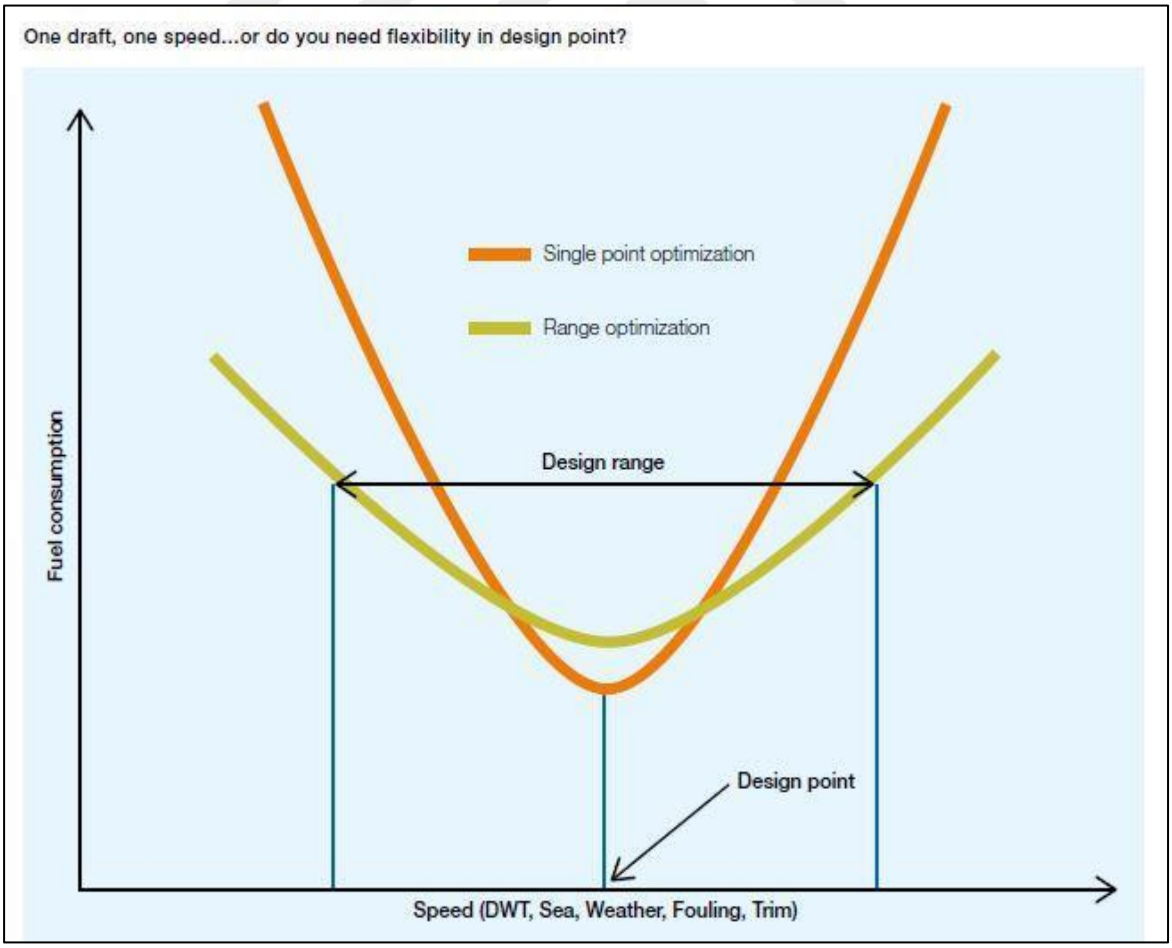

Figure 2.1. Propulsion Design for Fuel Consumption versus Vessel Speed for Design [3].

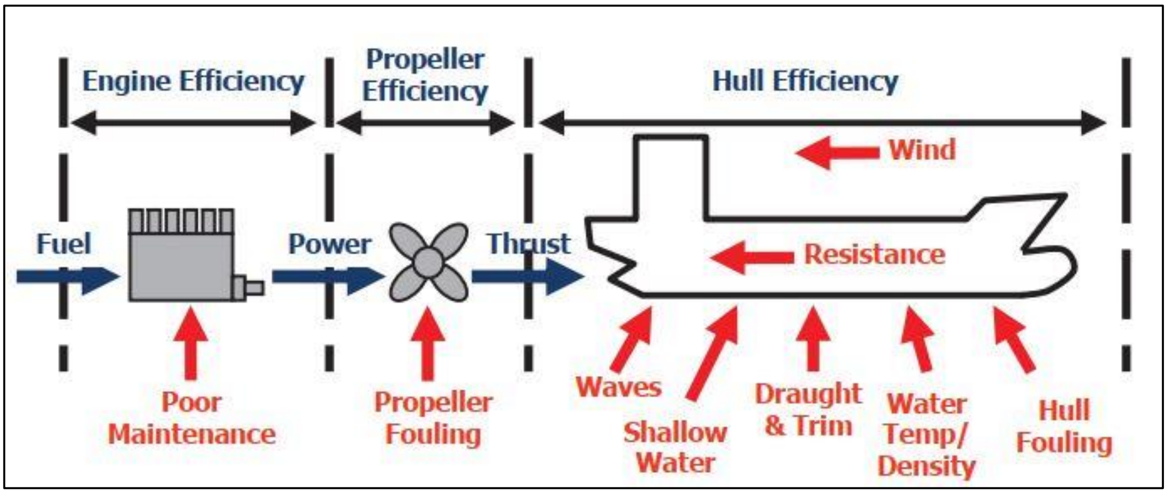

Figure 2.2. Ship Propulsion Energy Efficiency and Negatively Affecting Factors [4].

Draft, trim, cargo intake and sea/weather conditions are the factors, which frequently vary in time with respect to propeller and hull cleanness of vessels. That is why fouling is an important factor that does not frequently vary in time moreover it increases gradually unless there is not any cleaning of dry docking of vessel. "Fouling Release" become more important in terms of energy efficiency and more efforts on R&D on the antifouling coatings as well as other green coating technologies in parallel are concentrated on this field [3].

In general R&D efforts are focused on laboratory based methods and effective hydrodynamic testing tools supported by advanced CFD methods in terms of anti-fouling performance predictions. For future valuable work, "in-service" performance prediction should be replaced or compared with laboratory and CFD methods [5]. CFD computation is used for integration of the hydrodynamic components, surface technologies is used for ensuring hull resistance and for propeller features are predicted via an artificial neural network (ANN) [6].

Ship's building year, salinity concentration, water temperature, cleaning intervals of the ship hull, and its coating, the proportion between the duration of staying in port to sailing at sea and the speed of the vessel are the factors which affect the fouling status of hull. The fouling influences total resistance of the ship and it depends on speed as result of Reynolds number on the coefficient of this friction. Specific fuel-oil consumption(SFOC) hypothetically depends on propeller speed and shaft efficiency regulated engine load. This consumption variables are generally given in engine layout diagrams. Fuel consumption and power deviations coincide with particular fuel-speed law in these diagrams [4].

The energy efficiency optimization can be different for each vessel, since their hull form and operation are distinctive. Therefore R&D projects are conducted specifically on different types of vessels. Since the hull forms are different it is very difficult to set one equation for each type of vessel. Hull resistance remains in all types of vessels, which comprise of many sources, can be divided into three principle classifications [8]:

1. Frictional resistance: Frictional resistance (R_F) originates from hydrodynamic friction subjected to the hull as the vessel sails on the water. It increments roughly by the square of the ship speed. Fouling of the hull, corruption of the structure smoothness by disintegration, development of marine life forms and clasped base plates that will build the frictional resistance and eventually creates energy inefficiency of the ship.

$$R_F = \frac{1}{2} C_F \, \rho_w S V_s^2 \qquad (2.1)$$

Where;

R_F : Frictional resistance

C_F : Frictional resistance coefficient which depends on Reynolds number

ρ_w : Water density

V_S : Ship Speed

S : Submerged area of a ship hull which is wetted under sea.

Fouling, one of the most common reason of frictional resistance, relies upon operation year of the ship, the saltiness and sailing sea or ocean temperature, the cleaning plan of the hull, the structure of hull, the proportion of sailing duration to anchoring duration at port and the speed of vessel. The fouling thus influences in general ship resistance and consequently speed of ship due to friction, however instant resistance increases by the square of ship speed [4].

2. Residual resistance: Residual resistance incorporates the wave (R_W) and eddy resistances (R_E). Wave resistance is the vitality lost due to producing waves as the ship faces with the water. Additionally, the vortex of water and reverse flow when a ship travels through a gooey liquid, especially towards back of the ship, is known as the eddy resistance. This impact can regularly be seen behind big rock in fast inland waterways, for instance [8].

3. Air resistance: Air resistance (R_A) originates from the movement of the ship through air, and normally represents just a little piece of the absolute resistance. Vessels with an extensive superstructure or container ships normally have a higher air resistance than some other ship types coming about because of a substantial breeze uncovered zone [8].

All the three resistances create total resistance applied to ships sailing. Since residual and air resistance is not a stationary aspect which can vary in time in terms of weather conditions, frictional resistance caused by fouling substantially increase until cleaning of vessel.

2.2. Factors That Affect Energy Efficiency

In today's world, ships are designed according to their operation modes and their expected propulsion power [9]. Electrical propulsion systems, which provide efficient and safe management of electrical driven systems, are preferred rather than mechanical driven systems in the design of propulsion systems in these vessels. Behind these design changes there are environmental regulations that include the limitation of the emission of gases like NO_x, SO_x, etc., ruled by International Maritime Organization (IMO), which is tightening them each passing year with Emission Control Areas (ECA). IMO put the MARPOL Annex VI Ship Air Pollution prevention contract into effect in 2005, which is accepted by Turkey in February 2014, including limit values for sulphur content in nitrogen oxide emission and fuel. IMO has set limit values for the new EEDI (Energy Efficiency Design Index) of new built ships by the regulation, which was introduced in 2014 in order to lower the fossil fuel emission emitted from the vessels, and it has made it necessary to prepare SEEMP (Energy Efficiency Management Plan) for all vessels for energy efficient usage. These regulations that determined in the relevant legislation, are taken into consideration and the existing ships are expected to improve the existing propulsion systems in order to be able to comply with these rules and, if they are not, they are required to revise their ships into revisions called retrofits.

It is possible to measure the efficiency of the ship operations with professional experience and operational costs at a high point of view, however at the lower levels, the method of improving it is to measure the sub-systems and which are efficient or not. Autonomous ships are expected to be the ultimate technology as a goal of controlling these subsystems on their own. It is not coincidence that marine technology companies working on this subject are data analytics products among all common features. Although these analytical calculations provide assistance to technical personnel such as the captain and chief engineer in the ship operation, the long-term target is the access of ship owners to the remote ship's operation and control. Although these concepts are new in the field of shipbuilding technology, there are examples in other sectors considering the fact that the data mining method is now spread across all sectors, on the other hand it is limited activities for maritime transport.

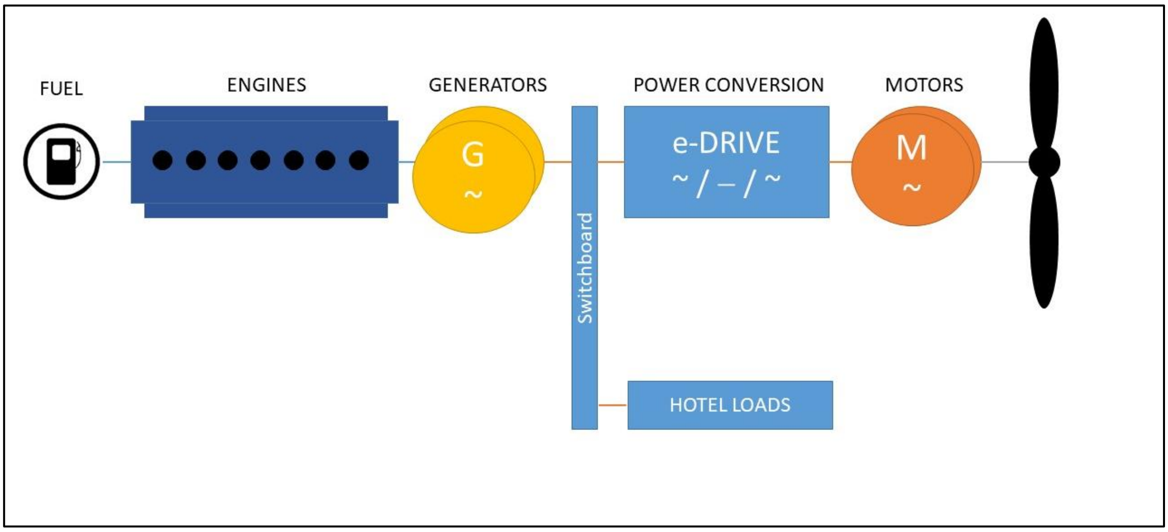

Figure 2.3. Block Diagram of Ship Electrical Propulsion Systems Components Overview.

Ship electrical propulsion system is different from conventional ship propulsion system in terms of power that rotates propeller. In conventional ship propulsion systems, rotation is supplied by engine that rotates the shaft and propeller mechanically [10]. On the other hand, in electric propulsion systems, electric motors provide this rotation, getting electrical power generated by electrical generator that engine supplies as all these systems and their correlations are depicted in Figure 2.3. In all electric ship concept, batteries that provide electricity replace engine and generator.

In marine systems literature, until electrification of vessels, ship energy performance management systems are analyzed by fuel versus vessel speed graphs, as one of the example graph is given in Figure 2.4 [11].

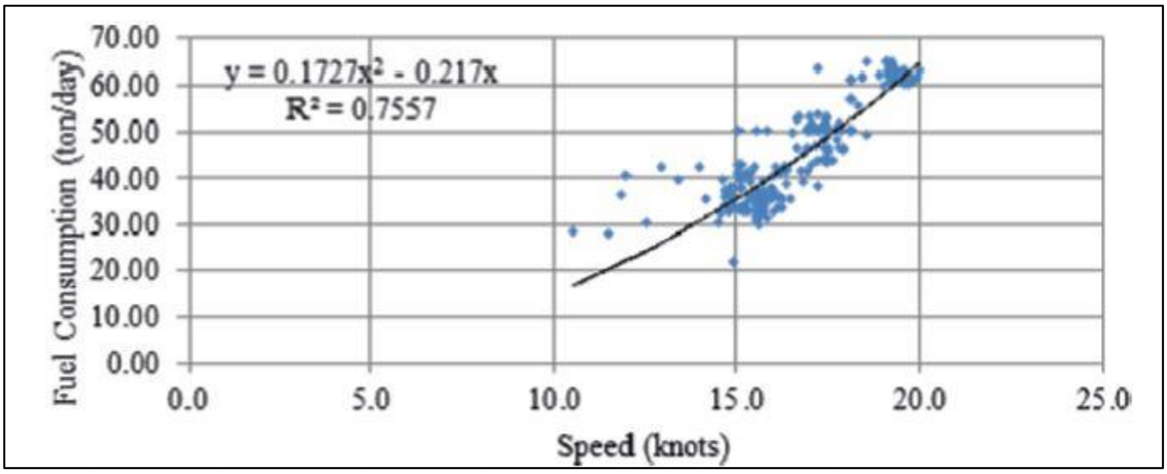

Figure 2.4. Ship Fuel Consumption and Vessel Speed Graph of a Mechanical Propulsion Ship [12].

