UNIVERSITY OF PIRAEUS

DEPARTMENT OF MARITIME STUDIES
MSc in SHIPPING MANAGEMENT

‘AN APPLICATION OF DELPHI METHOD ON VESSEL PERFORMANCE MONITORING & OPTIMISATION’

Alexandros Skamagkas

A Thesis

Submitted in the Department of Maritime Studies as a partial fulfillment of the requirements for the Master of Science degree in Shipping Management

Piraeus

April 2022

Tripartite Committee Page

This thesis has been unanimously approved by the three-member Examination Committee, which has been designated by Special General Assembly of the Department of the University of Piraeus, Department of Maritime Studies, in accordance with the Operating Regulations of the Masters' Program in Shipping Management.

The Committee members were:

- Dr. Karlis Athanasios (Supervisor)
- Dr. Polemis Dionysios
- Dr. Lagoudis Ioannis

The approval of the Masters' dissertation by the Department of Maritime Studies, University of Piraeus does not imply acceptance of the author's opinions.

Declaration of Authenticity

I Alexandros Skamagkas, the author of this Thesis, herewith declare that I wrote this thesis on my own and did not use any unnamed sources or aid. Thus, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person except where due reference is made by correct citation. This includes any thoughts taken over directly or indirectly from printed books and articles as well as all kinds of online material. It also includes my own translations from sources in a different language. The work contained in this thesis has not been previously submitted for examination. I also agree that the thesis may be tested for plagiarized content with the help of plagiarism software. I am aware that failure to comply with the rules of good scientific practice has grave consequences and may result in expulsion from the Programme.

Abstract

In the 21st century information will be a shipowner's most useful tool for improving vessel performance. The operational decisions made daily on how to plan and conduct a voyage, perform regular maintenance, monitor fuel consumption efficiencies, and comply with regulations that impact all outcomes. Moreover, the ship-to-shore communication and internet availability on board has been significantly improved, making it easier to transfer data from ship to shore. Before 2025, many ships, systems, and components will be linked to the Internet, making them accessible from almost any location in the world (The Digital World in 2025). For this, a Ship Performance Monitoring (SPM) software with continuous monitoring can be of valuable assistance to the ship crew and the owner. The basic concept and requirement for this system is to measure key parameters onboard, perform processing on these data, and present the results in an easy to understand and intuitive way for the onboard crew and onshore personnel. Performance monitoring systems will be an integrated part of (most) ship systems within the foreseeable future, because the decision-making process is made easier and more tangible when based on real-time ship data, as opposed to manually gathered data (noon-reports) and hard-to-transfer experiences of chiefs on board.

Accurate and regular energy consumption monitoring across an individual vessel or an entire fleet can highlight inefficiencies and provide a mechanism for continual improvement. Shipowners and shipping companies can use such information to predict maintenance costs and time, optimize fuel consumption, or plot shortest routes between ports. Sharing energy use data can promote best practices for fuel efficient operations among crews to improve performance. The captain for example can use such information to optimize the way he pilots the vessel.

Using fuel more efficiently also helps to comply with ever more stringent emission regulations and helps to achieve environmental objectives. These, and other similar efforts, are in line with the IMO guidelines on developing a Ship Energy Efficiency Management Plan (SEEMP) in which commitment is required by the entire shipping organization, from chief operating officer to the entire crew, to motivate the corporate commitment to energy conservation.

Περίληψη

Στον 21ο αιώνα οι πληροφορίες θα είναι το πιο χρήσιμο εργαλείο ενός πλοιοκτήτη για τη βελτίωση της απόδοσης του πλοίου. Οι επιχειρησιακές αποφάσεις που λαμβάνονται καθημερινά σχετικά με τον τρόπο προγραμματισμού και διεξαγωγής ενός ταξιδιού, την τακτική συντήρηση, την παρακολούθηση της απόδοσης κατανάλωσης καυσίμου και τη συμμόρφωση με κανονισμούς που επηρεάζουν όλα τα αποτελέσματα. Επιπλέον, η επικοινωνία από πλοίο στην ακτή και η διαθεσιμότητα διαδικτύου επί του πλοίου έχει βελτιωθεί σημαντικά, καθιστώντας ευκολότερη τη μεταφορά δεδομένων. Πριν από το 2025, πολλά πλοία, συστήματα και εξαρτήματα θα συνδεθούν με το Διαδίκτυο, καθιστώντας τα προσβάσιμα από σχεδόν οποιαδήποτε τοποθεσία στον κόσμο (The Digital World in 2025). Για αυτό, ένα λογισμικό Ship Performance Monitoring (SPM) με συνεχή παρακολούθηση μπορεί να παρέχει πολύτιμη βοήθεια για το πλήρωμα του πλοίου και τον ιδιοκτήτη. Η βασική ιδέα και απαίτηση για αυτό το σύστημα είναι η μέτρηση βασικών παραμέτρων επί του σκάφους, η εκτέλεση επεξεργασίας αυτών των δεδομένων και η παρουσίαση των αποτελεσμάτων με εύκολο και διαισθητικό τρόπο για το πλήρωμα και το προσωπικό της ξηράς. Τα συστήματα παρακολούθησης της απόδοσης θα αποτελούν αναπόσπαστο μέρος των (περισσότερων) συστημάτων πλοίων στο άμεσο μέλλον, επειδή η διαδικασία λήψης αποφάσεων γίνεται ευκολότερη και πιο απτή όταν βασίζεται σε δεδομένα του πλοίου σε πραγματικό χρόνο, σε αντίθεση με τα δεδομένα που συλλέγονται με μη αυτόματο τρόπο και δύσκολα μεταβιβάσιμα από τους αξιωματικούς του πλοίου.

Η ακριβής και τακτική παρακολούθηση της κατανάλωσης ενέργειας σε ένα μεμονωμένο σκάφος ή σε έναν ολόκληρο στόλο μπορεί να επισημάνει τις αναποτελεσματικότητες και να παρέχει έναν μηχανισμό για συνεχή βελτίωση. Οι πλοιοκτήτες και οι ναυτιλιακές εταιρείες μπορούν να χρησιμοποιήσουν αυτές τις πληροφορίες για να προβλέψουν το κόστος συντήρησης και τον χρόνο, να βελτιστοποιήσουν την κατανάλωση καυσίμου ή να σχεδιάσουν τις συντομότερες διαδρομές μεταξύ των λιμανιών. Η κοινή χρήση δεδομένων χρήσης ενέργειας μπορεί να προωθήσει τις βέλτιστες πρακτικές για αποδοτικές λειτουργίες καυσίμου μεταξύ των πληρωμάτων για τη βελτίωση της απόδοσης. Ο καπετάνιος για παράδειγμα μπορεί να χρησιμοποιήσει τέτοιες πληροφορίες για να βελτιστοποιήσει τον τρόπο με τον οποίο κυβερνά το πλοίο με ασφάλεια.

Η πιο αποτελεσματική χρήση καυσίμου συμβάλλει επίσης στη συμμόρφωση με ολοένα και πιο αυστηρούς κανονισμούς εκπομπών και συμβάλλει στην επίτευξη περιβαλλοντικών στόχων. Αυτές και άλλες παρόμοιες προσπάθειες είναι σύμφωνες με τις κατευθυντήριες γραμμές του IMO για την ανάπτυξη ενός Σχεδίου Διαχείρισης Ενεργειακής Απόδοσης Πλοίου (SEEMP) στο οποίο απαιτείται δέσμευση από ολόκληρο τον ναυτιλιακό οργανισμό, από τον επικεφαλής επιχειρησιακό διευθυντή έως ολόκληρο το πλήρωμα, για να παρακινήσει την εταιρική δέσμευση στην εξοικονόμηση ενέργειας.

Table Of Contents

List of Figures

List of Tables

Abbreviations

Air Layer Drag Reduction	ALDR
Anti Fouling Systems	AFS
Bubble Drag Reduction	BDR
Bunker Delivery Notes	BDN
Charter Party Agreement	CPA
Clean Shipping Coalition	CSC
Continuous Monitor	CM
Electromotive Force	EMF
Energy efficiency Design Index	EEDI
Energy Efficiency Operational Indicator	EEOI
Energy Efficiency Technical Indicator	EETI
Energy Saving Device	ESD
Expected Time of Arrival	ETA
Expected Time of Arrival	ETA
Flettner Rotor	FR
Global Positioning System	GPS
Health Safety Environment	HSE
International Energy Efficiency	IEE
International Maritime Organization	IMO
Key Performance Indicators	KPI
Maximum Continuous Rate	MCR
Monitoring, Reporting and Verification	MRV
Noon Report	NR
Oil Companies International Marine Forum	OCIMF
Partial Cavity Drag Reduction	PCDR
Performance Monitoring and Analysis system	PMA
Ship Energy Efficiency Management Plan	SEEMP
Ship Inspection Report Programme	SIRE
Ship Performance Monitoring	SPM
Specific Fuel Consumption	SFC
Specific Fuel Oil Consumption	SFOC
The Marine Environment Protection Committee	MEPC
The Maritime Environment Protection Committee	MEPC
Tributyltin (for antifouling coatings)	TBT
Volatile Organic Compounds	VOC

Chapter 1

1.1Purpose of this study

This study aims to develop and share knowledge and insight from a broad range of ship owners, operators and managers about the current views on energy efficiency solutions and the extent of fuel consumption monitoring. In this thesis we will be using the Delphi method a useful tool well used to collect 'experts' opinions in an emerging area, consolidate different opinions into a quantifiable outcome in a structured way and avoid the potential ties in the ranking. The object of this thesis is an investigation to identify any technology or economical implementation barriers, and a study to systematically investigate the adoption status of shipping monitoring tools and big data analytics in maritime organizations. This thesis details the developing tools the ship owners and operators need to utilize in order to optimize operational decisions, particularly with the aim of reducing fuel consumption and/or maximizing profit. This thesis has also highlighted the sensitivity of the performance indicator uncertainty to the uncertainty of the speed parameter measurement, thus a robust monitoring and analysis system could be used as a supporting tool which takes into account the ship's behavior in any foreseen state of loading and weather conditions, trying to assess and estimate power needed to overcome all resistance components, while assuming a clean hull and propeller condition of the ship. We will also state how the data acquisition parameters could improve by incorporating sensors to measure and capture an extensive set of data and improve its accuracy by utilizing o continuous monitoring tool rather than only with noon reports.

We have eleven experts that participated in the Delphi survey which includes operators each from different shipping companies with rich experience in maritime sector. The survey results will be presented in the following chapters. As seen in Figure 1 all participants are working in shipping companies with 11 vessels and above. The companies that participated can be considered to at least medium to large size regarding their number of vessels.

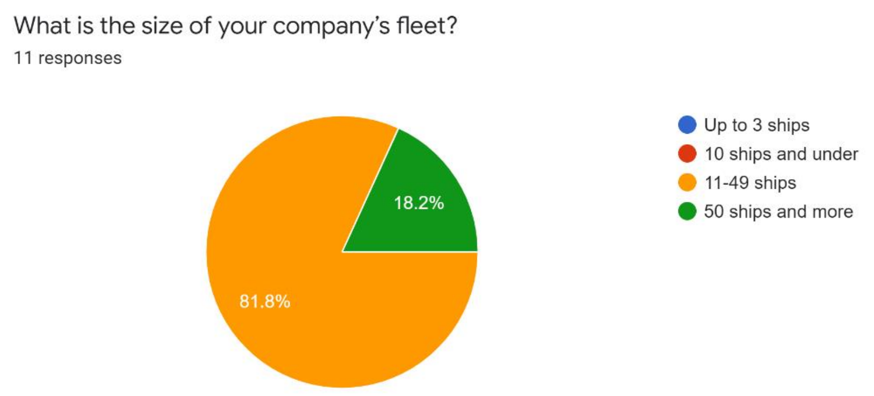


Figure 1.1 Delphi survey "What is the size of your company's fleet?"

The type of vessels that these shipping companies mostly operate are Tankers and are followed by Dry bulk vessels (Figure 1.2)

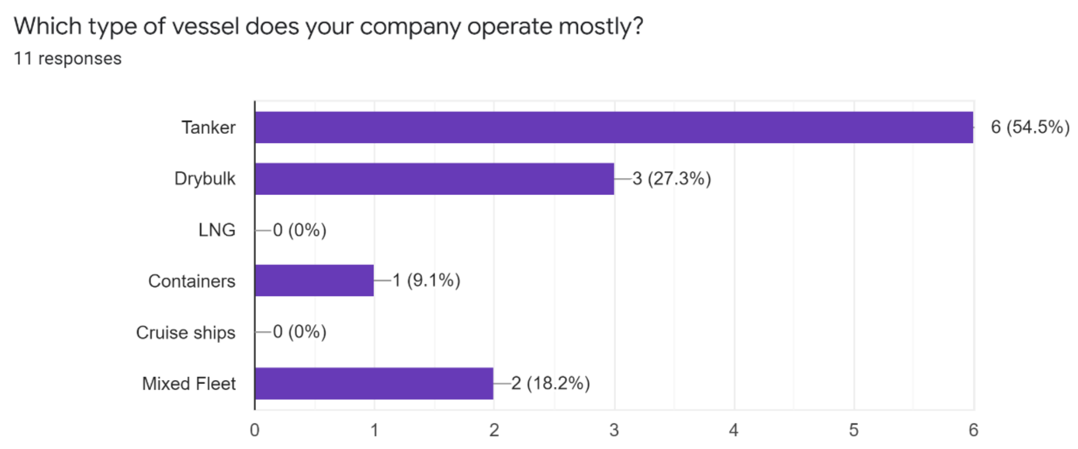


Figure 1.2 Delphi survey "Which type of vessel does your company operate mostly?"

1.2 Literature Review

Introduction

Compliance with emerging regulations regarding emissions to air will be one of the biggest challenges for the shipping industry in the future. Shipping companies are already under pressure to reduce energy consumption to meet the regulations for SEEMP, EEOI and EEDI.

In 2009, the IMO agreed to new measures to improve energy efficiency in global shipping: the Energy Efficiency Design Index (EEDI) and the Energy Efficiency Operational Indicator (EEOI). For newbuilding's, the EEDI aims to stimulate the development of more efficient ship designs and is sure to become an increasingly important design parameter. In January 2014 the IMO made amendments to MARPOL Annex VI Regulations for the prevention of air pollution from ships. This made mandatory the Energy Efficiency Design Index (EEDI) for new ships and the Ship Energy Efficiency Management Plan (SEEMP) for all ships.

For ships in operation, the EEOI enables you to measure the fuel efficiency of a ship over time and to gauge the effect of any changes during operation.