These graphs vary on vessel to vessel and voyage to voyage due to hull type of vessel and its condition, weather and sea conditions, and finally loading of vessel. As seen in Figure 2.5 fuel consumption is less when the ship is not loaded(Ballast), however fuel consumption increases when the ship is loaded with cargo(Laden) [12]. Because loaded ship has got more submerged area than ballast and hence frictional resistance increases accordingly.

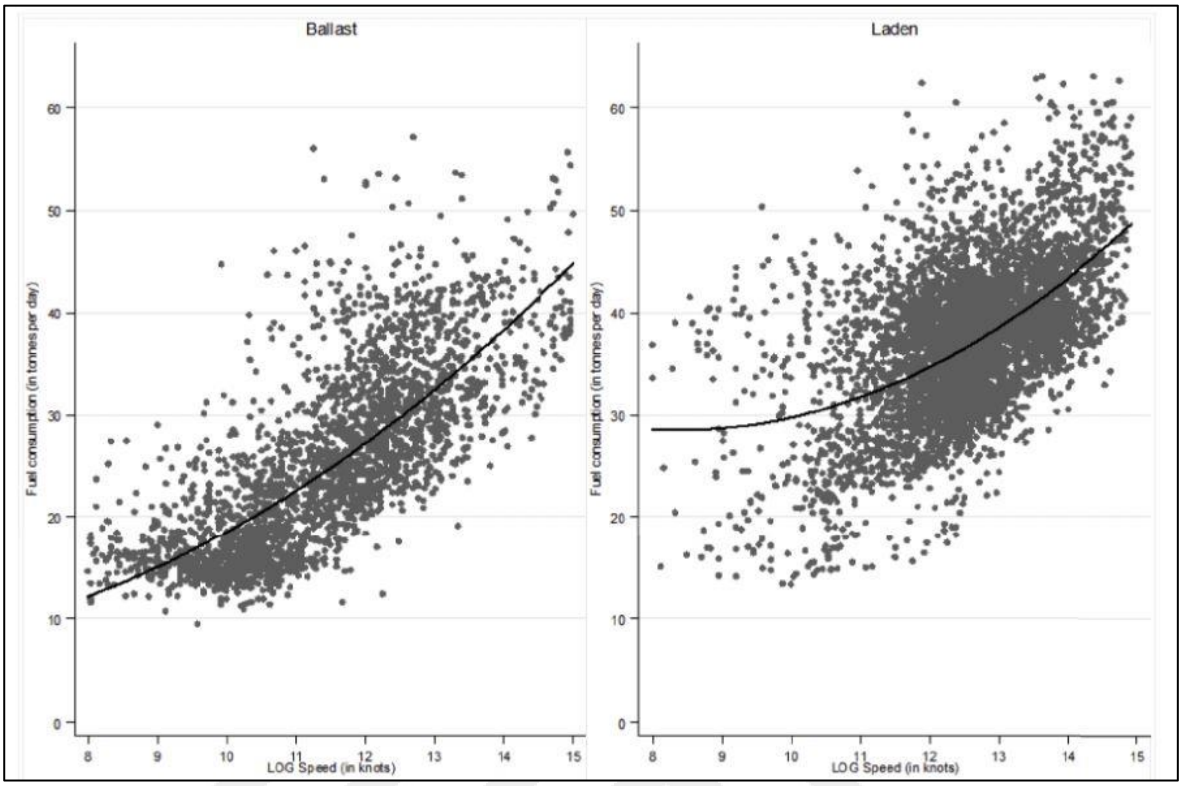

Figure 2.5. Fuel Consumption and Vessel Speed Graphs of Ballast and Laden conditions [12].

These graphs shown in Figure 2.5, are extracted from data that is collected from noon reports, which is a long time interval based and low quality dataset (nearly 24 hours of sample rate) is needed to identify the ship's performance with respect to consumption of fuel. Noon reports include the following data: Date Time, Ship's course, Weather/Wind direction, Weather/Wind force Current Speed Steaming time, Traveled distance, Ground speed, Main engine fuel oil consumption, Draft of ship [9].

On the other hand, noon reports are subjected to criticism due to data scarcity and uncertainty as it is shown in Figure 2.6. Thus data collection via continuous monitoring enable more data to analyze and more precision [13]. Development rate of the added resistance of fouling were also examined in 210 ships with all different types of hull coating systems. Due to fouling development rate, as it is seen in Figure 2.7, between 0.3% to 1.5% added resistances are observed per month, reaching up to total %40 - %45 band of resistance ratio within 5 years of dry-docking periods [14]. Figure 2.8 demonstrates that vessel speed loss can be up to %15 of the ship which might exposed to fouling for only 4 months [15].

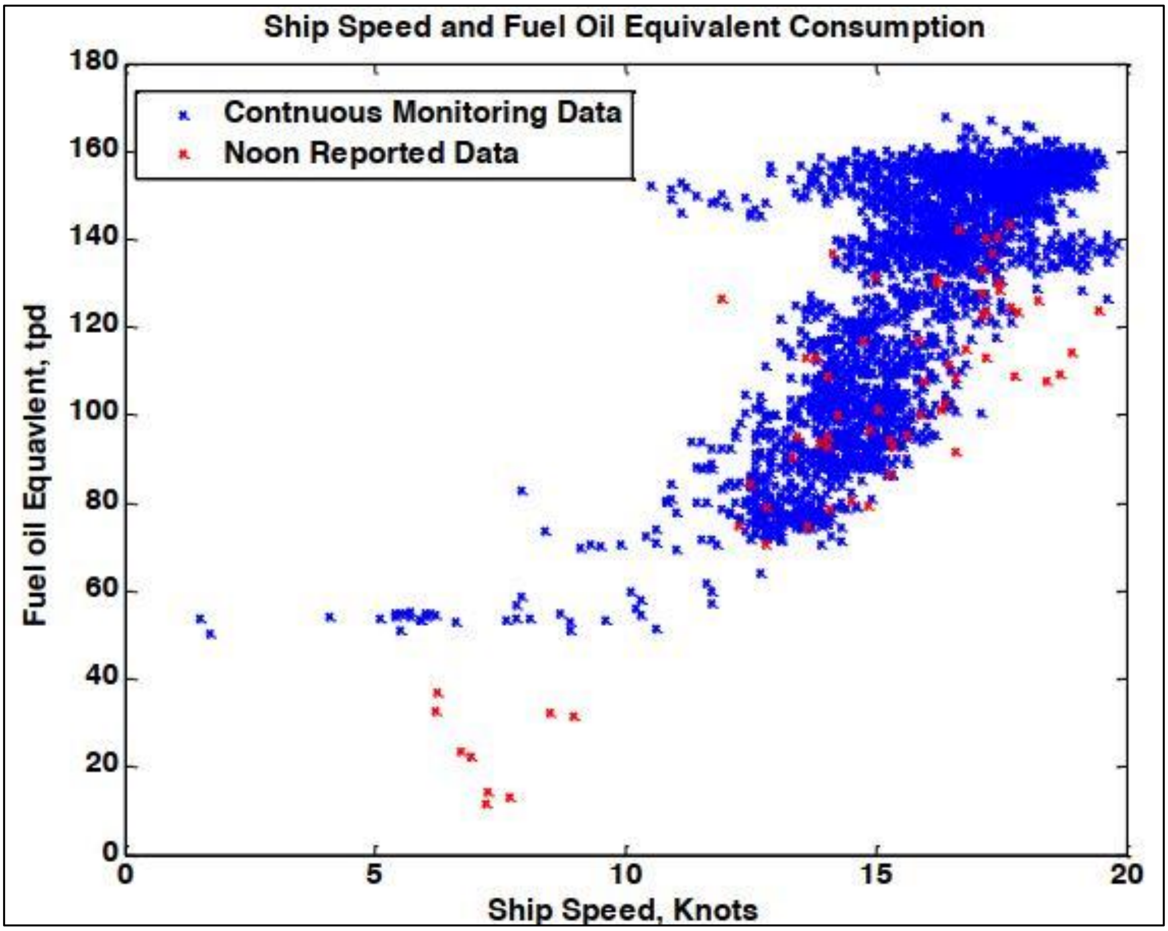

Figure 2.6. Difference between amount of data points for Noon Report and Continuous Data Collection [13].

Fouling and resulting shagginess on the vessel’s hull causes performance degradation of the ship. Around 5% of total amount of marine fuel costs are spent for antifouling precautions [16]. In order to detect fouling impact, there are deterministic corrections for external disturbances like wind, wave and current corrections. After these corrections are excluded, in service measurement and new built which has got sea trial data can be compared so as to detect biofouling degradation as indicated in Figure 2.9 [17].

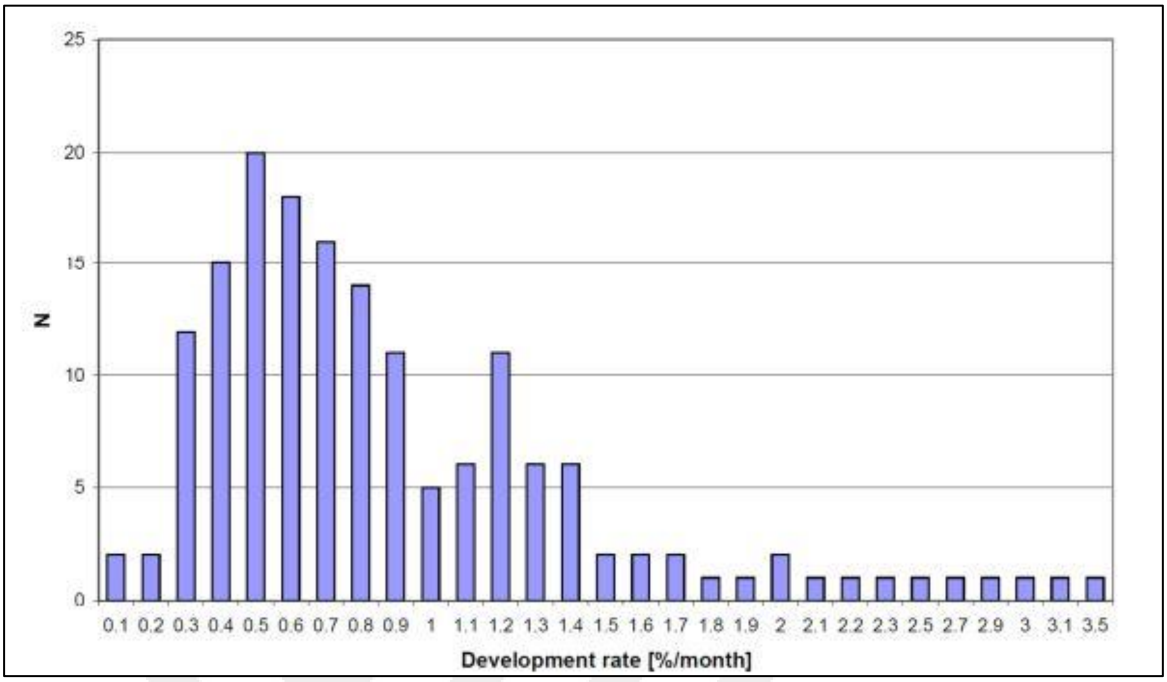

Figure 2.7. Distribution Number of Vessels on Monthly Fouling based Resistance Rates [14].

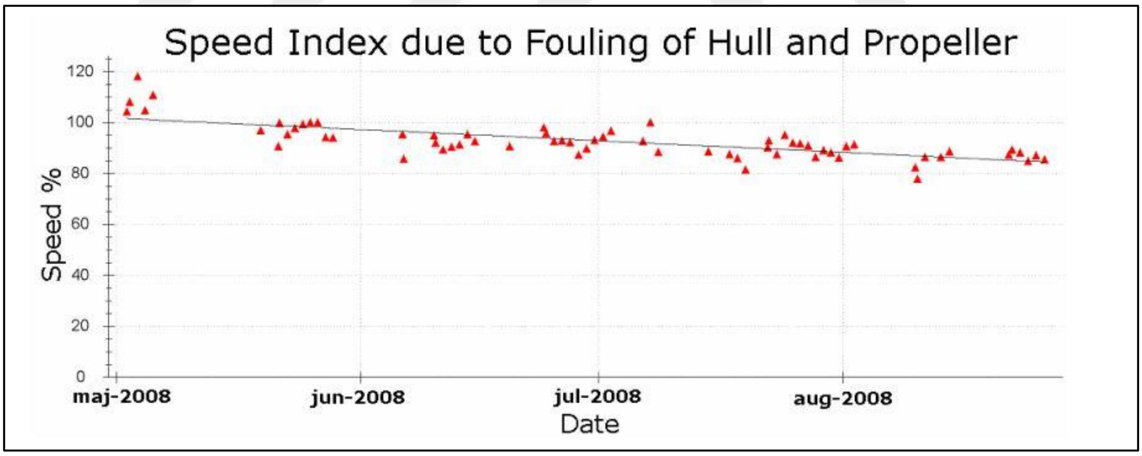

Figure 2.8. Distribution Number of Vessels on Monthly Resistance Rates [15].

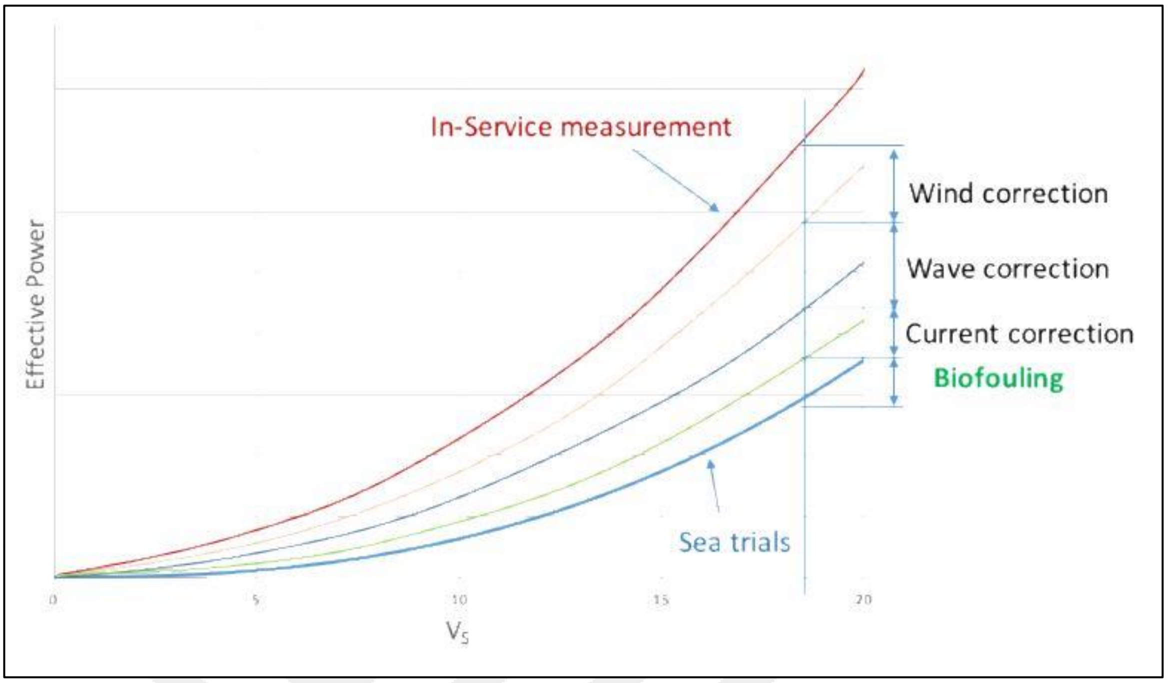

Figure 2.9. Difference between In-Service measurement and sea trials and types of External Factors [17].

3. FOULING

The term biological fouling, it is also abbreviated biofouling, is the unenviable situation of development of living beings on a ship hull's face drenched in water; made by microorganisms. Eventually this situation causes macroscale biofouling, abbreviated as macrofouling made by creatures (for example, barnacles). In order to keep away from these fouling forms or to relieve fouling utilizing different antifouling innovations are the common challenges of ship operations till today [18].

Level and growth rate of hull fouling would differ among ships and according to seas and oceans due to salinity of water. Irrecoverable activity of bacterial colonization has got numerous phases of enrollment of microorganisms over the exterior of marine bodies, regardless of either it has an antifouling paint or other coatings, resulting hard struggle with biofouling once it sticks over the strong surface as shown in Figure 3.1. Corrosion of coating framework and delamination of coating are depicted in Figure 3.1 (a) and (b) respectively. Figure 3.1 (c) displays intense biofouling on the surface of ship hull [24].

Each ship's hull condition is not able to be represented by hull fouling variable and the difference among sister ships or can be represented as one uniform hull. Dry-docking can achieve from 0.86 to 8 tons per day of FOC (Fuel Oil Consumption) savings, which can increase bigger values due to intense hull fouling situation [19].

In order to prevent biofouling and eventually undesirable rub on ship hull's surface, antifouling coatings are the first defensive precaution for ship operators. Usage of these coatings subserves an annual fuel saving that costs approximately $60 billion and reduction of annual emissions like 384 million tonnes in carbon dioxide and 3.6 million tonnes in sulphur dioxide as an estimate [20].

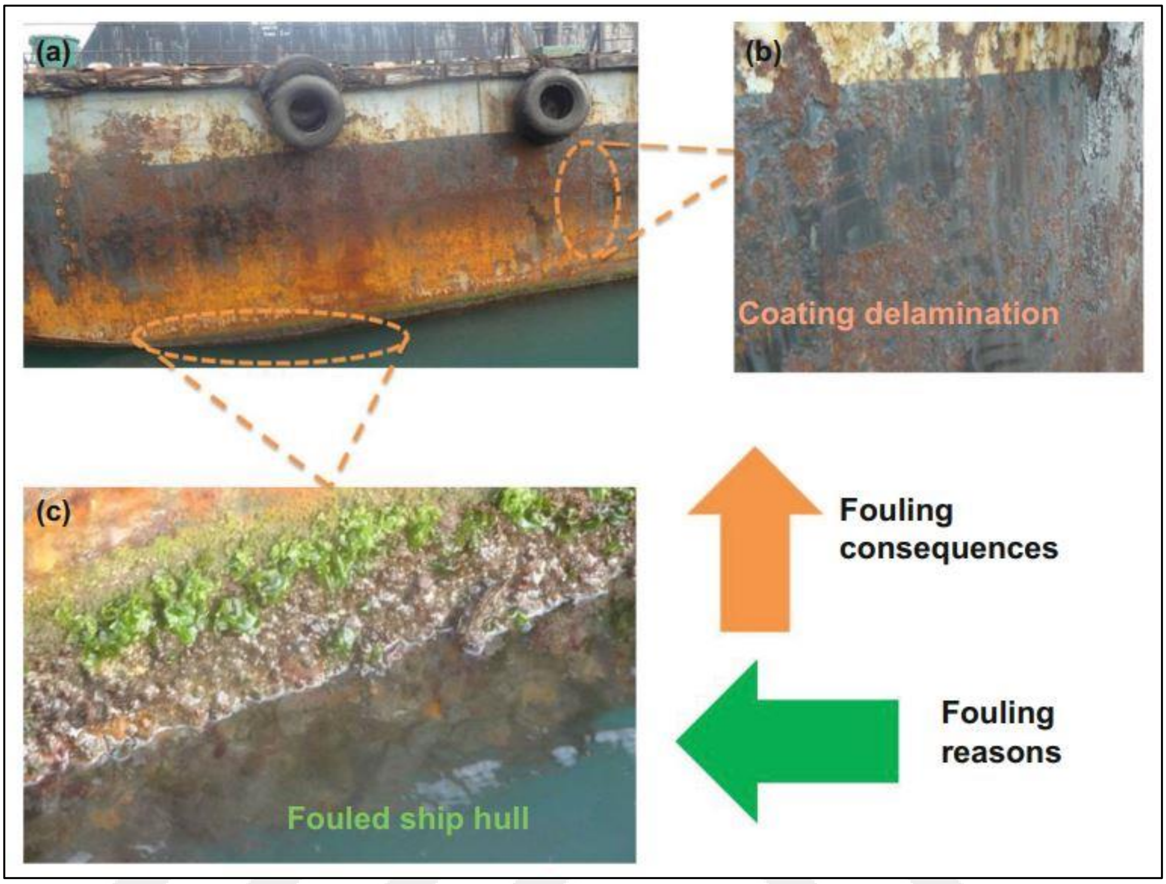

Figure 3.1. Illustration of fouling examples and outcomes on ship hulls [24].

Antifouling coatings have got various types, which mitigate proliferation for marine species on ship surface with the help of releasing biocides or surface properties. TBT antifouling paints performed low roughness at the beginning and perfect antifouling ability. Therefore they are favored for quite a long time and in addition to that TBT coated ships are rarely subjected to drydocking. However, TBT causes many adverse effects on blue marine life, like toxic effects to marine species. Until restriction by IMO in line with EU guidelines in 2003, TBT was an incredibly viable antifouling treatment for ships despite of its harm to marine environment. Because the bioaccumulation organotin compounds of TBT affect non-target organisms painfully. Prohibition of TBT has been succeeded by copper has in various antifouling coatings, in a silicone polymer matrix form it is characteristically with cuprous oxide like active biocide [23].

In order to examine effect of barnacle resulting biofouling on ship friction and propulsion power, special equipment are implemented in laboratory for towing tests using different artificial barnacles clad surface plates. Barnacle height and rate of coverage are measured to examine the impact on ship resistance and ship propulsion power. From surface plates, values of drag variables and roughness variables were commentated. Prediction of vessel's frictional resistance were made by comparison of these different artificial fouling imposed plates. Diagrams of added resistance due to fouling were plotted and calculation of additional propulsion power needs were generated according to these plots. Demirel, Yigit Kemal, et al demonstrated that impact of barnacle size is noteworthy, because a 10% surface coverage of barnacles bond, whose size is 5 mm each caused a comparable additional propulsion power level equal to a 1.25 mm length of barnacles bond with 50% surface coverage [7].

In order to evaluate energy efficiency effects of periodic ship hull cleaning, real 2012-2016 Aframax-size new built crude oil tanker vessels' performance and weather data was extracted by using their noon reports. Energy efficiency estimation is based on sudden change on fuel consumption before and after cleaning of these new built vessels which were in operation in 5 years time. Adland, Roar, et al. indicate that significant reduction in the daily fuel consumption is achieved by periodic cleaning of hulls. Approximately in between 17% versus 9% reductions in fuel consumption is calculated due to vessel hull's underwater cleaning, and it affects energy efficiency much more if the vessel sails loaded than the efficiency improvement in the vessel's ballast condition. These results reflect a significant impact of importance on cleaning timetable of a vessel operation and it should be optimized for energy efficient operation [12].

The more data collected means the more certainty. Since noon reports are highly dependent on crew's usual activities and procedures, collected data can be dirty and these data should be cleaned. Gathering data from a continuous alarm monitoring system rather than noon reports enables a significant decrease in ship's operational data uncertainty, whose standard error rate is 4.64% [13].

3.1. State of the Art Fouling Prevention Methods

Ship performance inefficiency because of vessel hull and propeller fouling can be significant, yet generally, they have been hard to evaluate since ship performance estimations persistently change as per a large group of factors, including draft, trim, rudder action, wind, waves, flows and water depth. Journey of vessels crossing distinctive oceans can be analyzed in order to break down the vitality ineffectiveness brought about by hull fouling and to recognize methods for moderating these efficiencies and lightening maintenance costs.

Since the beginning of shipping and maritime, fouling is common problem, which tends to be seen extreme in the tropics than in calm zones. There is unequivocal understanding among examiners that fouling fluctuates incredibly between regions in the types of creatures present and their force of development. These expansive, local contrasts are impacted by general geology, temperature, and the impact of flows upon water flows [21]. Figure 3.2 (a) and Figure 3.2 (b) reveals how fouling affect a gun and its mount on a navy ship stays under water for only 4 months [22].

The effect of biofouling on fuel utilization can be evaluated by applying a formula described by Schultz (2007), which models the impact of fluctuating degrees of fouling, got from information utilizing a research center scale model of a frigate, on frictional resistance and expanded propeller control. The outcome of overwhelming calcareous fouling on the frigate brought about an 59% more engine power requirement in contrast with a non-fouled 'clean' control for the same speed (15 knots). For the same power that engine operates, fouled frigate sails with a speed reduction of 10.7% [21].

Figure 3.2. Kongsberg Sea protector (a) in normal conditions
(b) after spending over 4 months underwater [22].

Prevention methods of fouling starts with biocide containing antifouling pre-treatments. Traditionally some methods focus on surface modification which reduces fouling species by killing or inhibiting their growth. On the other hand enzyme grafted polymers and specific coatings create innovative surface treatment without toxic compounds releasing into environment [23]. Conventional (has infinitesimal pores that permit the departure of the biocide), Erodible (biocide is discharged from layers underneath and Self-polishing (a hydrophobic paint network made out of the biocide connected to a polymer) are three primary sorts of biocide-containing antifouling paints. Initially the adjustment of the hull's physical and substance properties to deflect the perpetual connection of biofouling creatures by making inconsistent geography or surface science for example, Sharklet AF™ PDMSe is designed by inspiration from sharks' skin that is naturally fouling resistant.

3.2. Antifouling methods and Coating

State of the art technology on antifouling is solved with marine paints, coatings and some passive electronic devices attached to the ship hull. According to the American Coatings Association (ACA), (Figure 3.3), nearly 24 polymer technology based marine coatings from various types are used in market extensively as high performance coatings . A group of synthetic polymers which are called low surface energy polymers constitute main class of fouling release coatings. Siloxane and fluoropolymers are examples of these polymers [24]. Different polymer coatings such as polyolefinic PP, HDPE, PPPE, and EVA-12 films and the fouling release properties of these films were examined quantitatively by investigating how easily species of a fouling is released from film surfaces after exposing to hydrodynamic shear. Fouling removal from hydrophobic surfaces which showed the best fouling release properties, is higher which is consistent with the previously published results [25].

Existing patterns on marine defensive coatings are dependent on polymeric materials, which are composed by potential monomers of coatings either utilized in a matrix form or support structure. In either two structures, polymers complete the execution gap of the traditional TBT or metal form coatings, accordingly being harmless to blue life conditions. The greater part of the investigations managing the improvement of antifouling and foul-release coatings need think about on advancement in execution assessment of such frameworks through the advancement of independent research facility setups to gauge the antifouling and foul-release execution of the planned paints as far as harmfulness levels, bond quality, drag-decrease effectiveness, bacterial adhesion and other aspects. Types of coatings are categorized as shown in Figure 3.3 [24].

Methodology called Life Cycle Assessment (LCA) is a common itinerary used in order to evaluate the lifetime biological impact of the to-be-developed antifouling coatings and select the environmental friendlier. LCA is able to empower an examination between the new antifouling coatings and the conventional ones, so as to advance the advantages as far as ecological effect of waterborne transportation [26].

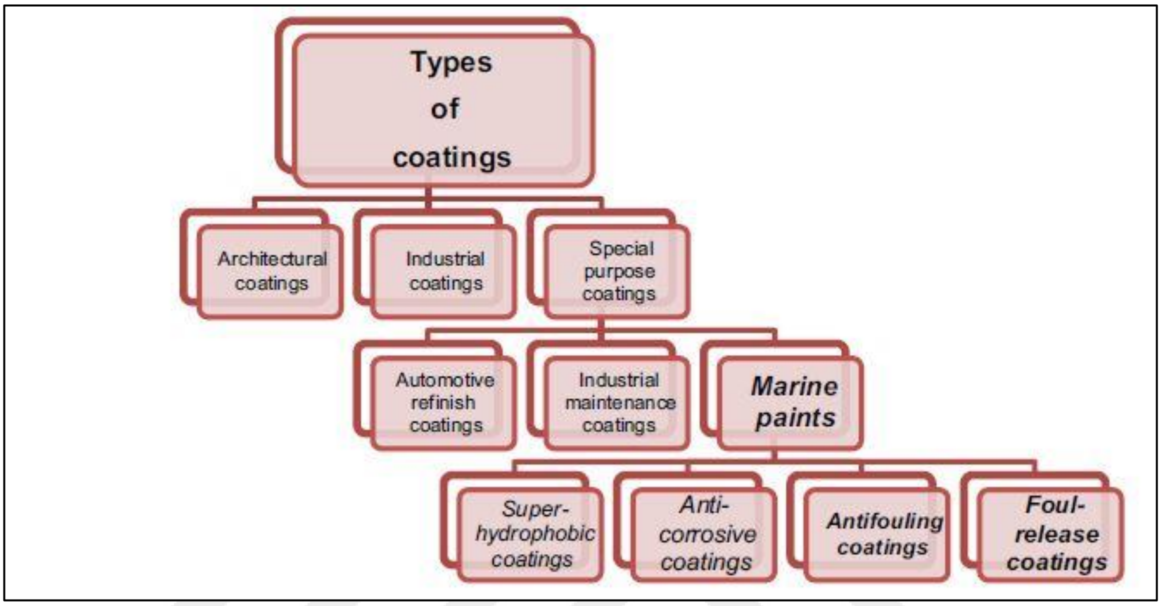

Figure 3.3. Tree diagram classification based on types of coatings [24].

In Figure 3.4 FR (Foul Releasing) type coated and uncoated propellers difference are shown. can be seen. FR type coated propeller after 37 months is not as smooth as new propeller however it seems in better condition than the uncoated propeller exposed to fouling for only 14 months. Due to the fact that propeller fouling has an adverse effect on propulsion, FR type coatings with other green coating technologies keep their importance on ship energy efficiency [5].