Iso 19030 and Hull and Propeller performance

In a global industry for which analysis of ship performance and detailed understanding of the drivers of fuel consumption, these new knowledge contributions are of great relevance and timeliness. A fact evidenced by the inclusion of much of this work in the development of ISO 19030 a new standard for the measurement of hull and propeller performance. Compared with the Energy Efficiency Operational Indicator (EEOI), ISO 19030 takes the physical factors of actual ship navigation into consideration and might have better accuracy with the added sensors.

Hull and propeller performance monitoring acts as a decision support tool for determining dry dock intervals, hull coating type and quality, the extent of any hull pre-treatments applied, the frequency and method of hull and propeller cleaning, and of hull and propeller modifications (Munk and Kane 2011).
Hull and propeller fouling has been an area of interest not only for ship owners and operators, but it is also recognized by the MEPC as an important factor in reducing the industry's GHG emissions. The Clean Shipping Coalition (CSC) have estimated that the impact of the deterioration in hull and propeller performance is likely to result in a 15 to 20 per cent loss in vessel efficiency on average over approximately 50 months (IMO_MEPC_63/4/8 2011). This is significant in terms of fuel consumption costs and GHG emissions.

Methods for estimating hull and propeller performance

An implied purpose of any measurement standard is to facilitate general agreement on how to measure something. In the case of the ISO 19030 series, generally agreed upon methods for measuring hull and propeller performance are expected to make it easier for decision makers to learn from the past and thereby make better informed decisions for tomorrow. Also, to provide much needed transparency for buyers and sellers of technologies and services intended to improve hull and propeller performance. And finally, to make it easier for the same buyers and sellers to enter into performance based-contracts and thereby better align incentives, Søyland (2016).

Available methods for estimating hull and propeller performance from onboard monitored data are typically based on physical models. These methods aim at modelling and correcting for factors such as vessel loading condition, sea currents, wind resistance and added resistance in waves (Munk et al., 2009). Hansen includes theoretical models for added resistance in wind, waves, steering, and shallow water. Also, Hansen corrects for wind/weather to calculate the power demand at a reference speed and draft to quantify the fouling effect.

More recently, other methods such as multiple regression and machine learning have been suggested for detecting changes in hull performance, which are not based on physical modelling of the ship and includes the use of anomaly detection methods. These methods are, unfortunately, only demonstrated to differentiate between the clean hull and a fouled one. They seem to be unable to quantify the extent of fouling growth (Coraddu et al., 2019;).

Big Data in Shipping Industry

Ship operational efficiency studies are based on dataset which are broadly obtained from ship's noon-reports. However, the technological developments are allowed to use automatic data acquisition systems on board ships for obtaining high-frequency ship operational data. Taking advantage of the automatic data acquisition systems on board ship substantially improve the data quality when comparing with the noon-report based dataset (90% decrease in the data uncertainty level) (Aldous et al. (2015). Thus, the study analyses the quality and accuracy of the dataset obtained from automatic data acquisition systems and compares it with the dataset obtained from noon reports.

Ship operational performance is not only related with the ship conditions (i.e. hull and machinery) but also additional features such as, weather conditions, and loading conditions. A large number of features should be taking into account for developing reliable ship operational performance. Along with the increasing digital infrastructure investment, initiatives and transformation in maritime organizations, big data analytics becomes an inevitable topic for many players. Therefore, this study presents a case study of investigating the adaption rate for big data analytics to be adopted in Greek maritime organizations.

Continuous monitoring and noon report

Continuous monitoring and noon report datasets will be introduced in a later section. The merits and drawbacks of these acquisition systems, in terms of sampling, instrumentation and human influences are discussed in detail throughout this thesis. CM systems in general offer high frequency sample rates and remove elements of human intervention, however maintenance is required to avoid sensor drift and stuck sensors. In case of malfunction, it could be spotted by onshore personnel designated to the PMA system.

Chapter 2

International Standards & Regulations for Energy Efficiency

2.1 Introduction to ISO 19030

This standard aims at comparing the change of hull and propeller performance of one ship over time compared only to its own performance. Sister ships are regarded to have inherently different performance profiles based on trade and areas of operation. The focus of this standard is limited to hull and propeller performance and do not cover the overall performance of the ship. Covering overall ship performance would be a more challenging task as it includes engine train performance, quality of fuel, wind resistance as well as other drivers of energy efficiency used on board a ship. This first iteration of the hull and propeller performance standard covers fixed single or twin pitch propellers.

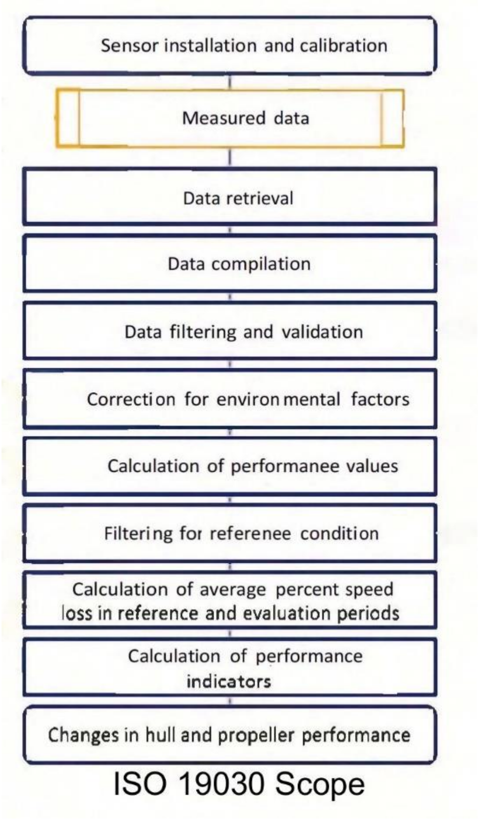


Figure 2.1 Iso 19030

ISO 19030 origin

The origin of ISO 19030 is the paint manufacturers' initiative to develop a standard based on which to measure how different marine coating systems impact on the performance and efficiency of a ship, say, over the five-year period between two dockings. The ship's operator would then be able to make a sound judgement on the need to take action at the right time to improve the ship's efficiency whilst maintaining the ship's safety and environmental competitiveness in the eyes of the Charterer.

What ISO 19030 cover

ISO 19030 outlines general principles of, and defines both a default as well as alternative methods for, measurement of changes in hull and propeller performance. The standard defines sensor requirements, measurement procedures, including various filters and corrections, as well as how to calculate a set a set of four performance indicators for hull and propeller related maintenance, repair and retrofit activities.

The ISO 19030 series consists of three parts

1. ISO 19030-1 outlines general principles for how to measure changes in hull and propeller performance and defines a set of performance indicators for hull and propeller maintenance, repair and retrofit activities.

2. ISO 19030-2 defines the default method for measuring changes in hull and propeller performance and for calculating the performance indicators. It also provides guidance on the expected accuracy of each performance indicator.

3. ISO 19030-3 outlines alternatives to the default method. Some will result in lower overall accuracy but increase applicability of the standard. Others may result in same or higher overall accuracy but include elements which are not yet broadly used in commercial shipping.

Why ISO 19030 is needed

Today hull and propeller performance is a ship efficiency killer. According to the "Clean Shipping Coalition" in MEPC 63-4-8, poor hull and propeller performance accounts for around 1/10 of world fleet energy cost and GHG emissions. This points to a considerable improvement potential, 1/10 of world fleet energy costs and GHG emissions translates into billions of dollars in extra cost per year and around a 0.3% increase in man-made GHG emissions.

The cost of outfitting ships with performance measurement systems can be done in an inexpensive way. The basic approach in ISO 19030-3 is to use noon reports. This way, operators will at least have indications on overall performance. By investing in some additional equipment, the accuracy can be significantly improved. In order to comply with ISO 19030-2, which is based on high frequency data, a datalogger, torque meter and some cabling is required. Alternatively, flowmeters can be used. Both torque meters and dataloggers are becoming very affordable these days, allowing for a quick return on investment. As a starting point, operators are recommended to start using the standard to improve the quality of the vessel noon reports in order to become familiar with the methodology. As a next step, they can then look into investing in the required equipment should they want to comply with ISO 19030-2 to get more accurate performance data.

This standard is intended for all stakeholders that are striving to apply a rigorous, yet practical way of measuring the changes in hull and propeller performance. It could be shipowners or companies offering performance monitoring tools, shipbuilders and companies offering hull and propeller maintenance and coatings. ISO 19030 will make it easier for decision makers to learn from the past and thereby make better informed decisions for tomorrow. It will also provide much needed transparency for buyers and sellers of technologies and services intended to improve hull and propeller performance. Finally, it will make it easier for the same buyers and sellers to enter into performance-based contracts and thereby better align incentives.

ISO 19030 metric indicators

ISO 19030 (ISO, 2016a) is a practical method for hull and propeller performance monitoring. It measures how much power is required to move a ship through water at a given speed, draft and wind condition. Ship owners and operators can compare hull and propeller performance by analyzing the operational data of ships to calculate the performance indicators and then select the most efficient options for their vessels. The standard shows four performance indicators for dry-docking performance, in-service performance, maintenance trigger and maintenance effect.

- In-service performance: Refers to the average change in hull and propeller performance over the dry-docking interval. Performance over the first year following the docking is compared with performance over whatever remains of the docking interval, typically two to four years. This performance indicator is useful for determining the effectiveness of the underwater hull and propeller solution, for example the hull coating system used.

- Dry docking performance: Hull and propeller following the present out-docking is compared with the average performance from previous out dockings. This provides useful information on the effectiveness of the docking.

- Maintenance trigger: Hull and propeller performance at the start of the dry-docking interval is compared with a moving average at a point in time. Useful for determining when hull and propeller maintenance is needed including propeller polishing or hull cleanings.

- Maintenance effect: Hull and propeller performance in the period preceding the maintenance event is compared with performance after. This provides useful information for determining the effectiveness of the event.

2.2 Independently measure hull and propeller performance

In the first revision of ISO 19030 it is not possible to independently measure hull and propeller performance. The four performance indicators defined in the standard are therefore based on measurements of changes in both. This complicates the determination of the effectiveness of individual hull or propeller maintenance, repair and retrofit activities.

If the propeller thrust is measured, the actual propeller condition can be separated from the ship's hull condition. This is important for several reasons:

- a. To determine the proper timing for a hull cleaning based on the actual hull resistance without the propeller condition taken into account.
- b. To determine the actual effect of a newly applied hull coating on the ship's resistance.
- c. To determine the proper timing for a propeller cleaning (this might differ from the hull cleaning timing due to measured difference in fouling condition of hull and propeller).
- d. To determine possible propeller damages, which result in a propeller performance decrease.
- e. To determine the optimal propeller efficiency conditions at several ship operational conditions (as an example to determine the effect of variable rpm versus constant rpm on propeller efficiency for a controllable pitch propeller).
- f. To determine the effect of energy saving devices (like a BCF or WED) or propeller or hull modifications (like for instance a new bulbous bow design).

Accurately and reliably isolating hull from propeller performance would require accurate and reliable thrust measurements. Sensors are expected to continue to mature and independent measurements of hull and propeller performance, as well as independent sets of performance indicators for the two should be considered in future revisions.

2.3 Getting better data with the right sensors

In recent decades, sensor technologies and data acquisition systems enable to obtain high quality ship operational data. It all starts with accurate data acquisition. If sensors or crews give wrong or no data, then performance monitoring is doomed from the beginning. Modern vessels incorporate sensors to measure and capture an extensive set of data including navigation, cargo, machinery and auxiliary systems.

The sensor's quality and accuracy are continuously improved giving very high level of precision in the measurements and data transmission.

Measuring Device	Measured Parameter
Anemometer	Wind Speed, Wind Direction
Echo Sounder	Depth measurement
Flow meters	Fuel consumption
GPS	SOG, Longitude, Latitude
Gyrocompass	Vessel's heading
Pressure sensor	Draft readings
Rudder angle indicator	Rudder Angle
Shaft torque meter	Propeller shaft torque, rpm
Speed Log	SOG, STW

Table 2.1 The measuring devices that are required onboard the ship to monitor the parameters of interest.

Crucial sensors for SPM

Propeller shaft power and ship speed through water are two of the most important parameters to monitor using sensors. The ISO 19030-2 defines a set of primary and secondary measurement parameters for measuring the vessel performance. The primary parameters are defined as speed through water, propeller shaft power (torque and revolutions), the time and date. To measure these parameters, the ISO standard states a minimum set of sensors, which in this case are a speed log, a shaft power meter, and a GPS (giving the UTC time).

Also adding accurate fuel oil consumption measurements to get the complete performance picture of a vessel. The fuel consumption will ultimately give the current cost and environmental footprint of the vessel. Marine fuel oil cost constitutes a significant part of the vessels operating cost, so a continuously monitoring of the fuel efficiency is essential to cut operating cost.

1. **Speed through water**

: An electromagnetic sensor (EM Log) can be used to measure the speed through water. The electromagnetic sensor relies upon the principle that any conductor movement across a magnetic field will have induced onto it a small electromotive force (e.m.f.). Assuming that, the magnetic field remains constant, the amplitude of the induced e.m.f. will be directly proportional to the speed of movement.

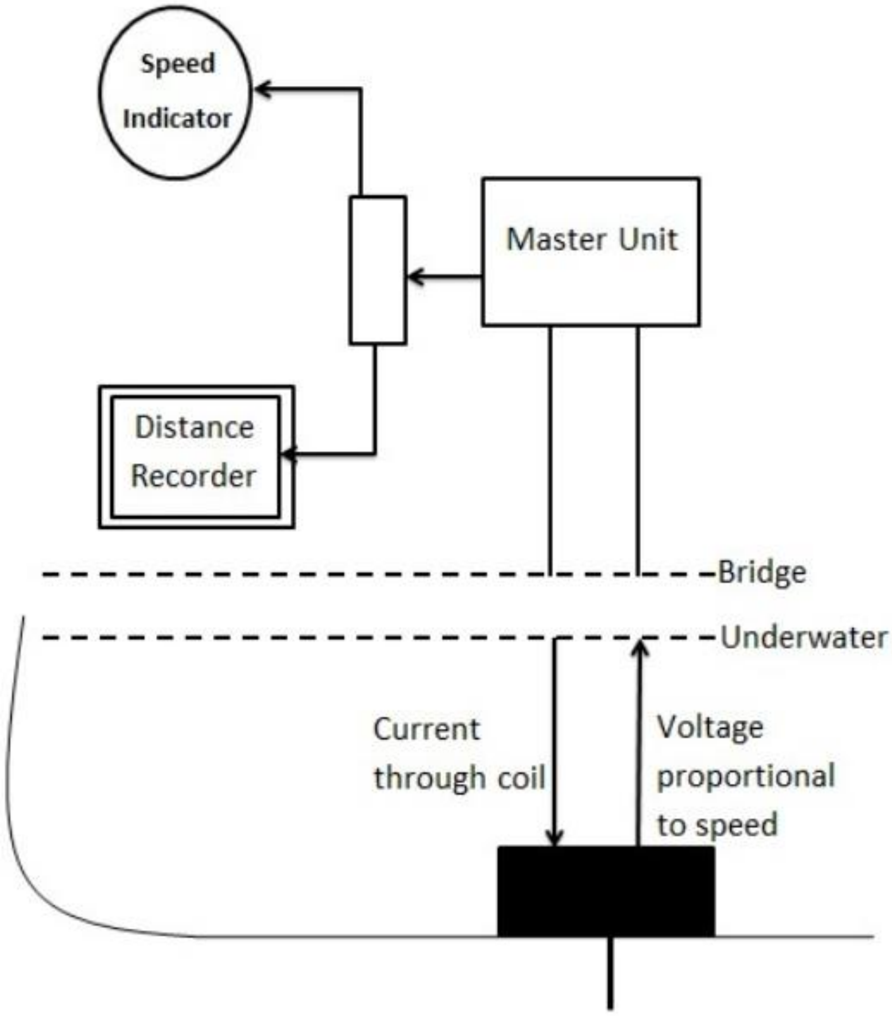


Figure 2.2 electromagnetic log sensor

In a practical installation, the EM-Log sets up a magnetic field. The induced voltage between the two electrodes measures the magnitude of this voltage signal, which is proportional to the ship speed. The EM-Log must be cleaned and calibrated regularly to keep the required accuracy.