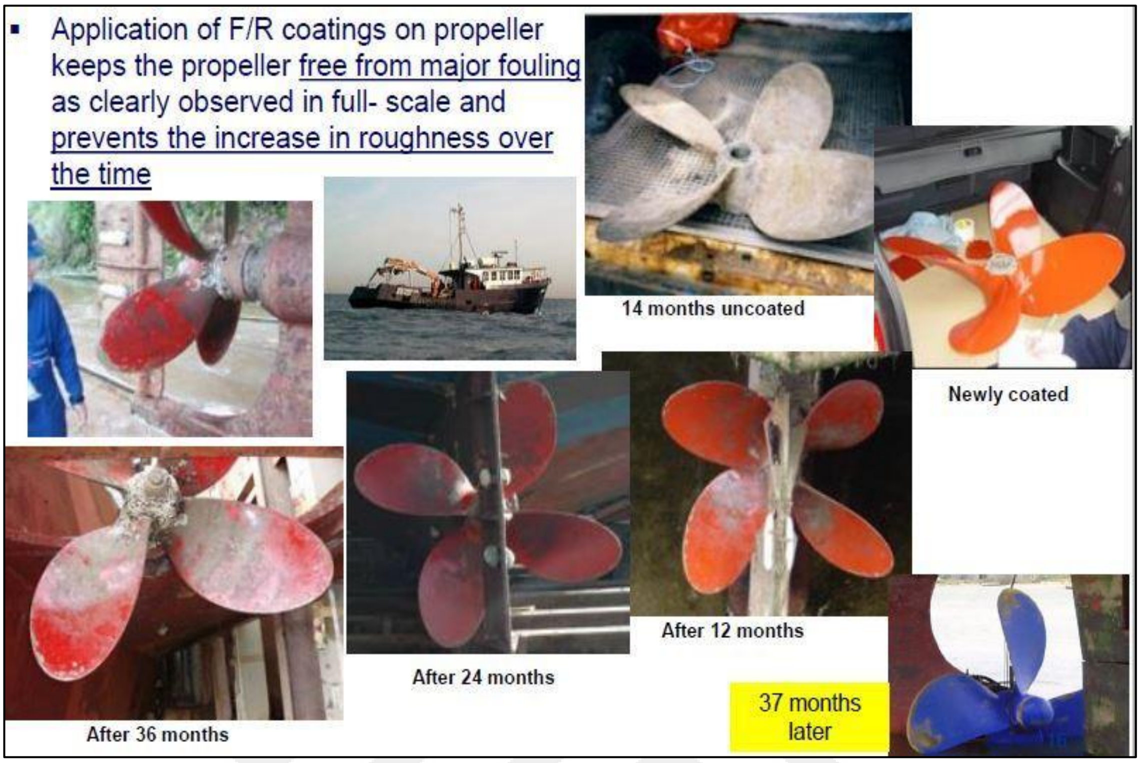

Figure 3.4. Propeller Conditions which Undergoes Fouling in time [5].

4. DATA ANALYTICS ON FOULING DETECTION AND CALCULATION METHODS

4.1. Dataset

Dataset includes two different raw data taken from alarm monitoring system of an anonymous hybrid vessel, whose single line diagram is shown in Figure 4.1, in July 2017 and April 2018 for two-week intervals. Table 4.1 includes physical parameters of vessel with specified data precisions. Table 4.2 includes fuel consumption and generated power amounts of the dual fuel engine of vessel. This generator is dual fuel which means it can consume either marine diesel oil (MDO) or liquefied natural gas (LNG) as input and it produces electrical power as an output. Table 4.3 defines data for four electric motors on hybrid vessel their rated capacity for electricity consumption. Port side and starboard side electric motors are rotating main propellers and two bow tunnel thrusters are used mainly for maneuvering.

Thanks to recent improvements on power electronics, this ship has got a Direct Current (DC) electrical microgrid instead of Alternative Current(AC) electrical microgrid. This DC grid architecture enables instantaneous control of electrical variables in comparison to AC grid vessels [27].

Table 4.1. Physical data types of vessel

DATA_ID	DATA DEFINITION	ENG.UNIT	DECIMAL
SPEEDOG	SPEED OVER GROUND	KNOT	1
TRIM_DraftAFT	AFT DRAFT	METERS	2
TRIM_DraftFORE	FORE DRAFT	METERS	2
TRIM_Trim_deg	TRIM	Degrees	2

Table 4.2. Generator data types of vessel

DATA_ID	DATA DEFINITION	ENG.UNIT	MAX
VF100	Main Engine (ME) 1 FUEL CONSUMPTION RATE	L/min.	N/A
DG1GCH	Main Engine (ME) 1 GAS CONSUMPTION RATE	GJ/h	N/A
VF200	Main Engine (ME) 2 FUEL CONSUMPTION RATE	L/min.	N/A
DG2GCH	Main Engine (ME) 2 GAS CONSUMPTION RATE	GJ/h	N/A
DG1_Power	Diesel Generator 1 POWER	kW	4200 kW
DG2_Power	Diesel Generator 2 POWER	kW	4200 kW

Table 4.3. Motor data types of vessel

DATA_ID	DATA DEFINITION	ENG.UNIT	MAX
MD1214	Port Side MOTOR POWER	kW	2500 kW
MD2214	Starboard Side MOTOR POWER	kW	2500 kW
MD1203	Bow Thruster 1 MOTOR POWER	kW	550 KW
MD2203	Bow Thruster 2 MOTOR POWER	kW	550 KW

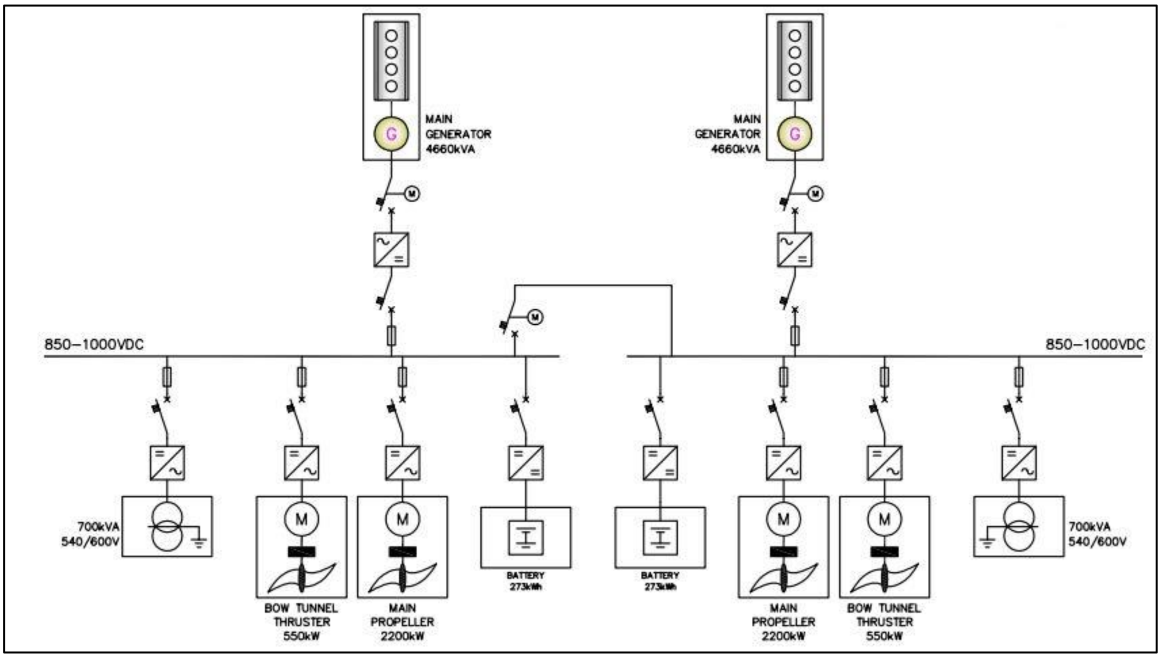

Figure 4.1. Single Line Diagram of a typical Battery Hybrid Vessel.

4.2. Data Import

Dataset includes two different raw data taken from alarm monitoring system of a hybrid vessel in July 2017 and April 2018 for two week slots. These raw data are imported in MATLAB and they are converted into timetables. Afterwards timetables are cleaned by missing, duplicate, or non-uniform times. A timetable is a data type in MATLAB, which has got time-stamped data values, for each row of data. In each row, time values are unique, sorted according to increasing order and time steps are common in a typical timetable however in these raw data it is not regular, unless there is a change that it is triggered. Therefore timetables that are created are irregular. They can contain rows that are not sorted by their row times. Timetables can contain multiple data set with the same time stamp, even though the rows might have different data values. In addition to that when time of the rows are sorted and unique, they might have got different sizes of time steps. Timetable data might include Not a Time(NaT) or Not a Number (NaN) values in order to express there is a missing value for that timestamp.

The reason for implementing timetable data type is to provide various ways to figure out these missing, duplicate, or non-uniform time data, and to reorganize or synchronize data to an ordinary timetable. Retime command is used in MATLAB codes in order form a successful timetable with unique and sorted dataset rows.

Firstly, data of the each data source that are shown in Table 4.1 4.2 and 4.3, are imported and synchronized hourly and minutely. Mean of values are taken into account due to high amount of big data and in order to remove outliers. After that process all separate data is merged in order to synchronize multiple timetables to a common time vector. Data extracted from two different intervals are processed and converted into a timetable data which includes vessel speed, trim generator and motor parameters all with common time stamped.

In order to implement data analytics on ship energy consumption data, previous works on ship big data are reviewed and many different algorithms are implemented like Model Predictive Control (MPC), Gaussian mixture models (GMMs), K-Means classification algorithm and Principal Component Analysis (PCA). These previous works starting from most recent ship data analytics, which have different goals, are examined in detail. Perera and Mo has been working together for ship performance and data analytics by classifying and modelling the data in many dimensions. Machine learning and artificial intelligence are utilized in addition to Gaussian mixture models (GMMs) with expectation maximization (EM) algorithm in order to increase the quality and visibility of ship big data [28]. Big data analytics are not used only in ship but also in energy trade systems. He, Huang, et al studied an optimization for increasing the share of electricity generated from renewable energy by using Vector Evaluated Genetic Algorithm (VEGA) by achieving 0.5 of crossover probability, 0.1 of mutation rate of genetic algorithm with maximum 50 times of iterations [29]. Yuan, Jun, and Victor Nian predicted on energy consumption estimation based on speed and trim angle of a cargo ship by Gaussian process model RMSE rate for training data was 0.3859 and the rate for validation data was 0.4418. Key findings of them were that speed reduction enabled approximately 19% less fuel consumption and optimization of trim and draught can enable up to a fuel consumption reduction in between 1.8% and 1.5% rates respectively [30]. Since energy efficiency changes in time varying factors, Wang et al worked on dynamic optimization method, which can decrease fuel consumption and CO_2 emissions by around 28% by using Model Predictive Control (MPC) algorithm [31]. Route of the ship and its planning plays an important role on ship energy efficiency and Wang et al worked also on route planning by using big data platform and 14 steps non-linear optimization which can save fuel consumption by 3.09%. [32]. Brandsæter et al examined 4 different sensors of an ocean going vessel to detect anomalies from the actual sensor information in the ship alarm monitoring system. By using Auto Associative Kernel Regression (AAKR) on 12000 time points ,in which 1000 time points that are reserved for parameter tuning for detection of anomaly and Sequential probability Ratio Test (SPRT) an anomaly detection application based on sensor data sources in shipping was presented [33]. Oneto et al provided decision support system for a tugboat performance and operation modes by getting data from the ship automation system by using Random Forests (RF) algorithm, Model Selection, k-Fold Cross Validation (KCV) [34]. Perera and Mo developed a search for a suitable method to address vessel operational performance and navigation data in large data applications. 22% data compression rate is observed in this situation and that still 99.5% of the vessel operational performance and navigation information remains [35]. Perera and

Mo Monitoring also put also an emphasis by increasing propeller performance of ship machine intelligence with Principal Component Analysis (PCA), Gaussian mixture models (GMMs) algorithms [36].

Starting from power quality issues in ship electrical system, Skjong et al. worked on data driven prediction on harmonic pollution, load demand and power quality by using MPC, Principal Component Analysis (PCA) method and Partial Least Squares Regression (PLSR) method. Optimal harmonic mitigation 80 different simulations were held for Total Harmonic Distortion (THD) and corresponding R-Square values in order to estimate ship electrical system quality [37].

This thesis focuses on detection on impact of fouling on energy, therefore curve-fit algorithm is implemented which enables identifying all the available energy consuming variables that sum up the total vessel propulsion energy consumption on board by recognizing and detaching the measure of energy devoured by various variables such as trim and vessel speed. In addition to that anomaly detection is examined by implementing DFA to time varying generator and motor power data sets.

5. RESULTS AND DISCUSSION

July 2017 and April 2018 Vessel Speed on time series by hourly is shown in Figure 5.1. These curves are put on curve fitting tool of MATLAB. By 4th degree polynomial mapping it is shown that April 2018 curve seems to be lower with the same amount of generated electricity since the output of generator is mainly driving the electricity of motor power as input. Besides generated power can also be used in hotel power and battery charging, ship speed and input power of the motor curves identify more precise analysis.

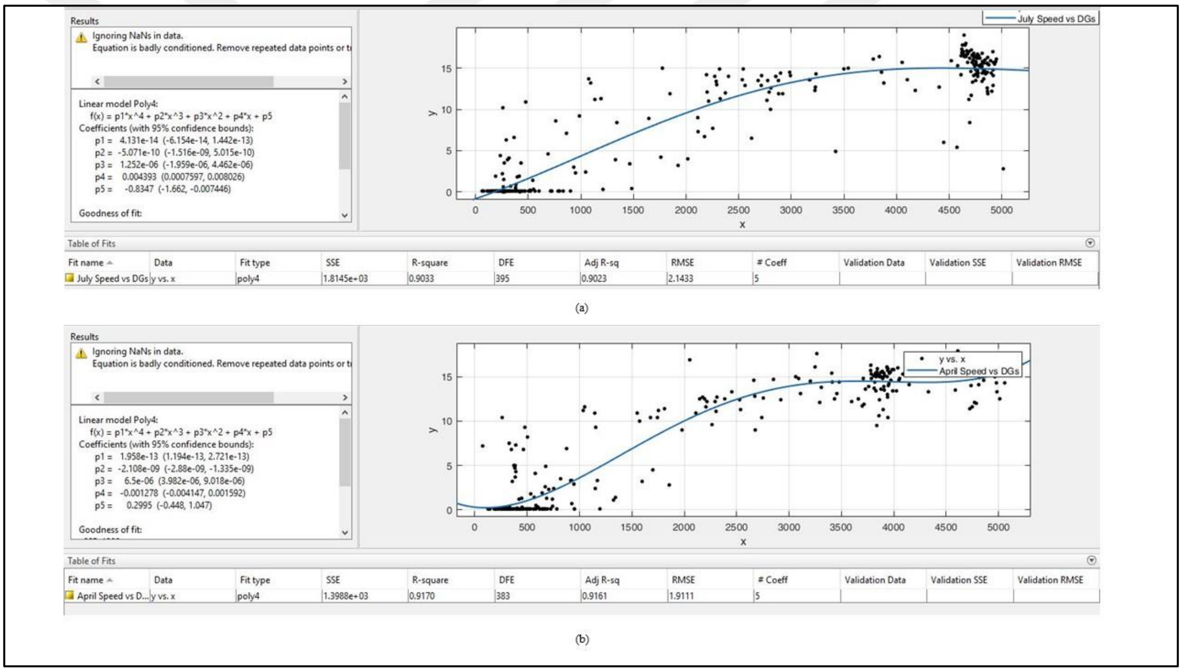

Figure 5.1. Curve Fitting of Vessel Speed vs DG Power Generated by Hour
(a) July 2017 (b) April 2018.

These data are also synchronized minutely and classified as modes of generated electricity versus vessel speed as shown in Figure 5.2. Minutely synchronization enables much more amount of data but less precise curve with respect to hourly synchronization. In this two different time intervals, first one is July 2017 data, which is more like new built ship, classification of power generated in order to achieve different ship speeds are configured as different colors. In order to reach above 18 knots speed, up to 5000 kW amount of power is generated. On the other hand on April 2018 data even 5000 kW amount of power is not sufficient in order to reach maximum 18 knots, and this ship is not able to exceed this speed many times with same amount of power generated. This situation is originated by the hull's frictional resistance due to biofouling exposure of the ship which is expected to have 0.5% per month.

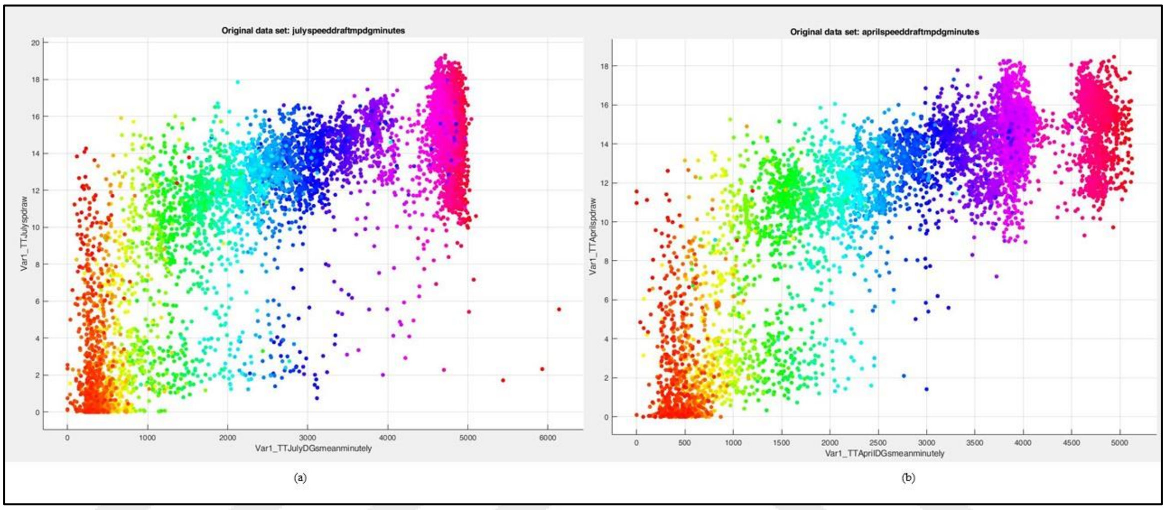

Figure 5.2. Classification of Vessel Speed vs DG Power by Minute
(a) July 2017 (b) April 2018.

Due to reliability and redundancy of ship electrical systems, there are more than two generators feeding the electric motors. These generators are operated according to efficiency of the system. If demanded power of the ship is covered by one generator, it will be enough to operate power system. Otherwise in order to feed more power to ship, second generator is synchronized and added to power system. Generated power of generators (DG1 and DG2) data which are synchronized hourly is shown in Figure 5.3. These curves reveal that which generator is used only or both in order to get same amount of power to reach vessel speeds. In July 2017 (Figure 5.3 a), mostly DG1 is used by vessel, on the other hand in April 2018 (Figure 5.3 b) DG1 and DG2 shares the load in order to get enough power. These curves can vary according to power demands of ship and sometimes according to chief engineer's or captain habits. Actually 3D parts of Figure 5.3 reveal on April 2018 data that ship sails more at constant and lower speed than July 2017 with parallel DGs are operated.

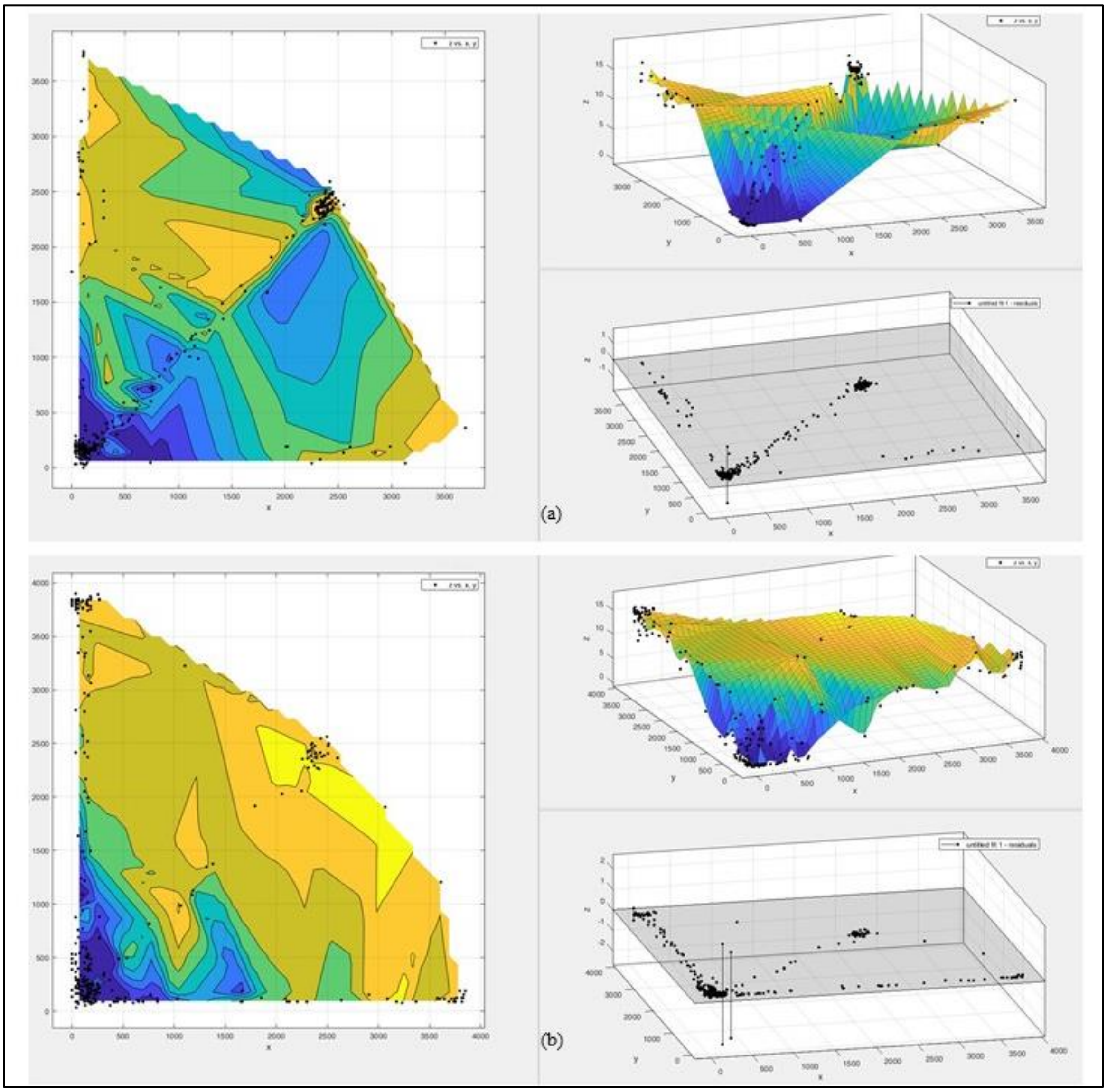

Figure 5.3. 3D Curve Fitting of Vessel Speed vs DG1 and DG2 Power
(a) July 2017 (b) April 2018.

Curve Fitting algorithm of MATLAB is applied to LNG consumption on engine versus generated power data of April 2018 (Figure 5.4 a) synchronized by hour and (Figure 5.4 b) by minute. Since this curve reveals engine performance of LNG fuel engine and its generated power, 1st degree polynomial is enough to determine engine performance and its formula does not change according to hourly or minutely synchronization. Only data volume is higher in minutely synchronization. Reason behind this smooth 1st order polynomial is engine is subjected to deformation and generator sets are in the beginning of their lifetime. Depending on ship's operating conditions, engine load, quality of fuel consumed, handling system of fuel, maintenance intervals and its conformance might have change this curve in the following years in ship operation.

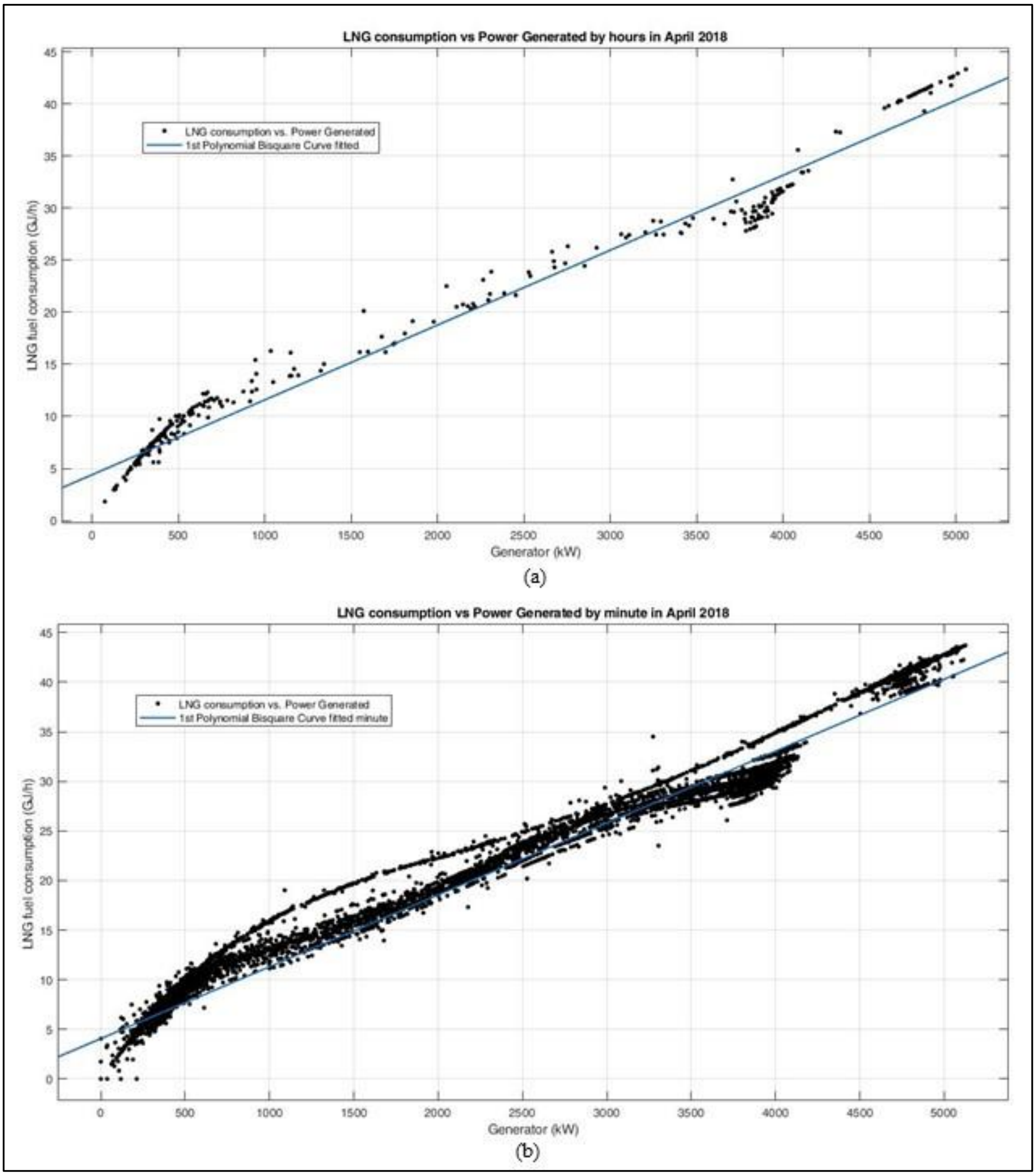

Figure 5.4. Curve Fitting Applied to LNG Consumption on Engine versus Generated Power on April 2018 (a) by Hour (b) By Minute.

Time series plots in Figure 5.5 (a) and Figure 5.5 (b) show two-week time series graph of sum of generated power and sum of motor power for July 2017 and April 2018 respectively. Blue color line indicates generated power, red color indicates motor power. The amount of power difference between the blue and red line appear to be approximately constant power used for charging the batteries and power consumption of hotel loads which means energy demand of whole ship except propulsion demand. Hotel loads can be lighting, heating ventilating and Air Conditioning (HVAC), pumps motors, starters and etc.

Motor power and speed curve of ship is the key graph of detecting fouling impact on ship hull performance and energy efficiency. Vessel speed versus motor power by hourly synchronization reveals data density is more on rated performance of motors nearly 4000 kW on July 2017 in order to speed up to 19 knots as shown in Figure 5.6 (a). On the other hand in April 2018 graph, which is shown in Figure 5.6 (b) motor power of 3000 kW and 4000 kW is common to reach around 16 knots.