2. **Speed over ground**

The speed over ground is measured either by a global positioning system (GPS) or by a Doppler log. The GPS system should operate in the Differential mode to ensure sufficient accuracy. A Doppler speed log can also be used to measure the ship's speed over ground by utilizing the principle of the Doppler effect, which defines that a signal emitted from a moving object is heard with its frequency shifted at stationary locations and the degree of the frequency shift is proportional to the speed of the moving object.

Difference between "Speed through Water" and "Speed over Ground "

In open seas, the sound pulse from the Doppler transducer may not reach the bottom but get totally internally reflected from a layer of water in between. This is known as the echo from the 'Water Track". When the sound is bounced off a water layer, called a water track, speed indicated is the 'Speed through Water". or from a layer of water and the echo is at a higher frequency. The frequency of the echo from the water track will follow the same Doppler principles as the echo from the bottom track. However, the speed measured from the 'water Track' will not be 'Speed over the Ground', but it will be 'Speed through Water'.

Speed over ground is the speed of the ship with respect to the ground or any other fixed object such as fixed buoy or island. Speed through water is the speed of the ship with respect to the water such as anything floating on water. A ship with her engine stopped in water with 2 knots currents will have zero speed through water but will have 2 knots speed over ground.

3. Shaft Power Meter

A marine shaft power (torsion) meter measures the real time torque (torsion), speed, and power output on a propeller shaft. When torque is applied to a shaft, a small amount of strain or "twist" occurs on the shaft surface. A shaft power meter measures this strain on the shaft with a sensor and wirelessly transmits the signal to a stationary receiver, which processes and calculates a torque value based on the mechanical properties of the shaft. The torque measurement is then combined with a speed measurement (usually measured with a built-in tachometer) to calculate power.

The primary difference between the various types of permanently installed shaft power meters is the method they use to sense strain (torque or "twist") on the shaft. The most common methods include: optical, magnetic, and strain gages.

Sensing Method	Strain Gage	Optical	Magnetic
Advantages	Very accurate Industry standard Fits small spaces (<152mm/6”)	Bolt-on system No chemicals required	Bolt-on system No chemicals required
Disadvantages	Installation process can be tedious Requires chemicals that expire	Expensive Susceptible to unwanted measurements (vibration, etc) Requires >305mm/12” of available shaft space	Not capable of thrust measurement Requires >6” of available shaft space
Ease of Install	Med	High	Med
Accuracy	High	Med	Low
Cost	$$	$$$	$
Required Shaft Space	Low	High	High

Table 2.2 Comparing most common power shaft meters

Optical

These systems rely on 2 bars that are bolted onto the shaft and aligned at a close distance from each other. A light is modulated between the two bars. As the shaft twists, the strength of the light changes which can be directly related to the amount of torque on the shaft. The advantage of these systems is that they are usually capable of detecting strain in multiple directions, meaning they can inherently measure torque and thrust with relative ease. However, this comes at the expense of decreased accuracy since the point of measurement is at a point removed from the actual shaft surface. The systems are also prone to picking up unwanted measurements (such as vibrations) and can be expensive.

Magnetic

In these systems, a magnetic band is strapped along the surface of the shaft. When torque is applied, the magnetic moments inside the shaft are reoriented, causing a magnetic flux to develop around the circumference of the shaft. The strength of the magnetic flux field is linearly proportional to the stress and therefore, the torque on the shaft, and the polarity of the magnetic field indicates the direction of torque. Magnetic field sensors positioned around the shaft determine the amount and direction of torque based on this flux. Systems that utilize this method tend to be relatively inexpensive and easy to setup. Getting bands to adhere perfectly to the shaft is virtually impossible, however, which induces a level of uncertainty into the measurements and decreases the overall accuracy.

Strain Gage

Strain gages are based sensors rely on a grid of metal foil bonded directly to the shaft. The instrumentation, i.e., transmitter, is connected to the gage and applies a voltage through the grids. As the shaft twists under load the grids or elements are stretched or compressed and change resistance which changes the voltage measured by the transmitter. Strain gages are very precise, although more care needs to be taken during the installation process to ensure the gage is adhered and environmentally protected. Due to their accuracy, strain gages are typically considered the golden standard for propulsion shaft torque measurement, commonly referenced in a variety of international standards.

Benefits of using shaft power meters

The key value proposition for any shaft power meter is that it provides an accurate, real-time, method for monitoring the shaft power on a vessel via a direct measurement of torsion on the propulsion shafting. Direct measurements of power can be 10-20% more accurate than engine estimations (Binsfeld Engineering). Making vessel efficiency decisions based on inaccurate data leaves efficiency gains on the table. Implementing direct power measurements eliminates the guess work and helps vessel owners and managers make decisions that maximize efficiency.

More accurate measurements of vessel horsepower and torque have been shown to:

1. **Increase maintenance intervals by up to 50%.** Through accurate measurements of real-time horsepower and/or other KPI's such as Specific Fuel Oil Consumption, owners can delay maintenance on an engine until truly necessary.

2. **Reduce fuel costs by 5%, or more.** This can be accomplished in several ways. Shaft torque/thrust measurements can help identify hull and/or propeller fouling at the on-set. Unchecked fouling has been shown to increase fuel burn by 5%. Additionally, monitoring shaft horsepower compared to a theoretical baseline efficiency curve established by the manufacture can help determine when inefficiencies are present. (Binsfeld Engineering)

Monitoring the above primary parameters with correct and reliable sensors will give the ship owner a good status of the vessel's efficiency. However, with this minimum set of sensors the efficiency will apparently vary quite a lot, because many external conditions will affect the result continuously. To be sure that the monitoring will be as good as possible and unaffected by any external sources like weather, cargo size, depth, etc., adding a few extra sensors to the sensor suite will give the full performance picture.

4. Wind and Wave sensors

The weather conditions will influence the measurement of a vessel's efficiency. The wind anemometer is a device that provides both, the relative speed and direction of the wind with respect to the ship's orientation. It consists of a helicoid propeller and a vane the measure the wind's speed and direction, respectively. The angular displacement of the vane helps estimate the wind's relative direction, while the rotational speed of the helicoid propeller helps estimate the wind speed.

Including measuring the wind speed and direction continuously and discarding any measured data if the true wind force is above a certain threshold will improve the SPM software. The threshold should be configurable, but the most common threshold used is to discard any performance data when the wind speed is above Beaufort 6. With wind forces above this threshold, it is normally very difficult to estimate the effect on the vessel's performance.

The wave height can also be estimated from the wind force. By including the data logged by the motion sensor placed in the bow section it is the intention to use this data to estimate the wave height and thus get a more accurate estimate of the sea state.

The way of calculation is done by determining the state of the weather (wind and waves) for a limited period of time after the installation and manually inputting it into the system. Afterwards it will be possible to use the gathered data to calculate the ship's performance under different weather conditions.

5. Depth measurement

Two echo sounders sensors are installed on the ship, one in the forward section and one approximately below the accommodation. The frequency ranges for the sensor are in the interval from 28 to 210 kHz and the measuring accuracy is in the order of 2.5% of the measured depth, Litton (1998). The echo sounder is used in confined waters for navigational purposes, for which the echo sounder frequency is set to 50 kHz. At this frequency the seabed detection level is around 90-150 m depending on sea water salinity and temperature. Therefore, no water depths are detected above this level.

Depth of water is another factor that will affect the 'power vs. speed' profile if the vessel enters shallow water. When the depth of water is less than a certain factor of the vessels draft, the hydrodynamic forces may increase, thus subjecting the propeller for a higher load. In general, the shallow water effect is insignificant in water depths of more than ten times the vessel draft. However, even though it is a small factor, a depth-measuring device can be a supplement to get the complete picture of external influencers on the performance. The higher the draft values, (more cargo), the higher necessary power is needed to get the desired vessel speed.

6. Rudder angle sensor

The electric rudder angle indicator equipment is used for measuring and monitoring the actual rudder angle. The rudders have also some impact on the vessels resistance, even though it is not a very large factor in the overall picture. Quite as expected, the resistance penalty increases with the rudder angle. To obtain a very accurate picture of the vessel performance, the rudder angle's effect on the vessel's resistance should be monitored. Normally, the rudder angle sensor connects mechanically directly to the rudder tiller arm or rudder quadrant. This mechanical signal, transformed to an electrical signal, is sent to a rudder angle indicator. The rudder indicator measures the rudder angle continuously and the measuring accuracy is usually below the range of +/- 0.5° at common angles and +/- 1.5° at hard over rudder, Sperry (1995).

7. Gyrocompass

The gyrocompass is a form of gyroscope (non-magnetic compass) that is used in ships for monitoring their heading orientation. It is based on a fast-spinning disc and the rotation of the Earth, to find geographical direction automatically. It has the ability to point always the true north, and so the ship's heading is accurately estimated with respect to this direction.

8. Density and temperature measurements

The recording of the seawater temperature and density enables the calculation of ship's displacement and corrections with regard to viscosity. The water temperature at the seawater inlet level is the preferred measuring point, along with the air temperature and atmospheric pressure, using a calibrated thermometer and barometer.

9. Draught Status

Draught information is given as manual input. At departure from port the draught forward and aft is taken from draught marks on the side of the ship. During sailing the draught information is updated daily and updates are based on daily consumption of fuel, oil and water.

Sensor's adaption rate

The speed log sensor is the most common one among the Greek companies which measures "speed over ground" and "speed through water". It is followed by Propeller shaft which measures the real time speed, and power output

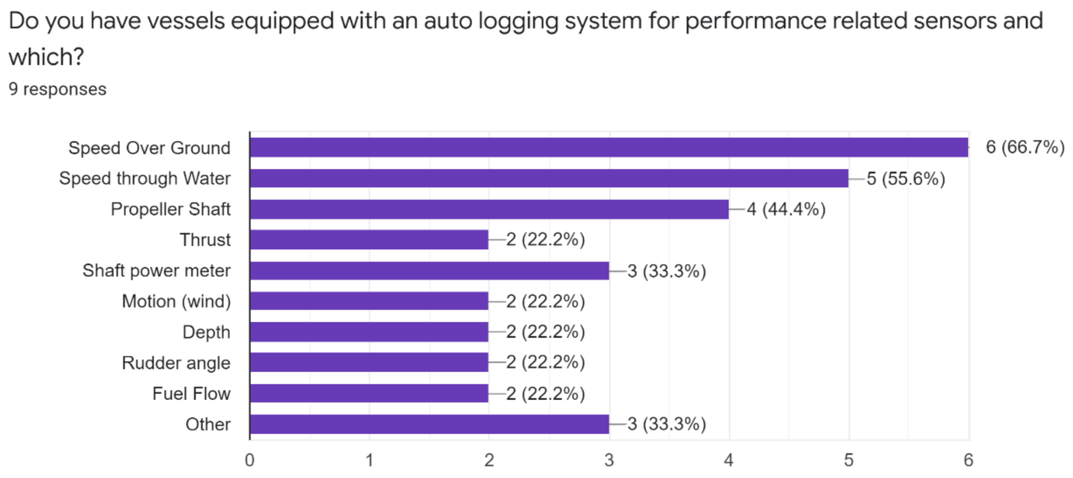


Figure 2.3 Delphi survey “Do you have vessels equipped with an auto logging system for performance related sensors and which?”

Chapter 3

Ship Energy efficiency Measures

3.1 EEDI (Energy Efficiency Design Index)

The Maritime Environment Protection Committee (MEPC) has introduced the Energy efficiency Design Index (EEDI) to regulate all new ship design (IMO, 2012a.c). EEDI is the tool that is used during the design or construction stage of the vessel. Its concept is according to the IMO to have the ships fitted with engines and equipment's that are less polluting. The calculation and verification of EEDI shall be performed for each:

- New ship before ship delivery.
- Ship in service which has undergone a conversion that is so extensive that the ship is regarded by the Administration as a newly constructed ship.

Survey and certification of the EEDI should be conducted in two stages: preliminary verification at the design stage and final verification at the sea trial. For the preliminary verification at the design stage, a Ship Owner or a Shipbuilder is to submit to a verifier (Administration or its RO) an EEDI Technical File containing the necessary information for the verification and other relevant background documents. EEDI technical file is first created during the design stage of the vessel. During the design stage, a model test is done and the EEDI is computed on the basis of that. A verifier (usually classification society on behalf of the flag) witnesses the model test, verifies the EEDI computation and reviews the initial EEDI technical file.

EEDI Technical File is to include at least but not limited to:

- Dead weight and shaft power of main and aux. Engines.
- Ship speed on deep water in the maximum design loaded conditions at the 75% of the maximum continuous rate (MCR) for the main engine.
- Specific fuel consumption (SFC) of the main engine at 75% MCR and auxiliary engines.
- Principal particulars, overview of propulsion system and electricity supply system on board.
- Estimation process and methodology of the power curves at design stage.
- Description of energy saving equipment and
- Calculated value of the Attained EEDI.

The verifier is to issue the report on the preliminary verification of EEDI after verifying the attained EEDI at design stage.

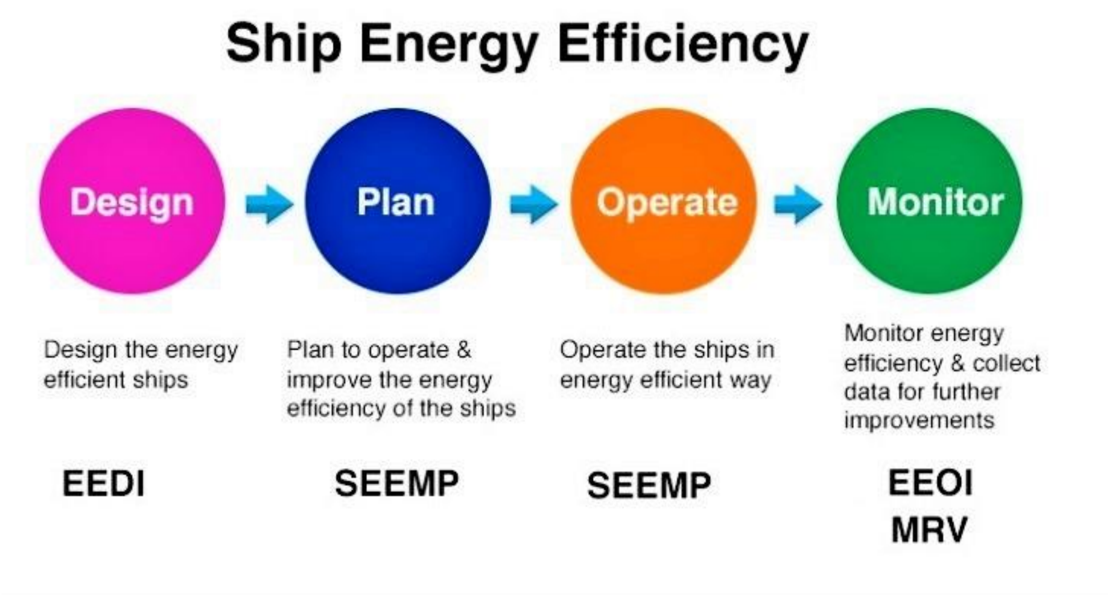


Figure 3.1 Ship Energy Efficiency Source: myseatime_Capt Rajeev Jassal

EEDI calculation formula

EEDI is the measure of the amount of CO_2 emitted by the ship per capacity mile (tonne-mile)

$$EEDI = \frac{Co2\ Emission}{Deadweight\ x\ Distance\ traveled}$$

Figure 3.2 Co2 Emission in grams , Deadweight in tons , distance travelled in nautical miles

The CO_2 emission is computed from the fuel consumption taking into account the carbon content of the fuel. The fuel consumption is based on the power used for propulsion and auxiliary power measured at defined design conditions. The Deadweight or else the designed ships capacity is multiplied by the ship's speed measured at the maximum summer load draught and at 75 per cent of the rated installed power.

If the ships need to be energy efficient as desired by IMO it needs to provide two things

- The maximum value of EEDI required for the ship (Required EEDI)

- The actual value of EEDI attained for the ship (Attained EEDI)

Required EEDI calculation:

$$\text{Required EEDI} = \left(1 - \frac{X}{100}\right) * \textit{Baseline}$$

Figure 3.3 Required EEDI calculation

Where the baseline value is the function of the “Deadweight” of the ship and the “Type of ship”. The “X” value is the reduction factor which is determined according to the year of built for new ships and the EEDI phase.

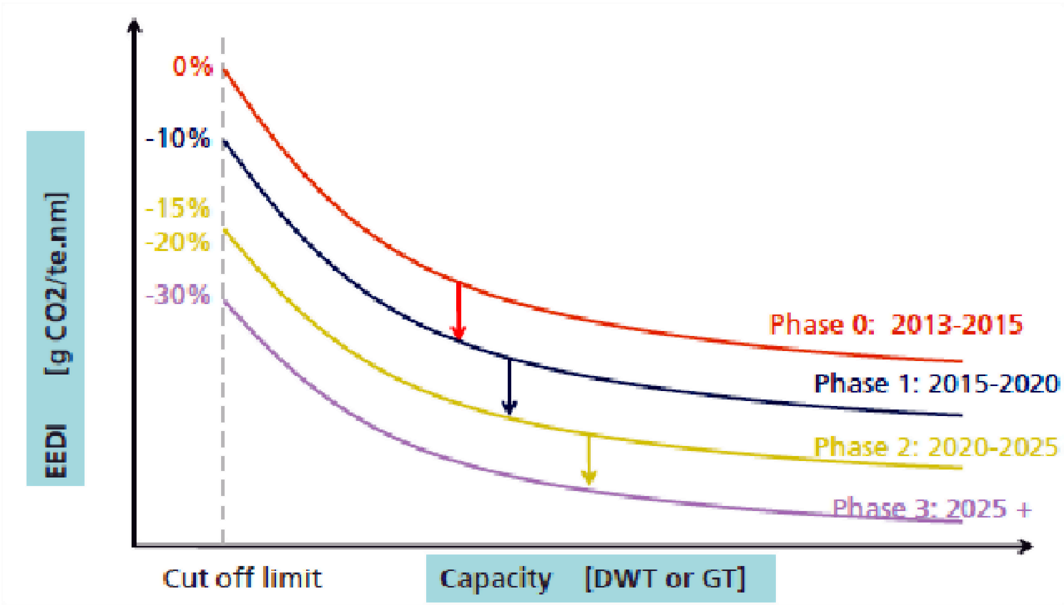


Figure 3.4 Phases for reduction factors of EEDI

The CO2 reduction level (grams of CO2 per tonne mile) for the first phase is set to 10% and will be tightened every five years to keep pace with technological developments of new efficiency and reduction measures. Reduction rates have been established until the period 2025 and onwards when a 30% reduction is mandated for applicable ship types calculated from a reference line representing the average efficiency for ships built between 2000 and 2010. The EEDI is developed for the largest and most energy intensive segments of the world merchant fleet and embraces emissions from new ships covering the following ship types: tankers, bulk carriers, gas carriers, general cargo ships, container ships, refrigerated cargo carriers and combination carriers. In 2014, MEPC adopted amendments to the EEDI regulations to extend the scope of

EEDI to: LNG carriers, ro-ro cargo ships (vehicle carriers), ro-ro cargo ships; ro-ro passenger ships and cruise passenger ships having non-conventional propulsion. These amendments mean that ship types responsible for approximately 85% of the CO_2 emissions from international shipping are incorporated under the international regulatory regime.

Attained EEDI

The Attained EEDI value of the ship which is the actual one needs to be less than the required EEDI. It is measured as -CO_2/ton mile

These are a few factors on which the actual EEDI value of the ship (attained EEDI) would depend upon.

1. Specific fuel consumption of engines

For producing the same amount of power, if an engine uses less fuel, it would be more energy efficient as it would emit less CO_2 too. Specific fuel consumption is the measure of fuel consumed for generating a unit of power. So attained EEDI would depend upon the specific Fuel consumption of ship's engines.

2. Type of fuel used

If the engines and other equipment's work on fuel that produces less CO_2, the vessel will be more energy efficient and will have lower attained EEDI value.

3. The speed of the ship

If the ship makes more speed with the same amount of engine power, the ship will be more energy efficient. Higher ship's speeds mean lesser attained EEDI value.

4. Deadweight of the vessel

5. Innovative mechanical energy efficient technology used

If the ship uses some innovative technology that reduces the wastage of the mechanical energy produced or that increases the efficiency of the engines, the ship would be more energy efficient and hence will contribute towards lesser attained EEDI value.

Final verification of the attained EEDI at sea trial

Prior to the sea trial, a Ship Owner is to submit the final displacement table and the measured lightweight, or a copy of the survey report of deadweight, as well as a copy of NOx Technical File as necessary. The verifier is to attend the sea trial and confirm:

- Propulsion and power supply system.
- Particulars of the engines.
- Other relevant items described in the EEDI Technical File.
- Draft and trim, sea conditions
- Ship speed, shaft power of the main engine.

The verifier is to issue the report on the verification of EEDI after verifying the attained EEDI after the sea trial and it is proposed to issue an International Energy Efficiency (IEE) certificate. During actual sea trials, the actual parameters are measured and EEDI technical file is revised if required. The attained EEDI value is also calculated based on this revised EEDI technical file.

Sea trials issues

There are cases where the sea trial results were good but actual performance after delivery was not as good as sea trial data. Fuel consumption and power per each speed are two important quantities for the ship. However, the speed-power curve does not always reflect the full spectrum of operating conditions of a ship in her lifetime. Measurement methodologies are certainly different or, better to say, measurements in operation are not standardized, i.e., for different loading conditions. As the ship ages, it needs a more accurate power-speed curve.

A disadvantage of ISO 19030 is the assumption that the main engine efficiency is not considered. SFOC (specific fuel oil consumption) of the main engine in operation is never the same as the one obtained at the shop test when the main engine is new. Depending on the M/E and maintenance, the SFOC curve may change over time, usually go up. This can be easily solved by enlarging the scope of ISO 19030 by measuring fuel consumption and calculating SFOC ISO corrected for benchmarking, with the ones coming from the shop test taking into account actual main engine load and RPM.

ISO 19030 does not clearly address all factors influencing fuel consumption changes over a certain period of time. The ship operator will want to look at how the ship performs over a given time, i.e., a reference period such as:

- Measure before dry-docking
- Measure when the ship leaves dry-dock

In addition, it is noted that the ISO 19030 applicability range is the speed range taken from sea trial (13-17 knots). This range is rather limited compared to actual sailing conditions.

3.2 Ship Energy Efficiency Management Plan compliance

Under the proposed amendments to MARPOL Annex VI, Regulation 22, all ships must have an International Energy Efficiency Certificate (IEEC), which requires the presence of a Ship Energy Efficiency Management Plan (SEEMP) on board. SEEMP is a ship specific plan developed by the ship owner, operator or charterer that provides a mechanism to improve the energy efficiency of a ship in a cost-effective manner.

SEEMP Development

When developing or revising an SEEMP, the process should follow a cyclical approach **Plan – Do – Check – Act**:

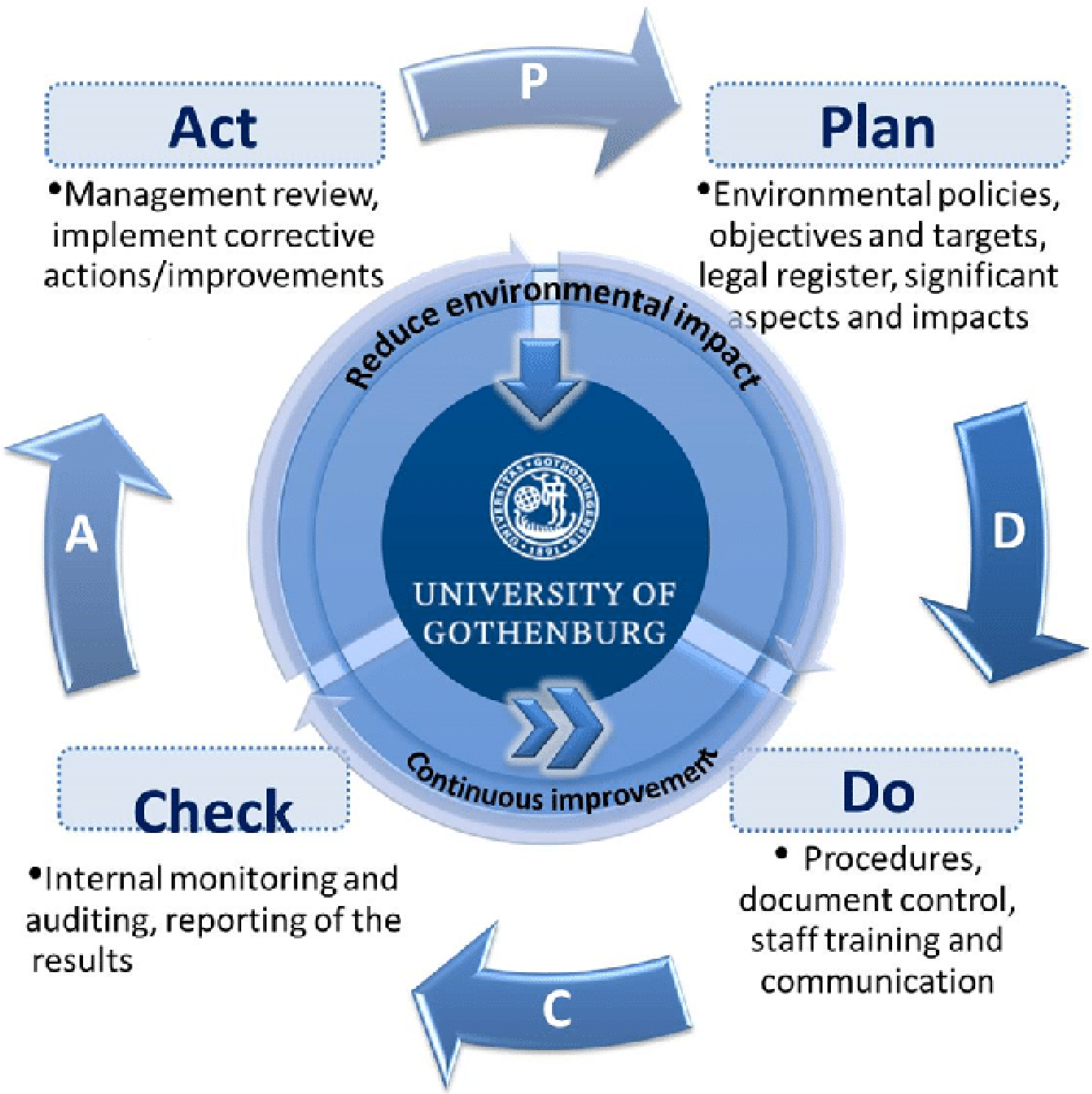


Figure 3.5 Plan-Do-Check-Act SEEMP development

1. **PLAN** includes ship- and company-specific measures, human resource development and goal setting, while bearing in mind the need to minimize on-board administration.

Important considerations: This is the most crucial phase of the SEEMP development and should reference company goals and processes, ship-specific features in technical and operational spheres, training, competence, and timelines.

2. **DO** includes attention to establishing and implementing an appropriate system that allows for each selected measure to be rolled out according to the plan.

   Important considerations: Any "system" can involve a mix of tools, processes and record-keeping that, when combined, enable the implementation of specific energy efficient initiatives. A communication plan that identifies who is responsible for each step in the process will both increase awareness and the likelihood of sustainable activity. The SEEMP may be part of the vessel's Safety Management System mandated by the ISM Code. It can form the cornerstone of a broader energy management initiative, or it can be kept separate, focusing on compliance only

3. **CHECK** describes the establishment of a monitoring system utilizing various tools, existing and new, that can provide a qualitative and quantitative basis for self-evaluation and subsequent performance review.
   Important considerations: This is perhaps the hardest area to activate in a consistent manner. The interaction of the right tools, systems and processes is crucial for measuring achievement and ensuring sustained improvement. Many organizations collect data from a wide range of sources, but not all manage this information systematically so that they know how well they are performing or whether they are on track.