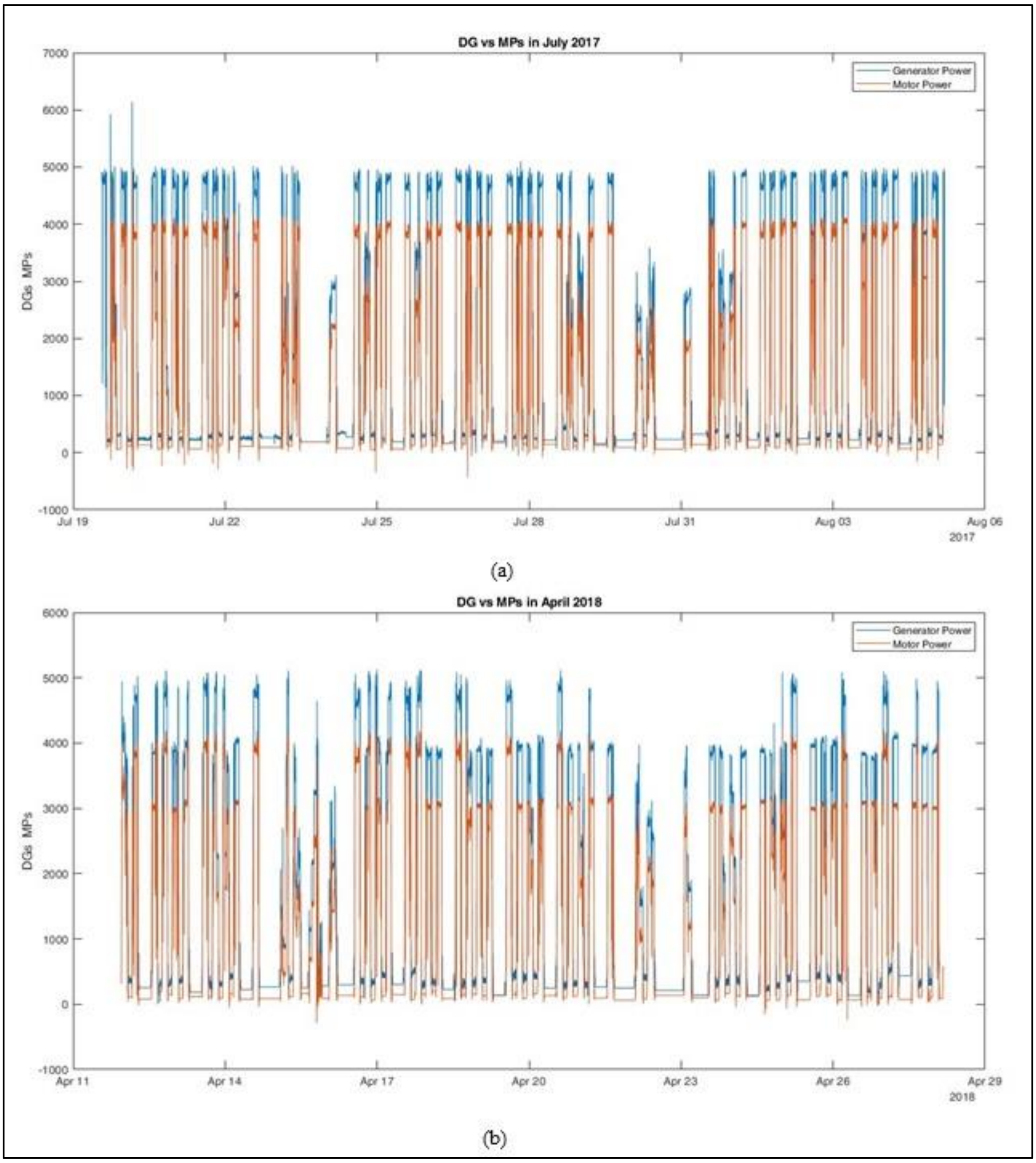

Figure 5.5. DG Power and Motor Power on Time Series for Two Weeks Interval (a) July 2017 (b) April 2018.

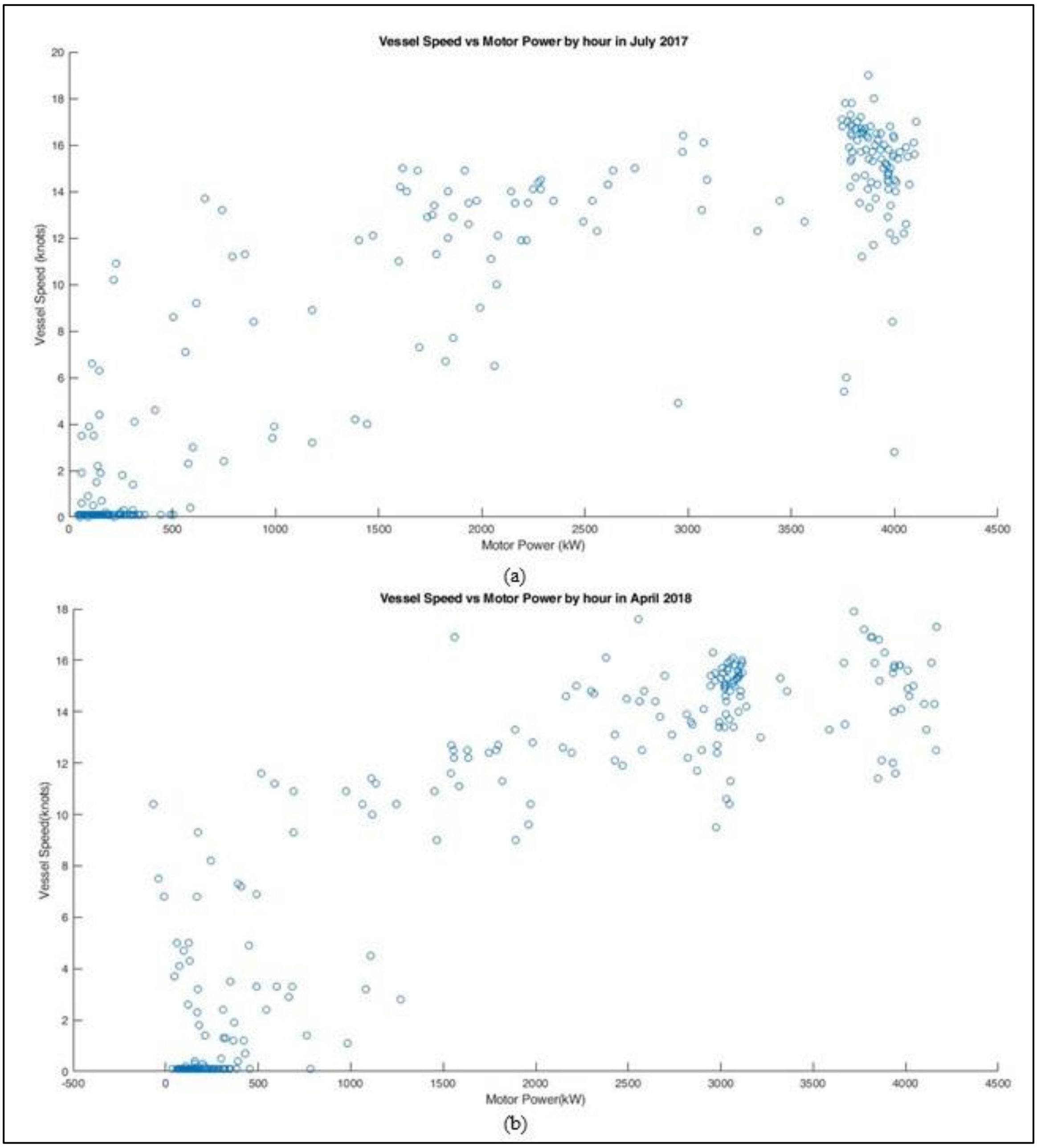

Figure 5.6. Vessel Speed vs Motor power by hour
(a) July 2017 (b) April 2018.

However it is very hard to identify fouling with classification of data points and their density with these graphs. Therefore curve fitting is used for determination the intensity of fouling with identifying speed versus power curves based on data collected in different time periods. In Figure 5.7 (a) the curve that is based on July 2017 data hourly synchronization, converges 16 knots speed levels by getting around 3000 kW motor power. Besides with only

9 months period of fouling impact, which increases resistance and causes a degradation on performance of the ship, the curve that is based on April 2018 data hourly synchronization in Figure 5.7 (b) could not reach or converge 16 knots speed. In Figure 5.7 (c) the curve is based on July 2017 data with minutely synchronization which enables more precise information compared to hourly synchronization. Similarly in Figure 5.7. (d) the curve is based on April 2018 data with minutely synchronization.

In addition to precise information minutely synchronization enables valuable information like motors might have negative input power that is defined as regenerative mode which means they can behave like generator when the ship was decelerating or braking for slowing down. In regenerative mode excess power can be consumed in batteries.

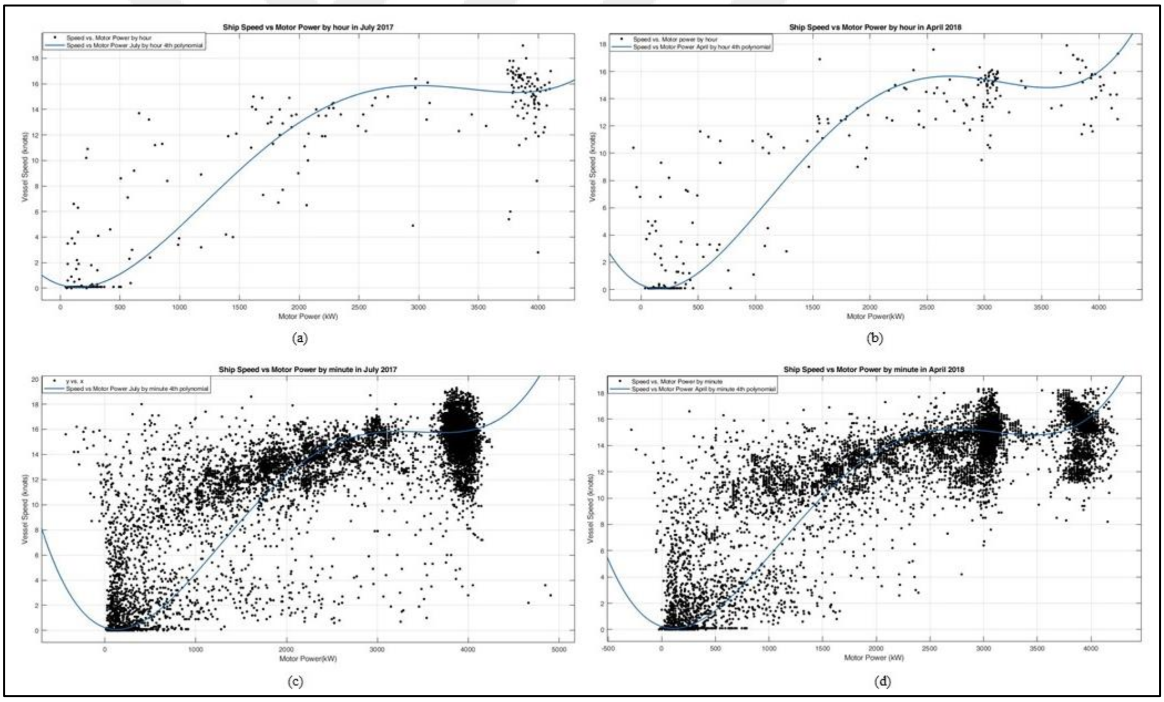

Figure 5.7. Curve Fitting applied to Vessel Speed vs Motor Power
(a) July 2017 (b) April 2018 by Hour (c) July 2017 (d) April 2018 by Minute.

In common statistical literature, a "good fit" is thought to be a model that is capable of estimating the model coefficients with little uncertainty, explaining a high proportion of data variability and predicting new observations with high certainty. Total deviation of response values from curve fit values to responses' square represent Sum of Squares in response to

Error (SSE) calculation. Good fitting model for a less random error reflects into SSE calculation which is closer to 0.

$$SSE = \sum_{i=1}^{n} w_i (y_i - \hat{y}_i)^2 \tag{5.1}$$

R-Square method is one of the measure used to determine how successful the curve fit is in relation to data variation. R-square is the square of this relation connecting the real response values of data and the mathematical model of response values prediction. R-square is defined as the ratio of the regression values' sum of squares (SSR) to total sum of squares (SST).

SSR is defined as

$$SSR = \sum_{i=1}^{n} w_i (\hat{y}_i - \overline{y}_i)^2 \tag{5.2}$$

$$SST = \sum_{i=1}^{n} w_i (y_i - \overline{y})^2 \tag{5.3}$$

where SST = SSR + SSE. Then R-square is defined as;

$$R\_square = \frac{SSR}{SST} = 1 - \frac{SSE}{SST} \tag{5.4}$$

Generating fitted polynomial curve of

$$f(x) = p_1 x^4 + p_2 x^3 + p_3 x^2 + p_4 x + p_5 \tag{5.5}$$

Table 5.1. Hourly Synchronized Motor Power and Ship Speed Curve Fit Models

Fitted Curves	p1	p2	p3	p4	p5	SSE	R-square	RMSE
July 2017 hourly Sync.	4.501 e-13	- 4.177 e-09	1.118 e-05	-0.002906	0.2698	105.1	0.9943	0.5171
April 2018 hourly Sync.	6.737 e-13	- 5.746 e-09	1.418 e-05	-0.003996	0.3539	88.61	0.9948	0.4791

Since both of the curves shown in Figure 5.7 (a) and (b), R-square ratio is near to 1, showing a better variance rate that is calculated by curve fitting model. By minutely synchronization displayed in Figure 5.7 (c) and (d), amount and density of data increase and these create better root mean square error (RMSE), as the curve fitting standard error and regression's standard error that enables more useful for prediction. In these polynomial curves that is depicted in Figure 5.8 , impact of fouling is observed by the lower fitted curve that in April 2018, it converges hardly on 15 knots speed in between 3000 kW to 4000 kW motor power. However, before fouling it converges nearly on 16 knots in between same amount of motor power.

Table 5.2. Minutely Synchronized Motor Power and Ship Speed Curve Fit Models

Fitted Curves	p1	p2	p3	p4	p5	SSE	R-square	RMSE
July 2017 minutely Sync.	3.854 e-13	- 3.646 e-09	1.001 e-05	-0.002443	0.2361	124.9	0.9999	0.07248
April 2018 minutely Sync.	6.158 e-13	- 5.18 e-09	1.252 e-05	-0.002597	0.2289	74.21	0.9999	0.05637

When fitted curves of both hourly and minutely synchronizations are plotted in Figure 5.8, the convergence of 16 knots in July 2017 is clearly shown in between 3000 kW to 4000 kW motor power. On the other hand April 2018 fitted curve is converged on 15 knots with the same amount of power of electric motors. The reason behind observing around these speeds is that low average velocities are usually referring to specific conditions in which vessels operate close to shore or accelerate / decelerate when there is a port call. Average speed loss of 6% is calculated of this ship which is exposed to fouling. This calculation is in concordance with Gundemann and Pedersen's observations. These were between 0.3% to 1.5% added resistance per month, reaching up to total %40 - %45 band of resistance ratio within 5 years of dry-docking periods [14] and up to 15% vessel speed loss which were 4 months of exposed fouling [15] respectively.