4. **ACT** completes the continuous improvement cycle by assessing the effectiveness of implemented energy efficiency actions, identifying ways to improve associated processes and formerly reporting results to stakeholders.
   Important considerations: Plan to communicate both good and not-so-good news to interested parties. This will increase awareness and build trust in the programme and activities. In addition, seek regular feedback from others via meetings, presentations, and emails to check and validate plans as they unfold. (DNV)

How SPM assists with SEEMP

Using a Performance Monitoring System, you can continuously log performance data, establish a valid baseline and have an easy-to-use management tool that minimizes the administrative burden on board related to the SEEMP. The system will also help you evaluate vessels' performance as well as providing you with input to setting new SEEMP goals. Another driving segment is customer requirements. For instance, concerns about the climate change, global warming and energy efficiency have encouraged ship management companies as well as ship owners to improve ship operational efficiency.

Moreover, the leading charterers of tanker industry require utmost care and practice during inspection, vetting and screening with respect to the ship energy efficiency. For instance, the OCIMF (Oil Companies International Marine Forum) requires SIRE (Ship Inspection Report Programme) inspections or more popularly known as vetting inspections in tanker industry. In the inspection, the performance of ship energy efficiency instruments are also checked along with safety and environmental protection concerns.

This should be done using an established method, preferably an international standard, such as the Energy Efficiency Operational Indicator (EEOI), which is proposed as the primary monitoring tool in SEEMP (IMO, 2012).

3.3 Energy Efficiency Operational Indicator (EEOI)

Within the SEEMP, the EEOI is listed as a recommended method for measuring energy efficiency improvement and the IMO has also provided guidelines for its use. However, the EEOI is not a mandatory measure, and it does not need to be calculated and results do not need to be public information. However, the EEOI results may offer companies a method of demonstrating their energy efficiency performance to the public and thus it may be beneficial to share the results.

The EEOI enables operators to measure the fuel efficiency of a ship in operation and to gauge the effect of any changes in operation, e.g. improved voyage planning or more frequent propeller cleaning, or introduction of technical measures such as waste heat recovery systems or a new propeller.

The EEOI is similar to the EEDI in that it is a calculation that quantifies the amount of carbon emission emitted dependent on the useful work done by the ship. However, rather than being based on fuel consumption for the designed ship, actual fuel consumption record for each voyage is used. By averaging the EEOI for many voyages (the rolling average) then operational performance over different useful time periods can be considered along with the performance of sister ships and fleets.

The EEOI value can be improved by reducing fuel consumption for the same voyages, or by increasing the amount of cargo carried and/or utilization of the ship (i.e. reduced time in ballast and in port). There are many uncertainties that remain with the EEOI, particularly with its benchmarking, and for this reason it has not been made mandatory and improved methods for quantifying operational performance are still being considered.

The voyage energy efficiency calculation using EEOI

In order to establish the EEOI, the company should set the procedure to be in force and the type of voyages to which the procedure would be applied. Ballast voyages as well as the voyages performed for transport of cargo will also be included. Voyages for the purpose of securing the safety of a ship or saving life at sea, as well as voyages which are not used for transport of cargo, such as voyage for docking service will be excluded. The following steps are to be completed for every ship:

- Define the period for which the EEOI is calculated;
- Define data sources for data collection;
- Collect data;
- Convert data to appropriate format; and
- Calculate EEOI.

Smaller EEOI value means a more energy efficient ship:

$$EEOI = \frac{\sum_j FC_j \times C_{Fj}}{m_{cargo} \times D}$$

Figure 3.6 EEOI calculation

For a number of voyages or voyage legs, the indicator is expressed as presented below:

$$AverageEEOI = \frac{\sum_i \sum_j \left(FC_{ij} \times C_{Fj}\right)}{\sum_i m_{cargo,i} x D_i}$$

Figure 3.7 Average EEOI calculation

Where:

- *j* is the fuel type.
- *i* is the voyage number.
- *FC ij* is the mass of consumed fuel *j* at voyage *i*; _
- *CFj* is the fuel mass to CO2 mass conversion factor for fuel *j*;
- *m*cargo is cargo carried (tonnes) or work done (number of TEU or passengers)
- *D* is the distance in nautical miles corresponding to the cargo carried or work done.

Is the EEOI the right indicator to demonstrate operational performance?

The usability of EEOI has limited relevance in the context of technical energy performance monitoring. If one measures and averages the EEOI over a long period, the EEOI would become less sensitive to voyage-related fluctuations that are beyond the control of the ship's operator. Even in this case, the EEOI would not be capable of capturing small energy efficiency improvements that the ship has taken, the so-called technical efficiency. EETI, a metric that corrects for the dominant sources of efficiency variability that are outside of the owner/manager's influence (speed and utilization), was shown to produce a more narrow-banded distribution than EEOI (consistent for a fleet of technically similar ships), and trends consistent over time with low average rates of performance deterioration (consistent for a fleet of aging ships). One issue which complicates EETI is its calculation and normalization, as the EETI must be determined for a reference condition and requires a conversion relating speed and fuel consumption that if incorrect can misrepresent performance/efficiency at high or low speeds. As has been highlighted in many other publications, depending on the ship type and its machinery, the relationship between fuel consumption and speed is not always well captured by a simple cubic relationship. In such instances, the speed factor may be calculated using a more sophisticated mapping of the relationship between speed and fuel consumption if the data are available. Similar consideration may be given to the adoption of Admiralty formula which is unable to monitor power changes due to large draft changes in modern hull shaped vessels.

Chapter 4

Performance Monitoring Data Acquisition and Processing

4.1 How the Performance Monitoring System works

The Performance Monitoring System allows deep insight into your vessel's performance. It works by gathering consumer signals and displaying real-time data on the bridge, in the engine control room or headquarters. By installing one or more mass flow meters, fuel consumption can be monitored closely in real-time. The main objective is to measure the flow of fuel before and after the engine and/or generators. When you combine the consumption data with measurements of actual speed and position (based on speed log and GPS signals) you are able to directly measure the fuel efficiency. If you require more detailed readings, additional flow meters can be installed, a propeller shaft torque meter, speed log, anemometer, gyro, motion sensor and power meters on generators, and get for instance KPI's (Key Performance Indicators) for engine and hull performance calculated and visualized.

4.2 Big Data Analytics

Shipping industry handles a vast amount of data which is crucial in the time of any incident. The ships in future will be in need of Big Data Analytics for efficient condition monitoring, auto-piloting, freight tracking, ship building etc. Big data analytics (Mishra, 2017) are related to data in large volumes, of different varieties, and at high velocities because the manual daily reports for a ship are replaced with the data directly obtained from the machinery. The data diversity is changed from several times per day to several seconds. The advancement of Big Data will enable the ship to communicate with another through intelligent condition monitoring systems and engines. Thus, Big Data Analytics enhances the safety as well as the efficiency of the maritime industry.

Big data can be used to determine patterns and predict outcomes that can be used in various areas of shipping, from operations and chartering till the regulatory environment and energy saving. The participants seem to be aware of the usefulness of the vessel big data in the case that they can service the shipping business model as shown in figure (4.1) and 9 out of 11 agree with that statement.

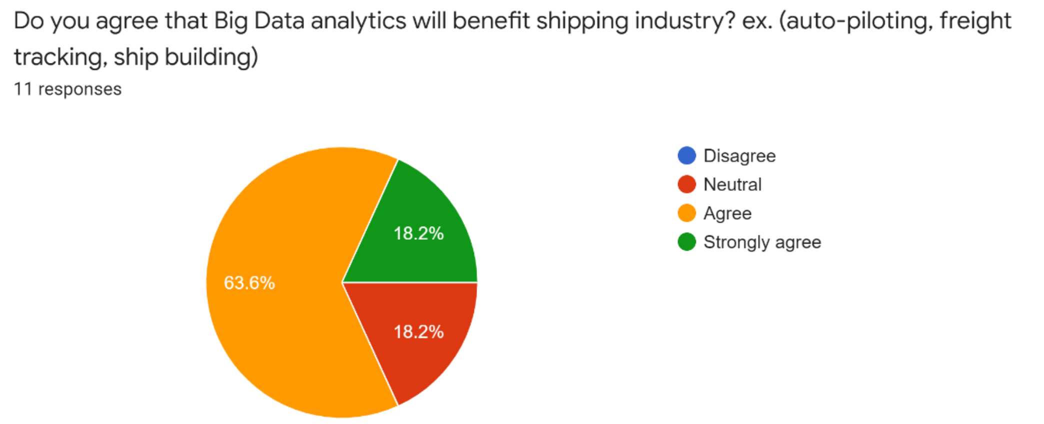


Figure 4.1 Delphi survey “Do you agree that Big Data analytics will benefit shipping industry?”

The participants also seem to be fully aware of the importance of the vessel data in the case that they can be used by intelligence technology and are willing to adapt to any new one to automate processes and functions on board the vessel figure(4.2).

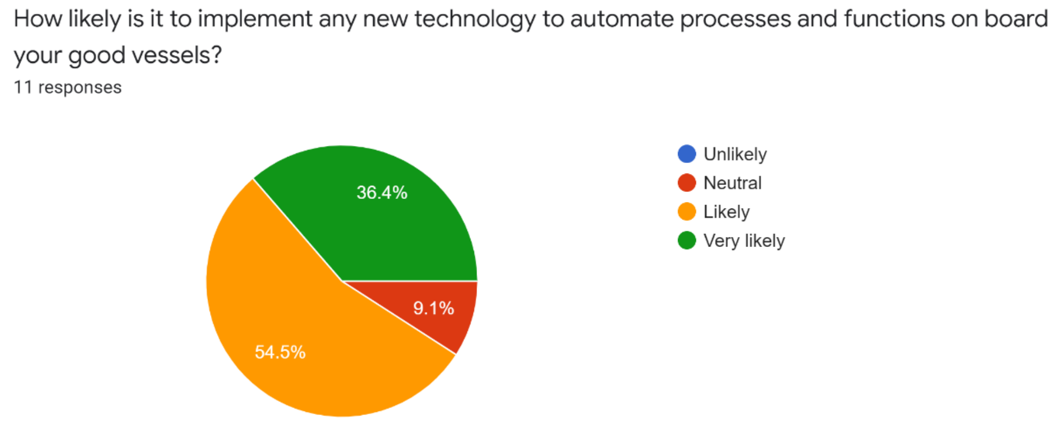


Figure 4.2 Delphi survey “How likely is it to implement any new technology to automate processes and functions on board your good vessels?”

Big Data Characteristics

Big data covers information from various sources i.e. sensors. There are many difficulties associated with capturing, sorting, analyzing, and managing data. Big data has four main characteristics and referred to as the 4V’s (Volume, Variety, Velocity and Veracity).

- Volume refers to the massive quantity of the data. Nowadays, sensors produce a massive amount of data in terabytes, petabytes and beyond.

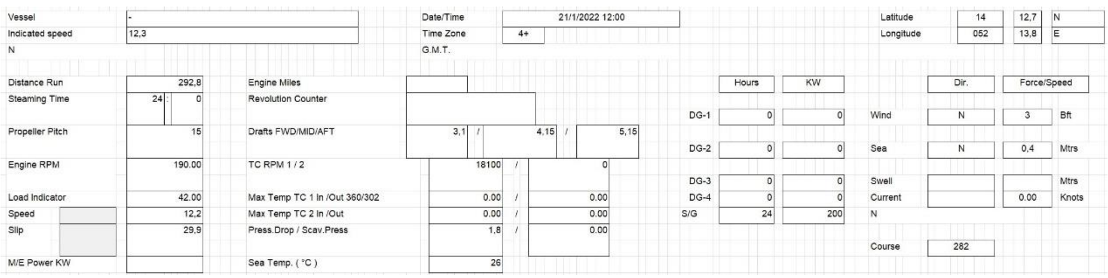
• Variety refers to the form of the data. In big data, the datasets are stored across in multiple formats. Data variation differentiates big data from traditional data.

• Velocity defines the speed of the data creation and movement. The data is created at different rates and must be stored for processing. Generally, a huge amount of data is created in real-time and data flow rates are themselves increasing rapidly.

• Veracity refers to the data accuracy and trustworthiness. Datasets from different sources may use different scales to measure the same variable and this raises issues of how to maintain data quality. Veracity needs to be addressed and maintained throughout the data lifecycle. (IBM the 4Vs ,2016)

4.3 Data Gathering

In the data acquisition, the information and data of ship fuel consumption are acquired mainly from daily reports of the vessel. These reports are mostly 'noon reports', that are recorded each day at noon whilst full away sailing at sea. There are also "port reports" and other reports that are recorded on approach to port, on arrival, daily in port, on departure. This Daily Data is based on real data which is recorded daily by crew and collected by head office of the company. The daily data of the ships includes the information below:



Vessel: -
Indicated speed: 12,3
N
Date/Time: 21/1/2022 12:00
Time Zone: 4+
G.M.T.
Latitude: 14 | 12,7 | N
Longitude: 052 | 13,8 | E

Distance Run: 292,8
Steaming Time: 24 : 0
Propeller Pitch: 15
Engine RPM: 190.00
Load Indicator: 42.00
Speed: 12,2
Slip: 29,9
M/E Power KW:

Engine Miles:
Revolution Counter:
Drafts FWD/MID/AFT: 3,1 / 4,15 / 5,15
TC RPM 1 / 2: 18100 / 0
Max Temp TC 1 In /Out 360/302: 0.00 / 0.00
Max Temp TC 2 In /Out: 0.00 / 0.00
Press.Drop / Scav.Press: 1,8 / 0.00
Sea Temp. (°C): 26

	Hours	KW
DG-1	0	0
DG-2	0	0
DG-3	0	0
DG-4	0	0
S/G	24	200

	Dir.	Force/Speed	
Wind	N	3	Bft
Sea	N	0,4	Mtrs
Swell			Mtrs
Current		0.00	Knots
N			
Course	282		

Figure 4.3 Daily report using excel

• Date and Time

• Voyage Number

• Position (Lat., Long.)

• Port name

• Engine Room

• Average Speed

• Beaufort number

• Wind direction

• Loading condition

• Operation Type (Sailing, Port Stays (Loading or Discharging Operations), Waiting (Anchorage or Drifting)

• Drafts (forward, mean, aft)

• Next Port, Miles to port and ETA next port

• Main Engine Fuel Consumption

• Auxiliary engines consumption

• Boilers fuel oil consumption in addition to daily reports, ship particular information and sea trial conditions are used to compare to the performance of ships with its actual performance and the other ships.

In order to observe and evaluate the changes in the operation systems of ships, which sail in various conditions, acquiring daily data is very important. Daily reports are a major indicator of the amount of fuel that ships consume in varied weather conditions and at varied sailing speeds. They provide valuable information on the fuel consumption of ships under various loading, speed and weather conditions that can be utilized for fuel consumption prediction and forecasting.

Use of the data

Once the data is acquired and displayed, use it to:

- Optimise operational efficiency by testing your trim tool
- Implement and maintain your SEEMP
- Create KPI's for each voyage
- Evaluate improvement projects before fleet roll out
- Monitor the ship's consumption trend over time to improve your maintenance planning

And most importantly let the crew get data insight to increase crew awareness as well as improving knowledge of operational performance.

<u>Performance Indicators KPI</u>

Bazari (2007) asserts that key performance indicators (KPIs) for performance benchmarking/rating should have the following characteristics:

- Be indicative of ship performance
- Show appropriate and consistent variations with ship size

- Require minimal measured data
- Be unambiguous and easy to understand

This is expanded on by Deligiannis (2014) to include also:

- Dimensionless number
- Unique for an individual vessel
- Be easy and accurate to determine from common speed trial data
- Inclusive of hull resistance effects (wave, wind, swell, current) – Statistically constant
- Capable of providing diagnosis on efficiency of main engine and power transmission system
- Specific for crew to grasp
- Measurable, achievable, realistic and timely

These characteristics are meaningful in providing background information. Using the KPIs as main indicators of the vessels performance, any change in condition or operation that affects the performance, will result in changes in the KPIs. As all readings are available centrally, running conditions of monitored vessel components can be checked right away, and troubleshooting, corrective and optimising actions can be identified a lot easier compared to manual visual inspections, potentially leading to savings in fuel as well as crew resources.

KPIs Evaluation with PMS

Using the vast trove of information derived from performance monitoring systems, performance management analyses interpret data into meaningful KPIs that can then be utilized by an operator, manager or the ship's crew to improve the vessel's operational performance.

KPIs can also be used to benchmark vessels in a fleet. The benchmarks are provided as feedback to operators and crews on a regular basis and the information is used to promote best practices across the fleet with regard to energy efficiency.

The derived KPIs create dashboard displays that provide an overview of the vessel's performance. Indicators include vessel base load and total energy consumption, main engine condition, added fuel consumption, hull and propeller condition management and trim optimization.

The dashboard information is then used by the owner as decision support for actions taken to improve a vessel's performance and efficiency, always with a focus on safety.

4.4 Data collection: low-frequency vs high-frequency SPM

There is an old and recurrent dilemma for the shipping companies: Ship performance analysis based on noon-to-noon report (manual readings/noon-reports) or based on a ship performance monitoring system (SPM) collecting high frequency data (automatically or semi-automatically). While some companies are very open to innovation and at the forefront of technological evolution, others are much more traditional and conservative in terms of adopting new technological solutions.

The application of the high-frequency data collected by SPM system gives the chance of a better and more accurate results due to the possibility of using actual measured data with selected filters for any conditions (wind, ship´s speed, etc.). This is not possible with low-frequency data available on noon reports to reach this high level of accuracy. Unfortunately, noon-reports have several limitations, especially when using for monitoring ship operational performance. The frequency of recording, required to human intervention, and provide restricted number of features are some of them (Erto et all., 2015). Human error can happen at any measurements and at any time if the report completion is not automated. Other issue that may occur when the data collection and reporting is not made automatically is the difficulty of doing the data entries at same time every day, this may cause inaccurate information, for example for distance sailed daily, total revolution per day, etc. More will be discussed regarding human error in later chapter

In addition, the possibility of keeping the historical data stored and apply powerful data-management tools, it permits the companies to make ship´s models and predict the vessel's behavior to take better decisions and possibly get greater savings. As an example, it is possible to analyze the historic data for the ship's fuel and speed data for the last 6-12 months to get valuable information (by applying filters on high-frequency database to avoid wrong readings, unsteady data which could invalidate the analysis).

There is no question that more data reduces random errors and thus increases accuracy, but data frequency is only half of the "data acquisition" equation, the other is data quality. The real issue is: Can once per day data acquisition be accurate enough for performance monitoring if data quality is high, especially if combined with a good hydrodynamic model for the data processing? From a ship operator perspective is it viable to invest in sensor technology and sampling frequency, or crew training and real-time input checking?

As seen in the chart most of the companies use an automated continuous monitoring system while only 3 still use noon reports. While the sample might be kind of low it still shows the tendency of the Greek companies to invest in shipping performance monitoring tools. We can also make an observation that the low usage of noon reports is due to having no data of smaller shipping companies. These companies probably would not be able to sustain such expensive systems.

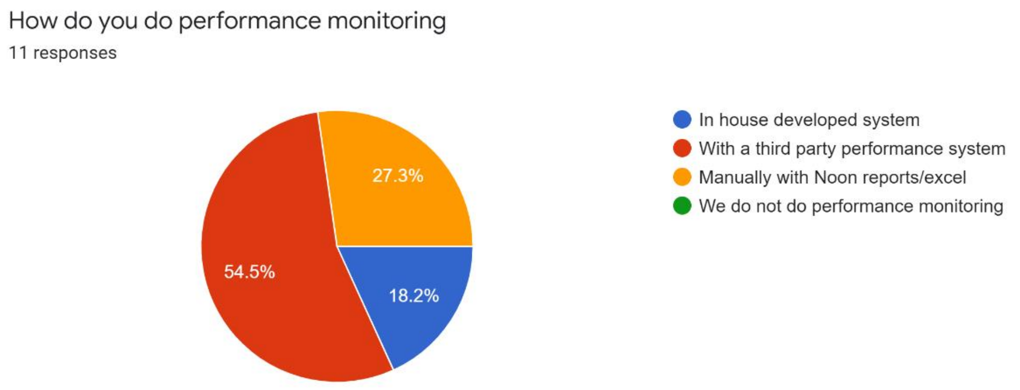


Figure 4.4 Delphi survey “How do you do performance monitoring?”

They also agree with the statement that this will change the way they operate their vessels in a daily basis. We can also speculate that noon reports might change their form to a more digitalized one or a hybrid system using both.

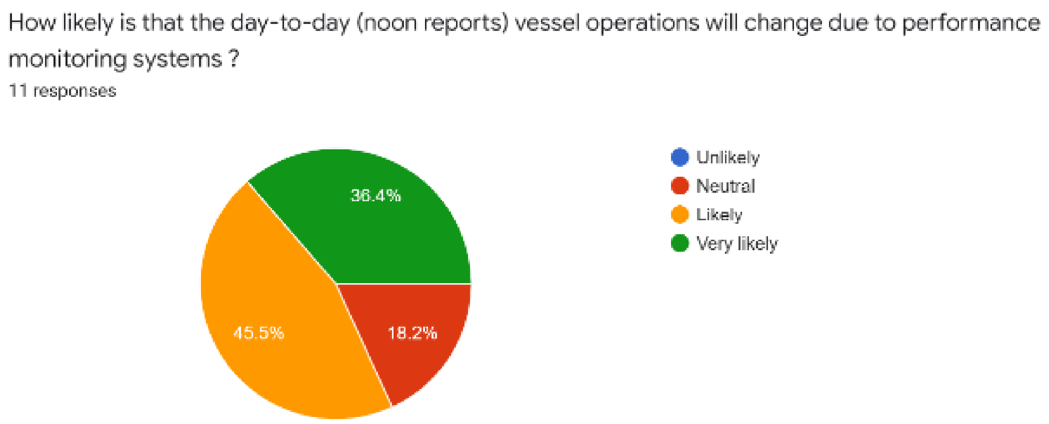


Figure 4.5 Delphi survey “How likely is that the day-to-day (noon reports) vessel operations will change due to performance monitoring systems?”

Smart filtering of the data

The data from the sensors are not always steady, so in order to get sensible and understandable instant values for the operators, the SPM are applying smoothing algorithms to calculate the average of the data. Only smart processing leads to good insight. This starts with filtering out data with high error or uncertainty. These simple and explicit filtering specifications of ISO 19030 unfortunately lead to too many data sets being filtered out unnecessarily.

The ship performance is highly influenced by the environment conditions. The wind and the waves might increase the ship´s resistance which will cause a consequent increasing on the fuel consumption due to extra power required. A known issue in performance monitoring is the correction for added resistance in waves. Contrary to researcher and vendor lore, there is no cheap and simple way to predict added resistance in waves. Even worse, the traditional estimates by "experienced crew" have been shown to be way off objectively measured wave heights. It is possible to analyze only the ship performance for good weather condition, discarding the bad weather conditions. We can set up the wind limit at "x" knots, so data above this limit is removed for the corrected fuel consumption analysis shown in the performance monitoring tool

The pragmatic approach of ISO 19030 has been to filter above low sea states. There seems to be a silver lining on this particular horizon. "Rune Gangeskar" a sensor development manager describes radar-based wave and current capturing. This is an important milestone on the way to better correction methods for changing ambient conditions. With such detailed and objective wave information, advanced numerical methods can then predict added power requirements in these sea states.

Smarter data processing could also help with human factor issues. Using data from different sensors or simulations, to crosscheck manual input results. The idea is to identify implausible data logging immediately, fixing sensor failures or human error on the spot.

Data Quality control

It is essential to pay attention to the effect that any filtering, correcting or transforming algorithm acting upon the quality of the data that may have on them. He level of filtering is subjective and requires balance between removing inaccurate data points that will incorrectly skew the results and preserving valuable information about the system physics (Aldous,2015). The wider array of data fields collected using CM system can introduce possibilities of data quality control checks.

4.5 Fleet Performance Monitoring

A shipping company with a large number of vessels in the fleet would try to establish some sort of automation in the evaluation of the different ship's performances to avoid time consuming manual analysis work. Data handling routines to avoid drift in timing of the signals, eliminating noisy signals and setting up boundaries for valid performance evaluation results are suggested.

In such a system it will not be possible to have manpower to supervise manually each individual ship. It should be possible to extract reports on each ship when necessary. Otherwise, boundaries giving alerts of when the ships performance should be examined would have to be determined in the system. It should be possible to handle changes in the data e.g., voluntary changes by the crew or faults in the signals like spikes etc., without giving alert.

Automatic data collecting, filtering and transfer of data to a central database allows the ship owners to follow up the performance on the entire fleet. Furthermore, combining this database with a tailored dashboard system will make key performance indicators of the entire fleet available for the management and for making strategic performance decisions. Comparison within the fleet identifies the low efficiency vessels, making it possible for planning corrective actions accordingly.

To follow up the performance of the fleet is essential to business and should have a strong focus in every shipowner's mind. Some owners may want to develop their own tailored analysis system, while other may want to team up with suppliers of such systems.

Chapter 5

Fuel Consumption Report methods

5.1 MRV Monitoring Regulation

Further incentive on the collection of data may come from rules related to fuel consumption and emission monitoring which are being discussed by the European Commission in the form of its Monitoring, Reporting and Verification (MRV) scheme. Upon approval of the European Parliament and Council, ship owners will have to monitor and report the verified amount of CO2 emitted by ships above 5,000 gross tonnage on voyages to, from and between EU ports regardless of flag as of January 1 2018. The MRV scheme is the first step of the EU's strategy to reduce CO2 emissions from maritime transport. The two consecutive steps are likely to be to set GHG reduction targets for the maritime transport sector and introduce further measures such as market-based measures in the medium- to long-term (European Union MRV Regulation).

5.2 Bunkering report methods

The cost of a running a vessel breaks down into fixed and variable or voyage costs. Voyage costs usually include bunker consumption, port costs, channel tolls and cargo handling costs. Bunkering is the largest cost item for shipping lines and often exceeds 40% of total cost. Therefore, one of the main parameters to be reported is the fuel consumption on board. In this regard, there are mainly two methods used by the shipping companies to record the fuel consumption on board:

- Bunker Delivery notes (BDN) + Tank Soundings (checking the Remaining Fuel On-Board, ROB)
- By flow meters

Tank Soundings + BDN

Tank sounding (by gauges or manually) is common practice in the sector. Sounding frequencies on a ship, however, differ from company to company and depend on company policies and the nature of operations on board. In regards to fuel oil tanks, lube oil tanks and diesel oil tanks these must be sounded twice a day, once in the morning and once in the evening, and recorded in the event of a leak or any other emergency related to the oil content of tanks. The depth of the fluid from the surface to the bottom of the tank is thereby derived first and the corresponding volumetric quantity is then calculated. Sounding tables are necessary to convert tank level to volume. Typically, this is available in an approved form through the ship stability documentation. Fuel density information is necessary to calculate the corresponding mass. This is available from the BDN, however blending on-board may cause slight complications. Fuel temperature will also affect volume. It should be noted that both the Chief Engineer and the Master should sign for acceptance the Bunker Delivery Note issued by the bunker barge only if they agree with the figures received.

Measuring the fuel tank levels can be done in several ways: electronic, mechanical and manually.

Electronic sounding: In electronic sounding, a sensor is used which senses the pressure inside the sounding pipe or by sensing the tank pressure and sends a signal to the receiver. Here the signal is translated to the tank's content value with the help of a PLC circuit. The value is displayed using electrical operated servo gauge or electrical capacitance gauge.

Mechanical sounding: Mechanical provisions are made inside the tank so that the quantity of tank can directly be read through a level marker or an indicator or a float level sensor. In the tank a float can be attached to a pointer through a pulley. As the level varies pointer readings will change accordingly. A level gauge glass is also attached to the tank to read the quantity of the fluid inside the tank. The gauge may also be a pneumatic/hydraulic operated gauge or differential pressure gauge.

Manual sounding: In this method, a sounding tape is used with a heavy weight bob attached to one end of the tape using a strap hook. It is the most commonly used method used for calculation of tank capacity. If the capacity inside a tank is more, free space of the tank is measured to calculate total capacity of the tank. This method is called ullage measurement.

Flow meters

The other approach to monitor the fuel consumption of a ship can be by means of flow meters. These meters allow for determining the amount of fuel that is flowing through the respective pipes and represent the actual fuel usage. The fuel flow is often measured directly (by volume, velocity or mass) or indirectly (inferential) by pressure. In order to monitor all the fuel oil used on-board, all input flows of to all consumers on-board would actually need to be monitored.

A wide variety of flow meters is available, such as electronic, mechanical, optical and pressure based. These below are the different types of flow meters used for fuel consumption monitoring.