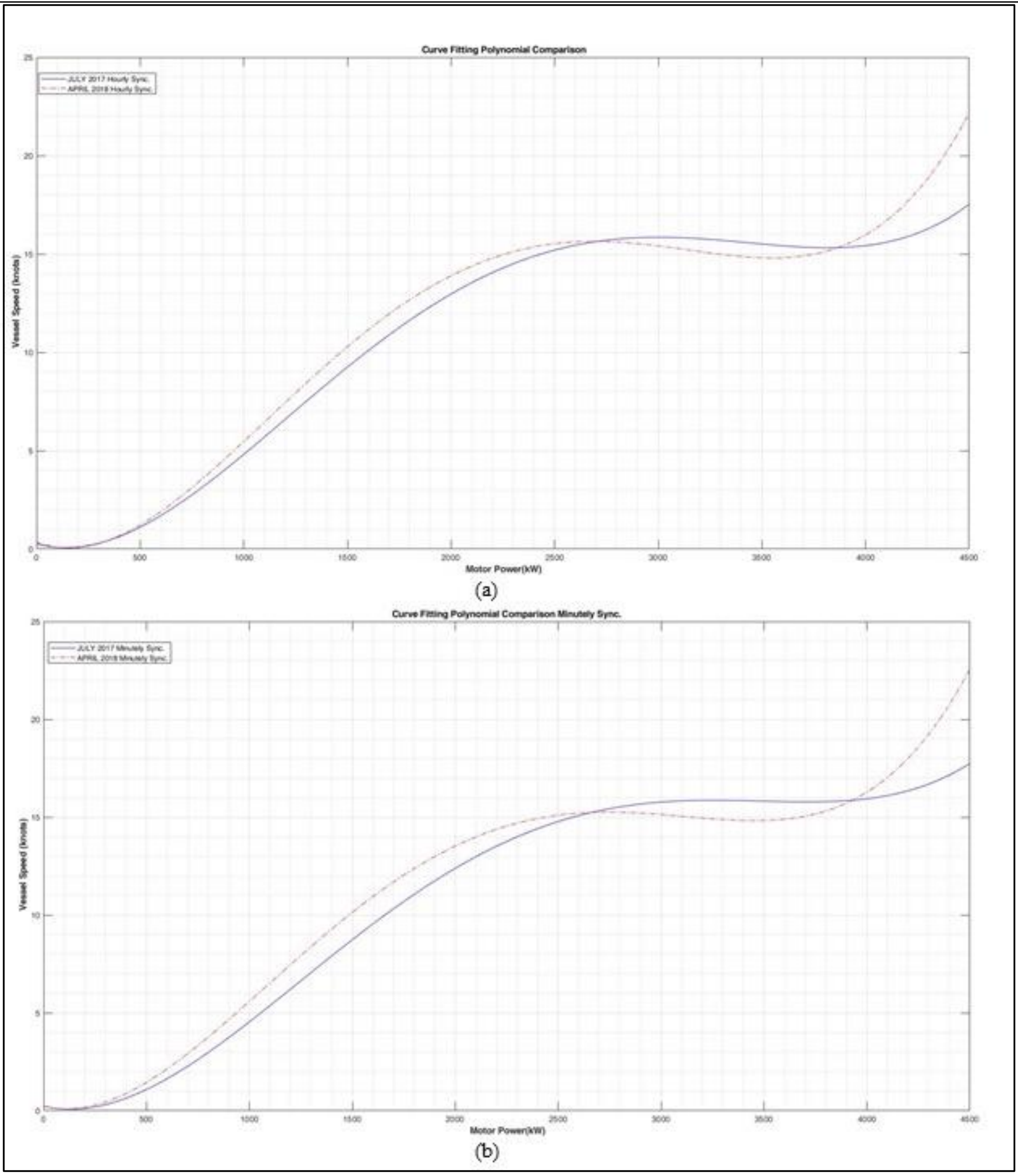

Figure 5.8. Motor Power and Ship Speed Curve Fit Models (a) Hourly Synchronization (b) Minutely Synchronization.

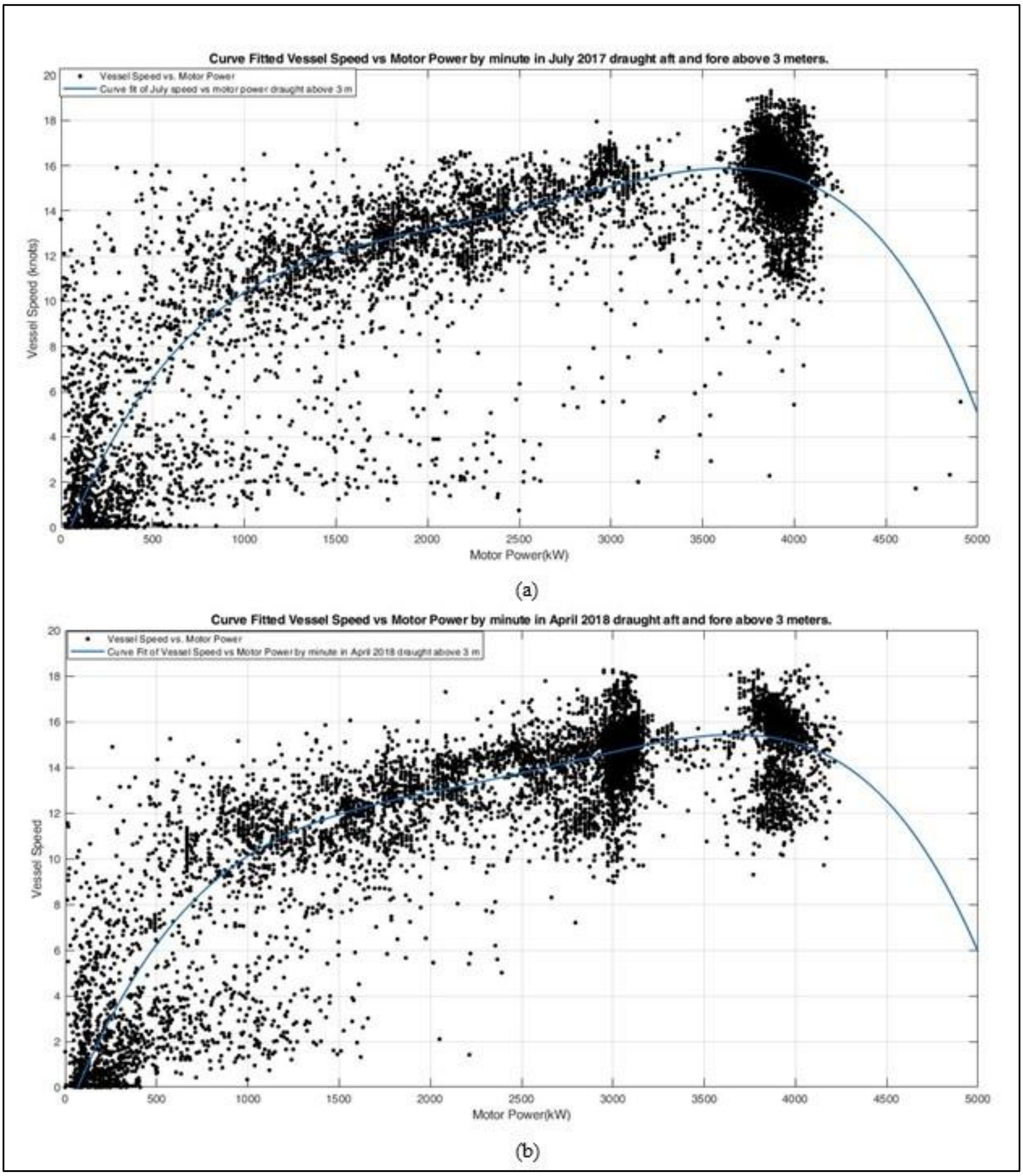

Figure 5.9. Curve Fitting applied to Vessel Speed vs Motor Power by Minute draught above 3 meters (a) July 2017 (b) April 2018.

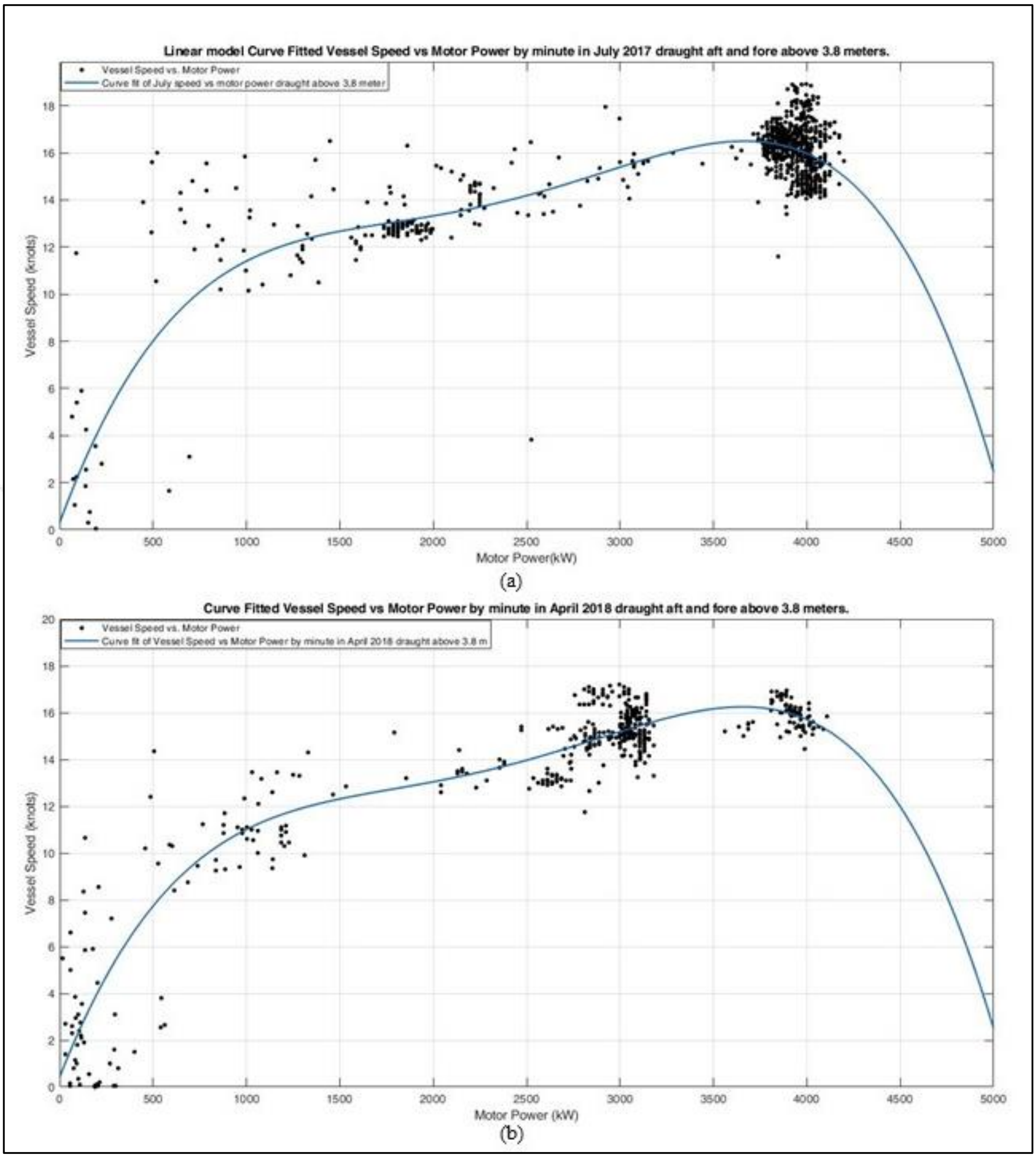

Figure 5.10. Curve Fitting applied to Vessel Speed vs Motor Power by Minute draught above 3.8 meters (a) July 2017 (b) April 2018.

When ship is loaded (laden), friction on hull of the ship increases. Therefore, motor power needs to be increased in order to compensate the energy to reach this energy demand of propulsion. Figure 5.9 displays vessel speed and motor power curve whose hull draught values are above 3 meters on both aft and fore of the ship. Figure 5.10 displays vessel speed and motor power curve whose hull draught values are above 3.8 meters on both aft and fore of the ship. After 9 months of fouling period of the hull these curves shown in Figure 5.9 (b) and Figure 5.10 (b) which are based on laden April 2018 data, are both lower much more than the curves for laden July 2017 data shown in Figure 5.9 (a) and Figure 5.10 (a).

Table 5.3 Effect of Trim draught aft and fore on Motor Power and Ship Speed Curve Fit Models

Fitted Curves	p1	p2	p3	p4	p5	SSE	R-square	RMSE
July 2017 aft and fore above 3 meters	- 3.525 e-13	3.407 e-09	-1.206 e-05	0.0204	-1.013	2.373 e+04	0.8738	1.65
July 2017 aft and fore above 3.8 meters	-4.57 e-13	4.297 e-09	-1.428 e-05	0.02154	0.3013	922	0.8134	1.029
April 2018 aft and fore above 3 meters	-3.3 e-13	3.251 e-09	-1.178 e-05	0.02033	-1.358	2.406 e+04	0.8546	1.683
April 2018 aft and fore above 3.8 meters	-4.326 e-13	4.038 e-09	-1.336 e-05	0.02034	0.4243	512	0.9352	1.015

Since fitted curves for different draught levels are plotted in Figure 5.11, comparison shows that 3000 kW to 4000 kW motor power speed curves' corresponding speed difference is much more explicit for above 3 meters draught level. Since data points are less in 3.8 meters draught level, curves seem more efficient however this is because of low number of data points.

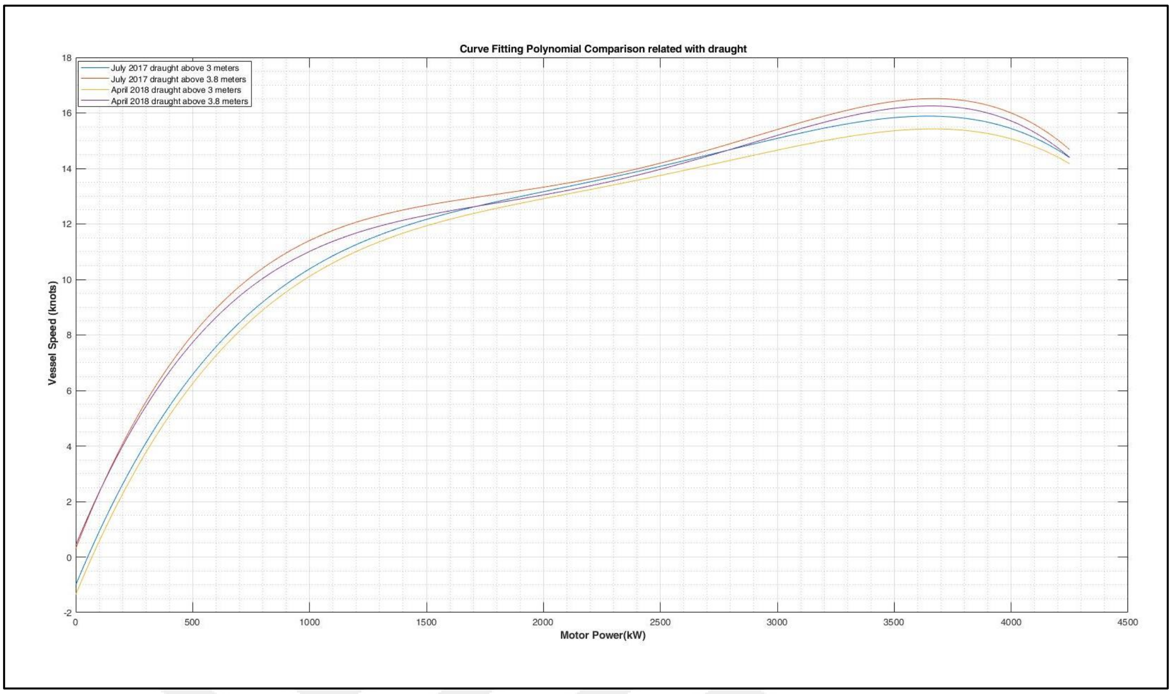

Figure 5.11. Motor Power and Ship Speed Curve Fit Models Draught Comparison.