Electronic flow meters (volume) Electronic fuel flow meters (with digital display) are meters that are fitted to the main engine fuel supply and monitor fuel consumption constantly. The values recorded by the flow meters are calculated in the fuel flow calculation unit and form the basis for all other functions in the system (CE Delft, 2009).

Velocity sensing flow meters (velocity) Velocity sensing flow meters are measuring the flow rate of the fuel based on the velocity.

Examples of these meters are turbine flow meters and ultrasonic meters.

- *Turbine flow meters* are common in bigger ships. Turbine flow meters measure rotational speed of a turbine in the pipe which can be converted to volumetric flow. In many cases, fuel flow to the settling tank or day tank is measured rather than net flow to the engine which requires two flow meters (supply and return flow).
- *Ultrasonic meters* measure flow velocity from observations on a sonic wave passed through the flowing fluid, that exploit either a Doppler effect or time-of-flight principle.

Inferential flow meters (pressure-based flow meter) Inferential flow meters do not sense flow rate through the direct measurement of a flow variable (such as volume, velocity or mass) but estimate flow by inferring its value from other parameters (differential pressure, variable area) They measure differential pressure within a constriction, or by measuring static and stagnation pressures to derive the dynamic pressure. (University of Exeter, 2008a).

Optical flow meters Optical flow meters use light to determine flow rate. Small particles which accompany natural and industrial gases pass through two laser beams focused a short distance apart in the flow path. By measuring the time interval between pulses, the gas velocity is calculated.

Positive displacement flow meters (volume) These meters measure flow-rate-based on volumetric displacement of fluid. They remain accurate at small fractions of rated capacity but have relatively high head-losses. Therefore, they are generally suited to higher flowrates. Mechanical parts of the meter are exposed to the fuel. If these were prone to wear or failure, such an event could potentially cause obstructed fuel flow. For this reason, the fuel meter should be installed with a by-pass leg. Examples of positive displacement flow meters include: oval gear flow meters, reciprocating piston flow meters, and nutating discs (wobble meters).

Mass sensing flow meters (coriolis) Mass flow meters are meters that measure the mass flow rate, which is the mass of the fluid traveling past a fixed point per unit of time. Examples are the coriolis meter, linear mass meter, thermal mass meter. The coriolis meter measures the force resulting from the acceleration caused by mass moving toward (or away from) a center of rotation. Since mass flow is measured, the measurement is not affected by fluid density changes. Coriolis mass flow meters can measure flow extremely accurately, so they are often used to measure high value products or the introduction of fluids that affect the production of high value products.

Accuracy

The accuracy of tank sounding, estimated at 2-5% (Saniship), is very sensitive and depends on the means by and conditions under which the sounding is carried out. Furthermore, larger ships have several fuel tanks, with different quantities, temperatures and fuel qualities. The accuracy of tank readings may be limited by the ship's motions, trim, etc. Manual sounding may be very inaccurate at sea, due to the ship´s movements, *IMarEST (2012)*. Another way in which inaccuracy may occur is because the tank monitoring devices, such as gauges, that need to be regularly calibrated to ensure accuracy and this may currently not always be done as there are no regulations for this, *CE Delft (2009)*.

The bunker delivery notes (BDNs) have an accuracy level of 1 to 5% (Bunkerspot, 2009) and according to Cardiff University (2013a; 2013b), disputes over the quality and quantity of fuel is common between bunkerers and ship operators. The BDNs also provide information on the quality of the fuel that is bunkered. This information is necessary for the calculation of the emissions related to the bunker fuel consumption.

Fuel flow meters have the highest potential accuracy. Depending on the technology selected, their accuracy can be an order of magnitude better than the other systems, which typically have errors of a few percent. A wide variety of flow meters is available, such as electronic, mechanical, optical and pressure based. Electronic fuel flow meters provide an accurate and reliable method of measuring fuel consumption in marine diesel engines. Their accuracy is ±0.2%, *CE Delft (2009)*. Coriolis flow measurement technology measures the mass flow directly, eliminates the need for any mathematical conversions, and is very accurate (between 0.05 and 2%). In general, the accuracy of flow meters may vary depending on the installation, maintenance and calibration requirements of the system and on-board operator competence, *IMO (2012)*

Investment Cost

Bunker delivery notes and tank soundings have the lowest investment cost, *Delft March (2013)*. The former because no equipment is needed, the latter because the majority of ships have tank sounding systems. However, unless tank sounding is automated, these systems have higher operational costs than fuel flow meters monitoring because manual readings have to be entered in monitoring systems. Moreover, manually entering data in systems may result in errors. The costs of verification could therefore also be higher.

The costs of equipment for the different flow meters vary largely. Electromagnetic flow meters for In-Line style version cost $1,200 to $5,000 but Coriolis meter can run upwards of $9,000 or more (maxmachinery.com).

For ship owners two direct impacts are conceivable. On the one hand, they may have to incur costs for purchasing and installing additional equipment as well as for monitoring and reporting data. These costs could vary between the approaches. On the other hand, through this work they might identify potentially new fuel consumption savings opportunities if the data monitored provided new and useful insights.

Which method is better to use?

For the shipping market as a whole, bunker monitoring may result in more transparency about the fuel-efficiency of ships, depending on the circumstances and on what is being monitored and reported. Charterers could take better-informed decisions if ship fuel consumption data were publicized.

By providing real time feedback on fuel use, fuel flow meters monitoring provides ship operators with the means to train their crew to adopt fuel efficient sailing methods and to optimize their maintenance and hull cleaning schedules. The latter can, to a lesser extent, also be provided by tank soundings. However, bunker delivery notes are unlikely to provide this benefit as bunkering's may be several weeks (and hence several voyages) apart. *Delft, March (2013)*

Except for bunker delivery notes, all systems allow for both time-based and route-based (or otherwise geographically delineated) systems. Because a ship can sail for several weeks after one bunkering, and is not restricted to routes or area, bunker delivery notes cannot be used to monitor emissions in a geographically delineated system. *Delft, March (2013).* A last note is that all systems can monitor CO2 and provide estimates of SO2 emissions. Only direct emissions monitoring can also monitor other non-CO2 exhaust emissions, Delft, March 2013.

Even though fuel flow systems are the most accurate they are also considerably more expensive than tank sounding systems and as seen in the chart fewer Greek shipping companies have them regardless their size of fleet, figure (5.1).

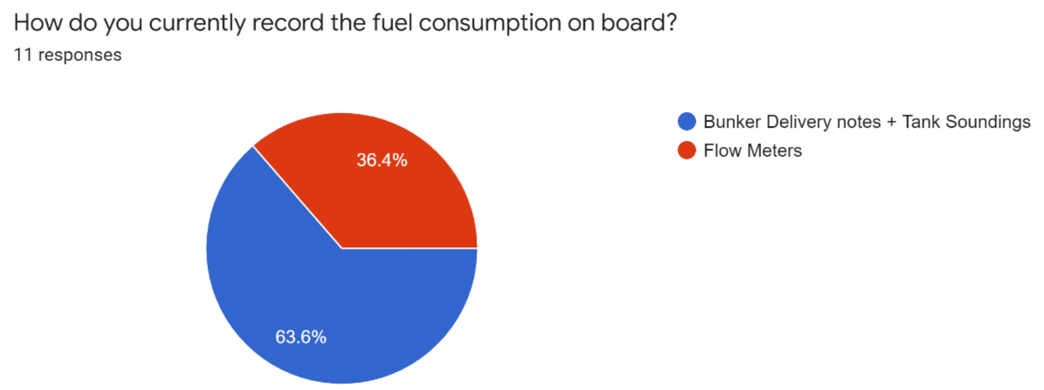


Figure 5.1 Delphi survey "How do you currently record the fuel consumption on board?"

Chapter 6

Operational Ship Energy Efficiency Measures

6.1 Speed Optimization

Speed is an important element in maritime transportation. High-speed ships are required with the growth of the world trade volume. The high ship speed provides economic benefits such as the receipt of the cargo in time, lower inventory costs and increasing trade volume per unit time. However, the increase in fuel prices and the environmental problems have brought a new perspective to ship speed.

Therefore, optimizing the ship speed has become an important research topic. The optimum ship speed is not the lowest speed, but the speed determined by considering all the parameters affecting the voyage plan. Although the speed reducing is profitable in terms of fuel consumption, it must be balanced in line with other commercial and operational needs. A very low speed could deteriorate the vessel engines and shorten the lifespan of vessels. On the contrary, a high sailing speed would increase the fuel consumption cost. For instance, increasing the sailing speed by just 20% could increase the fuel consumption cost by up to 50% (Ronen, 2011). Such an increase in the fuel consumption cost may not be desirable, as the fuel consumption cost may account for about 75% of the total operational cost of vessels (Ronen, 2011).

Among the tactical-level decision problems in shipping, the vessel scheduling is the most intricate one (Dulebenets et al., 2019). Each vessel schedule contains the information regarding port arrival times, waiting times, handling times, departure times, etc. Moreover, each vessel schedule also has to incorporate some other important considerations, such as sailing speed, environmental sustainability issues, customer preferences, and others. The sailing speeds may be adjusted after the vessel schedules are published as long as the planned port arrival times are not violated.

The optimum speed for voyage should be determined taking into consideration all costs to create an appropriate balance between low-speed sailing, fuel economy and market demands. Because market demands show a continuous alteration, the optimum speed is not constant during the voyage. The optimum speed of the ship should be updated in accordance with the information obtained from related parties (maritime companies, ship agents, ship charterer, etc.).

Reducing the speed of the ship is the most efficient method in terms of fuel economy. There is a non-linear relationship between ship speed and fuel consumption. The ship speed has a major impact on fuel consumption due to its third-order function with the power output required for propulsion

What is Slow Steaming?

Slow steaming is a process of deliberately reducing the speed of cargo ships to cut down fuel consumption and carbon emissions. When a ship is slow steaming, it reduces its travel speed down to somewhere between 12 and 19 knots. This can sometimes mean half the speed of the normal 20 to 24 knots. This results in reduction of engine power and fuel consumption.

Slow steaming has successfully helped ship owners in reducing the amount of fuel needed to run ships, which in turn has led to significant decrease in carbon emissions. It has also been adopted by majority of companies and ship owners in order to survive in the tough times of rising fuel prices and financial recession. The pressure to reduce carbon emissions and improve ship efficiency has also pushed shipping companies to implement slow steaming on their ships.

Benefits of Slow Steaming

There are primarily financial, environmental, and performance-related benefits. In order for shipping companies to stay afloat when fuel prices rise and when recessions occur, slow steaming becomes more of a necessity than an option. However, the decision for slow steaming is also made by companies to become environmentally responsible.

1. Slower speeds generally improve vessel fuel efficiency allowing carriers to save on bunker, a volatile and expensive cost item. As bunker prices have increased considerably in recent years, slow steaming has become more appealing to carriers.
2. As a second slow steaming benefit, reduced fuel consumption directly corresponds with lower levels of GHG emissions, namely CO2. Despite other emission-reduction options like hull design changes, routing, propeller polishing and kite systems, slow steaming represents an immediate approach for carriers to improve their environmental impacts. According to a study conducted by environmental group, (Seas at Risk), a 10% reduction in the speed of world fleet would result in a 19% reduction in CO2 emissions.
3. Slow steaming also enables carriers to absorb excess fleet capacity during periods of slack demand. As an example, throughout 2009 and 2010, ocean carriers took delivery of vessels ordered before the economic downturn, nearly doubling available capacity. Since slower vessel speeds essentially reduce capacity on a service string, carriers can deploy excess vessels to the string to maintain capacity under slow steaming.
4. Schedule timeliness represents a fourth primary benefit of slow steaming. Delays in ocean shipping can arise from a broad spectrum of sources such as port congestion, terminal productivity, weather and mechanical issues. Container ships, on average, spend 6% of their time, every year, waiting at

anchor due to delays at port (Wartsila 2019). Uncoordinated ship-to-shore operations often results in congested ports and further raises the risk of accidents. Reduced vessel speeds and longer transit times conceptually enable greater carrier flexibility to adjust speeds to overcome delays, allowing better schedule adherence. For shippers, better schedule reliability can reduce uncertainty and subsequent safety stock needs while also saving fuel.

Concerns and challenges

With the above benefits, carriers appear to be standing firm on slow steaming practices. However, shippers have voiced significant concerns over the parity of the benefits, mainly regarding longer transit times. First and foremost, longer transit times directly increase shipper in-transit (pipeline) inventory levels. Also, even though carriers contend that slower vessels can improve schedule reliability and subsequently lower safety stock needs, speed is often more important than reliability for ocean shipping.

Another concern is that slow steaming can foul up the turbochargers. This results in a reduction of the ship’s efficiency. Turbochargers that operate beyond the range they have been designed for will lead to less air flow. With this reduction comes the potential for more carbon deposits. The increase in these deposits on the fuel injectors can negatively affect the ship’s performance. Other fouling issue is of the exhaust gas economizer. The result of this is that there is less capacity and more danger of a hazardous soot fire breaking out.

Running a marine engine at low loads is not something that shipping vessels have been designed to do. Traditionally main engines are designed to run between 70 % to 85 % load range during continuous operation. The matching and designing of all the auxiliaries is based on this load range operation. As low speed marine engines are not traditionally suited for prolonged slow steaming, a number of precautions need to be taken in case slow steaming operations are adopted without modification.

Impact and Implementation

The impact of slow steaming on both shippers and carriers is essentially a mixed bag. While there are financial, environmental, and efficiency benefits that can be gleamed, there are also precautions that need to be taken so that damage is avoided.

There is also a time factor that is impacting shippers and carriers. The process of slow steaming increases the duration of transit time of a vessel. This impacts customers, who will see their goods become delayed and need to be educated.

When freight rates are high shipping companies have a high profit margin, so from an economic perspective energy efficiency is relatively less important than completing as many legs per year as possible. However, if freight rates are low shipyards compete for clients and if fuel costs are also high ship owners are more willing to build more efficient vessels and opt for slow steaming as a very efficient measure. Since the financial crisis of 2008, the speed of Panamax containers and large containers has dropped from 25–27 knots to 20–22 knots.

6.2 Fleet deployment in liner shipping

In a market where low freight prices are squeezing the margins to a minimum, it is safe to assume that every ship owner would aim to run their fleet as optimum as possible in terms of fuel efficiency. An increased focus on environmental regulations and smaller profit margins in the shipping industry make fleet performance and efficiency key topics within the maritime world.