Lastly, Detrended Fluctuation Analysis (DFA) is applied into generated power, motor power and vessel speed time series data to estimate long-range power-law correlation exponent. DFA is an interesting method, which was first introduced of long range dependence in DNA sequences, for the scaling of long-term non-stationary signal autocorrelation likewise in vessel operation in time series [38]. In order to determine self affinity of signal, removing noises and getting whether a correlated dataset, DFA method can be applied.

$$F(n) = \sqrt{\frac{1}{N}\sum_{t=1}^{N}(X(t) - X_n(t))^2} \tag{5.6}$$

Equation 5.6 gives the root-mean-square undulation of a time series data length, N, divided by equal length of window size n, of equal interval, n. In each box of interval, n, a least squares line is placed to the data and a logarithmic graph of F(n) against n is plotted. A direct line which is not deflected on this log-log graph indicates statistical self-affinity. Fluctuation of this line is characterized by a scale, α, which indicates a correlation in Table 5.4 [39].

Table 5.4. DFA α correlation value table

Value	Self correlations
$\alpha < 1/2$	Anti-correlated
$\alpha \cong 1/2$	uncorrelated, white noise
$\alpha > 1/2$	correlated
$\alpha \cong 1$	1/f-noise, pink noise
$\alpha > 1$	non-stationary, unbounded
$\alpha > 3/2$	Brownian noise

DFA has been recently used in many other disciplines which include time series data analysis [40]. Although it is used for detecting anomalies in biomedical area inside EEG and ECG signals [41] [42], which are time series data, it is also used for detecting power quality incidents in electrical networks [43] [44] and diagnosing other time series signals in other areas like seismic research [45].

Figure 5.12 represents DFA applied to generated power, motor power and vessel speed data of different time intervals. These figures reveal that DFA applied July 2017 and April 2018 datasets represent similar curve ruptures. Hence these different data intervals do not include any anomalies except fouling of performance degradation of the vessel. According to the seasonal change in climate, the values of α in DG and MP, are increasing from April to July. This change can be attributed to possible transition in the biological signal dynamics that leads us to pink noise behavior in biofouling mechanism.

Table 5.5. DFA results of applied to DGs and Motor power

Data set applied to DFA	D	α	Value	Self correlations
DG July 2017	2.2959	0.7041	α > 1/2	correlated
DG April 2018	2.3261	0.6739	α > 1/2	correlated
MP July 2017	2.2761	0.7239	α > 1/2	correlated
MP April 2018	2.3152	0.6848	α > 1/2	correlated

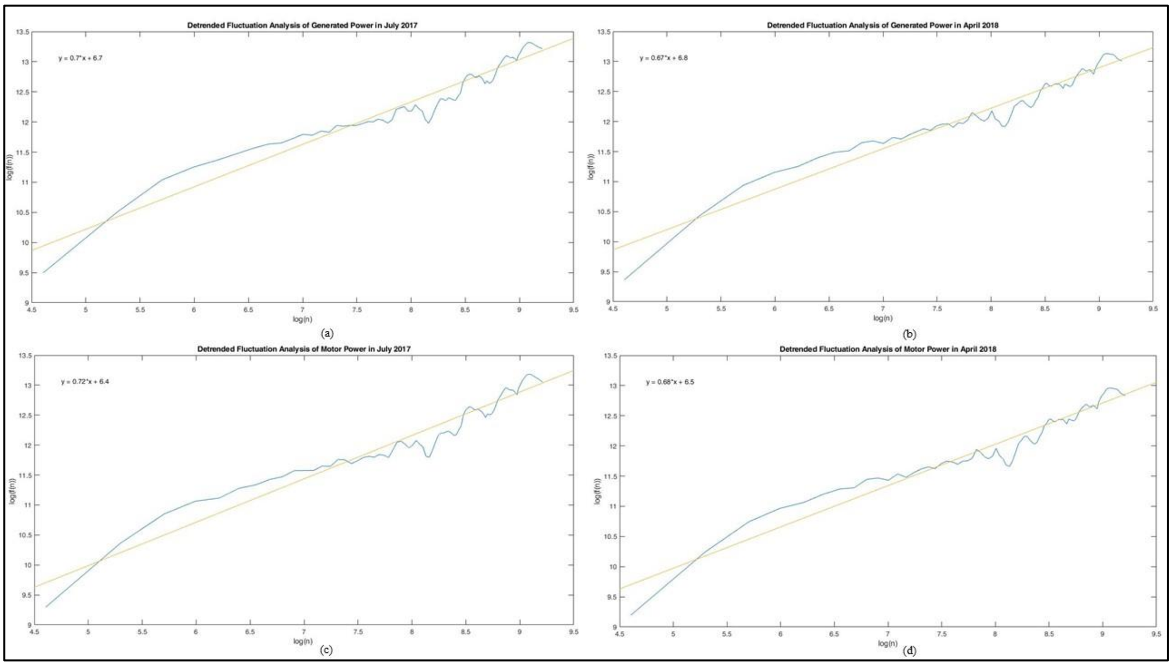

Figure 5.12. DFA Applied to Generated Power by Minute
(a) in July 2017 (b) in April 2018 DFA Applied to Motor Power by Minute
(c) in July 2017 (d) in April 2018.

6. CONCLUSION

The optimization of mechanical and electrical systems for efficient operation on ships has a significant impact on ship hull and propeller cleaning and route planning. All equipment and machines on the ship are independent energy consuming systems and the data are based on collection of all automation systems that can be taken from a single source and controlled for optimum operation. Technology companies offer data analytics services, which include innovative aspects of for ship operators, are being commercialized and give advantages to themselves and other manufacturers both in sales and after sales. This enables equipment manufacturers to monitor the performance of their equipment and to monitor efficiency of other equipment manufacturers.

This thesis hinges on a collection of recent studies on evaluation of vessels' energy efficiency and one of the key factors, which is fouling, ship exposed to that effect in time. Until recent studies, ship energy efficiency is evaluated by graphs plotted for fuel consumption versus speed of ship comparisons. Data of continuous monitoring is used instead of noon report based data, which increases data uncertainty and better evaluation of ship energy efficiency. Ship fuel and generator graphs reveal about engine health and how efficient it is operating. Since generated power and transferred power to motor have got similar patterns, which motor power rating is less than generated power due to hotel loads of ship and battery charging power. Marine fouling impact is determined by using curve fitting like PCA and these graphs, which have two different time intervals. This enables detection of performance degradation of ship hull in only 9 months around 6% of speed loss with the same power driven to propellers.

As a recommendation to ship operators, cleaning and dry-docking periods of each vessel should be decided according to fouling degradation detection and resulting inefficiencies. Analysis of ship data is vital if ship operators would like to sail their fleet cost effective and energy efficient. This will enable data scientists and other data driven service providers more work on these operational ship data which is a milestone for implementation of autonomous ship activities in future.

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CURRICULUM VITAE

Erdeniz EROL
R&D Manager
Tel: +90 533 558 65 90
e-mail: erdeniz.erol@gmail.com
Address: Aydinli Mahallesi Gurpinar Caddesi Canbaz Sokak Gunaydın Konakları C Blok Daire:20 Tuzla Istanbul/ TURKEY
Date of birth: 20.01.1985
Place of birth: Canakkale/ TURKEY

WORK EXPERIENCE:

August 2015 – …

ELKON Elektrik Sanayi Ticaret A.S. (Istanbul, Turkey)

- R&D Manager of Elkon Marine Electric R&D Center
- TIM Inosuit Corporate Innovation System Deployment
- Project Manager of Naval and Commercial Vessel projects
- Leading first R&D and EU projects of company
- Business Development activities

May 2013 – August 2015

Enerjisa Electricity Distribution A.S. (Ankara, Turkey)

- R&D Project Manager of SEAS (Smart Energy Aware Systems) project which is TEYDEB 1509 funded project composed of 34 partners from 7 countries in EU aiming energy efficiency and awareness for Smart Buildings and Micrograds.
- R&D Project Manager of USTDA (United States Trade and Development Agency) funded feasibility project of Smart Grid in Turkey Distribution Grid.
- Project Member in various smart grid projects of metering, distributed generation, GIS and demand response.

September 2010 – May 2013

STM A.S. (Ankara, Turkey)

Performed Systems Engineering activities of

- AIRC2IS, NATO Air Command & Control Project
- JHM Project, which consists of developing a Digital Moving Map and Mission Planning Ground Station to the Sikorsky Helicopters of the Turkish General Command of Gendarmerie
- Erciyes Project, which consists of developing a Mission Planning Ground Station to C-130 cargo aircrafts of Turkish Air Forces.

August 2009 –August 2010 **Turkish Land Forces (Military Service, Turkey)**
Completed military service as a Tank Team Commander.

March 2007 – July 2009 **GATE Elektronik A.S. (Ankara, Turkey)**
Developed TPS (Test Program Set)'s for DSBCA (Depot Level Maintenance Cougar Helicopters) project and documentation of COUGAR avionic boards on S40 Pilot LX test equipment.

(February 2009 – April 2009) ***on duty for*** **SEICA (Torino, Italy)**
(Oct. 2008 – February 2009) ***on duty for*** **GET Electronique (Castres, France)**
Developed functional test programs with SEICA VIVA platform for migration of functional test programs which was developed at Teradyne test bench before.

(October 2007 – April 2008) ***on duty for*** **EADS Test & Services (Toulouse, France)**
Developed TPS's for IFS (In Flight Entertainment Systems) project of THALES by using Visual OSS

June 2006 – July 2006 **Summer practice at Akcansa Cement Factory (Canakkale, Turkey)**
Observed PLC systems and Electrical Maintenance.

January 2006 **Practice at PHILIPS Medical Systems(Ankara, Turkey)**
Observed Repair & Maintenance of Biomedical Devices.

October 2004 – July 2005 **Part-time work at GATE Elektronik A.S.(Ankara, Turkey)** Performed Sales and Marketing of Tektronix Test and Measurement devices.

EDUCATION:

2017- 2019 **Piri Reis University, Istanbul, Turkey**
M. S. in Computational Science and Engineering, Graduate School of Science and Engineering

2012- 2015 **Middle East Technical University, Ankara, Turkey**
M. S. in Geodetic and Geographic Information Technologies,
Institute of Natural Sciences *(thesis not submitted)*

2009- 2012 **Middle East Technical University, Ankara, Turkey**
M. S. in Informatics Online, Institute of Informatics *(not completed)*

2003- 2007 **Middle East Technical University, Ankara, Turkey**
BS in Electrical and Electronics Engineering, (Power Area)

2002-2003	**Middle East Technical University, Ankara, Turkey** Department of Basic English (Prep. School)
1999-2002	**Çanakkale Fen Lisesi, Canakkale, Turkey** High School
1995-1999	**Çanakkale M.P. Anadolu Lisesi, Canakkale, Turkey** Secondary School

PROFESSIONAL AFFILIATIONS:

2007-2015	**Member of Canakkale Kultur ve Dayanisma Dernegi** Member of the society board.
2005-2007	**Member of Institute of Electrical and Electronics Engineers, METU** (METU branch of IEEE)
2005-2007	**Member of Çanakkale Kültür ve Dayanışma Derneği** Vise chairman of student council
Since 2002	**Member of Odtulukartallar**

COMPUTER SKILLS:

- SysML: System Modelling Language
- Telelogic DOORS: Requirement Management Tools
- Visual SourceSafe: Configuration Management Tools
- Visual OSS, ATLAS, Visual ATEC , SEICA VIVA, Teradyne L200
- MS Office applications
- C/C++ programming language
- CADKEY, AutoCAD
- Electronic Workbench, Pspice, Proteus
- MATLAB
- Windows, Unix operating systems
- PLC, Ladder Logic, FBD

PROJECTS:

2017 – …	▪ TUBİTAK and R&D Projects Management
2015 – 2017	▪ Electrical Systems Projects of Navy Vessels
2014 – 2015	▪ Smart Energy Aware Systems Project
2013 – 2014	▪ USTDA Smart Grid Feasibility Project
2012 – 2013	▪ AIRC2IS NATO Command and Control Project
2011 – 2012	▪ Erciyes C-130 Mission Support Systems Project
2010 – 2011	▪ JHM Sikorsky Mission Support Systems Project
2008 – 2009	▪ THALES Migration Project
2007 – 2008	▪ THALES IFS Project
2007 – 2009	▪ DSB(C)-A D-Level Maintenance Cougar Avionics Project.
2006 – 2007	▪ "*Shape Sorer*" Design Project.
Fall 2006	▪ Participated in *"Audio Power Amplifier"* project.
Spring 2006	▪ Participated in *"Mastermind Game"* project.
Spring 2005	▪ Participated in *"Analog Modulator and Demodulator"* project.
Fall 2004	▪ Participated in *"Partially filled Triangle on Cathode Ray Oscilloscope"* project.

TRAININGS AND CERTIFICATES

February 2019	▪ R&D Management Mini MBA, Istanbul Chamber of Industry
June 2018	▪ Access to new patents using TRIZ by Ruhi Kaykayoğlu
March 2014	▪ Presentation Skills Improvement and Convincing by Sedef Kabaş
December 2013	▪ Advanced Project Management training by Savaş Şakar
November 2013	▪ Project Management Methodology training by Burcu Oğuz
September 2012	▪ “Requirement Analysis and Specification Writing” training (PPI, Amsterdam,Holland)
March 2012	▪ “Service Oriented Architecture” training (EDC4IT, on-site training)
July 2011	▪ “System Engineering with SysML” training (Objektum Solutions, England)
September 2007	▪ Functional test and SEICA VIVA training (SEICA, Italy)
September 2007	▪ Visual OSS (EADS Test & Services, France)
March 2007	▪ “AutoCAD” training (EMO Ankara)
February 2007	▪ “Automation, PLC and SCADA” training (EMO Ankara).

LANGUAGES:

English	Advanced level in speaking and writing skills.
French	Beginner level in speaking and writing skills.

PUBLICATIONS

1. Atmaca Ö, Erol E, Karabacak M, Kamal T “***Design of an H-Bridge Bidirectional DC–DC Converter with LCL Filter for High Power Battery Applications***” IEEE GPECOM Conference 2019
2. Atasoy T., Erdener Akinc H., Erol E., Ercin O., Gurec O., Benli O., ***"Challenges & Opportunities towards Smart Grid in Turkey; Distribution System Operator Perspective"***, IEEE PES Innovative Smart Grid Technologies Conference (ISGT), 2014
3. Dogdu E., Ozbayoglu A.M., Benli O., Erdener Akinc H., Erol E., Atasoy T., Gurec O., Ercin, O., “***Ontology-centric Data Modelling and Decision Support in Smart Grid Applications: A Distribution Service Operator Perspective***”, IEEE IEPS International Conference on Intelligent Energy and Power Systems, 2014.
4. Erol E., Erdener Akinc H., Atasoy T., Gurec O., Ercin O., Benli O., “***Consumer Engagement via Decision Support Systems in Smart Grids***”, ICSG 2nd International Istanbul Smart Grid Congress & Fair, 2014.
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