The tactical-level decision problems, which are made three to six months in advance, include port service frequency determination, fleet deployment, sailing speed optimization, and vessel schedule design. In order to reduce the waiting time at ports, a liner shipping company may increase port service frequencies. However, more frequent port visits would require deployment of a large number of vessels. Therefore, the liner shipping company will endure additional vessel operational costs

Several considerations are incorporated at the fleet deployment stage. The number of vessels in the liner shipping company's fleet (i.e., fleet size) is generally limited. In order to meet the existing demand, the fleet size may not be sufficient. In such cases, the liner shipping company has to charter vessels from other liner shipping companies' fleets, which incurs an additional cost (i.e., chartering cost). Moreover, based on the existing demand, the liner shipping company has to decide on the type of vessels (e.g., should the liner shipping company deploy mega-vessels that have large capacity or smaller vessels with lower capacity). Deployment of mega-vessels would result in economies of scale and would be suitable to meet high demand volumes. However, mega-vessels have high vessel operational costs and may cause some challenges for the marine container terminal operators, as they will be required to have a specific type of equipment in order to serve these mega-vessels.

6.3 Trim Optimization

Trim optimization is important to improve fuel economy and reduce emissions. The optimum trim is specific to the ship and depends on the ship's speed and draft.

The trim of the ship leads to hull resistance. Hull forms usually have been designed by taking into consideration the specific drafts. If the trim of the ship is set according to these drafts, the ship resistance will decrease. In some cases, if the trim is not suitable despite the low ship draft, much ship resistance will consist on the appropriate trimming situation whose ship draft is much.

The fluid pressure resistance which is formed by area of the ship under the water and the resistance which is caused by the waves during movement of the ship vary while the trim changes. Optimizing the ship trim improves fuel efficiency for the specified draft and speed. Trim changes are performed with load stacking, fuel distribution and the ballast changes. In addition to the ship, ballasting increases the fuel consumption because of increasing the ship's displacement. It is possible to provide economy up to 5% in fuel with trim optimization. (*IAMU 2014)*

There are some operational risks and challenges caused by the oversights of bending moments and shear forces of the trim optimization. In addition, the trim changes due to the consumed fuel and water during the sailing, the ballast exchange requirements, designing trim of the ship (such as the location of drains and scuppers) and the control of the vessel in bad weather conditions are some of the practical difficulties throughout the voyage

6.4 Weather Routing

In recent years, the routes, whose safe and energy-efficient are high, are emphasized instead of fast routing. The aim on weather routing is to achieve optimum speed in order to provide the voyage plan energy efficiency and to reduce fuel consumption by providing the safety of ship, crew and cargo.

Being the ship at the port on time and effective ship planning of the port constitute a part of the weather routing. The potential of performing weather routing reduces fuel consumption by up to 3% apart from time savings (Armstrong 2013).

Ship weather routing is defined as determining the optimum route by taking into account the weather forecasts, specific characteristics of the ship and sea conditions along the designated voyage. The optimum route designated for the voyage is considered as the route with safety and comfort, greatest energy efficiency, or the combinations of these factors under various weather conditions. Weather routing optimization aims to provide the expected time of arrival (ETA) with the minimum fuel consumption and sailing time based on the safety margins of the ship. Examining the actions of the ship in various weather conditions provides benefit both economically and environmentally. In order to achieve the fast and safe voyage of the ship at a low cost, its actions in various weather conditions have importance in terms of ship owners and ship's crew. While the serious rate decreases due to weather conditions, the power consumed by the ship and therefore the fuel consumption increase.

There are usually two parameters that affect the weather routing optimization: Voluntary and involuntary speed loss. Voluntary speed loss performance depends on the preferences of captain and navigator of the ship. The involuntary speed loss of the ship occurs due to the effect of sea and weather resistance on the ship. The ship resistance varies according to the weather conditions. The ship is exposed to strong environmental forces in heavy weather. Consequently, various dynamic factors lead to a decrease in ship speed. Increasing the ship resistance will increase the engine power required by the ship and hence, fuel consumption.

There are weather routing services provided by a number of companies to collect meteorological data, examine wind and sea conditions, evaluate ship responses in the predicted conditions and notify the route information should be followed based on weather conditions. The ship may get the weather routing information via e-mail or computer applications Furthermore, visual information sharing in a wide range including ship / ships and fleet management can take place with computer applications. The shortest distance between two points (ports) is not always the fastest due to the currents, wave height and winds. When the modern systems are integrated with the bridge computers, the fuel-efficient routing is possible according to real-time weather routing services.

In the survey, we asked the participants how efficient they believe each of these energy implementations are. As the chart shows the operators feel that speed optimization by reducing the speed of the ship is the most efficient method in terms of fuel economy. It follows by the weather routing which shows the importance of collecting and examining meteorological data. Last but not least energy implementations are voyage planning, optimized shaft and the cargo trim.

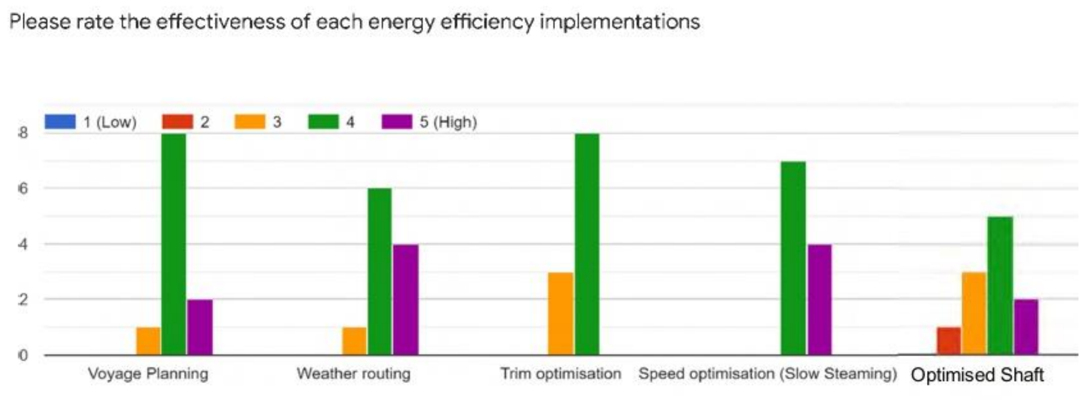


Figure 6.1 Delphi survey Effectiveness of each energy efficiency implementations

Chapter 7

The role of each party in optimizing performance

7.1 Energy Awareness

Energy awareness makes individuals and parties to draw on their knowledge and skills for ship energy efficiency. It also causes promoting motivation and focus or emphasis on daily operational activities. However, energy efficiency measures will require the cooperation of many parties. The departments and the individuals in the organization should reveal the necessary expertise in energy efficiency in order to overcome difficulties in implementing of measures.

The parties having a role in ship energy efficiency are described below:

Ship owner: Ship owner should make the optimum decision by keeping all the factors such as the investment decisions and operating costs related to the new technologies and techniques that can be implemented in terms of energy efficiency measures. However, the implementation of these technologies to the existing ships is often very difficult and may be costly.

In addition, the potential savings of new applications are less when compared to the investment risk. The implementation of appropriate technologies is more suitable for new ships due to the low-risk investment. In this case, the ship owner should save energy by increasing the operational efficiency of ships for existing ships.

Ship operation: The ship operation may be conducted by either the ship owner or the charterer that manage the ship for commercial use. If the ship is operated with a charter agreement, the charterer usually meets the fuel and port costs of the ship. Therefore, the voyage information (load information, estimated time of arrival (ETA) and voyage planning, etc.) are transferred to the charterer. The ship operator should evaluate issues such as performance of the ship, the maintenance activities of the ship, spare parts, shipyard time and personnel management by organizing all these activities in timely and cost-effective manner. It also provides technical support to the ship in the ship's operational procedures.

Ship: The ship is a party implementing operational measures within the scope of SEEMP. According to the distribution of shipboard duties, each seafarer will contribute within his expertise in respect of energy efficiency. In order to increase energy awareness of the ship staff, training should be conducted by the company and by the ship's captain.

The ship's personnel are responsible for optimum operation of the ship in many subjects such as the voyage planning, optimal weather routing, trim, autopilot use, cargo and ballast operations. However, the ship operators and other parties have also responsibilities to increase the awareness of the ship’s personnel in all these areas.

Other parties: The cargo owners, ship agency, port authority, brokers, weather routing other companies are the other related parties.

One disruption caused by one of the parties affects all other units. Therefore, awareness of this condition constitutes the importance for all parties. However, mutual support between the parties, cooperation and information sharing is extremely important and necessary to minimize these disruptions.

Be in compliance with charter parties

The Charterer wants to know how efficient the ship is at the time of chartering the ship. In practice, they cover the transportation cost with due regard to the ship’s draft (cargo loaded), weather factors (wind direction, waves and swell), the current, the ship traffic, the quality and specific energy of fuel and using the SOG.

One of the most commonly encountered disputes between owners and charterers relates the fuel consumption and vessel speed whilst under time charter. Monitoring and receiving early warnings with respect to your charter party in regard to the Charter Party Agreement (CPA) is one of the most effective ways of making sure the contractual terms you have entered are met. The most common charter parties include a warranted speed and consumption as agreed in the charterparty. Failure to perform may cause breach of contract and result in a claim. In most cases when the ship has failed to perform in terms of speed and/or consumption it is usual for the charterer to bring the claim in the form of a claim for damages for breach of this particular warranty.

7.2 Human Error

Human error (which is sometimes categorized as instrument uncertainty) may occur in any measurements when operating, reading or recording sensor values if the report completion is not automated.

The automation associated with continuous monitor data (CM) means that noon reports (NRs) are relatively more likely to be subject to human error, measuring sea state, wind speed or wave height is particularly subjective as is the case with hind cast data, and is very dependent on the training of the observer. It is also anecdotally suggested that crew may be inclined to report higher BF numbers in order to satisfy the ship performance as specified in charter party agreements. Manual inputs are affected if the conditions are unstable during measurements, for example in tank dip readings of fuel consumption. Miss-reporting either by repeating previous days data entries or, when recording continuous variables as daily averages, such as wind speed, the mean or mode or the instantaneous rather than the average may be reported depending on the crew, differences will arise if the ship has spent some of the period loitering. The noon data entry may not occur at exactly the same time each day as the recording of 'time spent steaming' may not be adjusted to compensate for crossing time zones and it is possible that different sensors are used to populate the same field, for example, some crew may report speed from the propeller rpm and others report speed through water.

As for our research 73% tend to agree that automated systems will decrease any uncertainty regarding data reporting thus having lower system failures and or incidents.

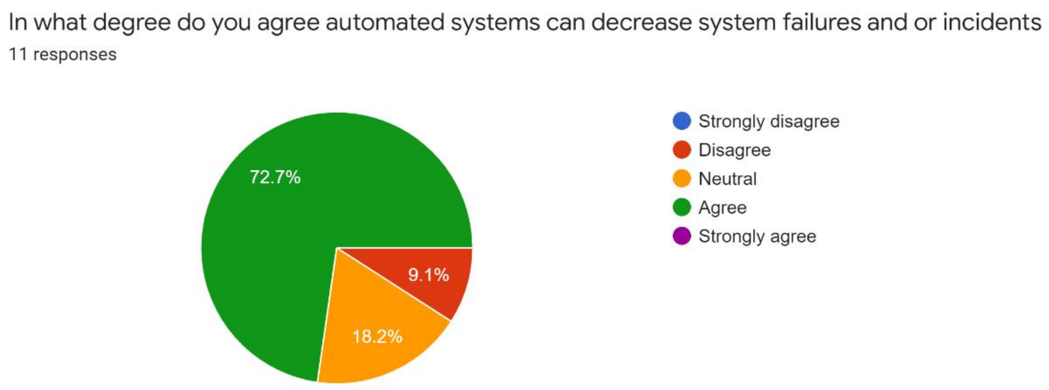


Figure 7.1 Delphi survey "In what degree do you agree automated systems can decrease system failures and or incidents"

7.3 Risk assessment

In order to inform a decision, be it related to design, policy or operation, and generally there is some cost related to the decision like cost of raw materials, investment in R&D, time, human life in safety decisions or macro-economic consequences for a nation or globally. Since no measurement can be known exactly then at least its accuracy should be reported in order to fully assess the risk associated with the decision. The risk of being incorrect implies serious economic consequences.

This risk assessment of decision making applies also to the measurement of ship performance. The relative accuracy which ultimately determines the risk, alongside which the cost and benefit of a decision is evaluated, is linked to the amplitude of the noise or scatter in the data relative to the underlying, longer-term trends that are to be extracted. The ship system interactions induce the scatter in the data, not only from inherent sensor imprecision but also from unobservable and/or unmeasurable variables. According to the central limit theorem (assuming independent, identical distributions), over time the scatter will tend to a normal distribution with zero mean. The actual time period length is dependent on the data acquisition and processing strategy and influential factors include the temporal resolution of sensors and data collection frequency, the sensor precisions and human interactions in the collection process and the processing method (normalization or filtering). There are also uncertainties in the data that will introduce a potentially significant bias in the results, and these too need to be understood and evaluated.

The magnitude of the underlying trends to be identified are a function of the modelling application, for example, in predicting the expected performance of new technologies the signal delta, i.e. the improvement in ship performance, may be a step change of the order of 1-3% (as in the case of propeller boss cap fins) or up to 10-15% as in the case of hull cleaning or new coating applications (Fathom 2011). In the latter case analysis of trends in the time domain is also necessary. Generally, the actual efficiency gains are specific to the ship's hull geometry, propeller characteristics, its operating profile and the current ship performance as determined by monitoring and analysis. The actual predicted fuel saving therefore has an associated uncertainty.

Determining with relative accuracy the associated cost (economic, time and resources) and the benefit it occurs. If the risk is deemed unacceptable given the overall cost and benefit, then it makes sense to re-evaluate investment in data quality and data analysis techniques in order to reduce the risk. This is particularly important in the shipping industry for example, measurement and verification is cited as a key barrier to market uptake in fuel efficient technologies and retrofitting. In order to secure capital, investment projects must be expected to yield a return in excess of some pre-defined minimum (Stulgis 2014). Weighing the economic risk of capital investment against the certainty of the effectiveness of a fuel-efficient technology is therefore the key.

Chapter 8

Hull and Propeller Optimization

8.1 Hull management

After slow steaming, hull management is the second largest fuel saving lever. But unlike reducing speed, antifouling and performance monitoring are complex topics where rapid progress makes yesterday's "proven" recipes questionable and yesterday's key players tomorrow's has-beens. One way to increase energy efficiency in the shipping sector is to better manage underwater hull and propeller surfaces, which are prone to mechanical surface defects and marine growth, or biofouling. Additionally, less biofouling would mean a lower risk of spread of non-native invasive aquatic species that may be transported on ship hulls and disturb receiving ecosystems (Davidson et al., 2016). However, for evaluating the effectiveness of different hull management options, any improvements in hull and propeller condition must be measured accurately and transparently (IMO, 2011a).

Hull cleaning process

Remove all marine growth and oxidized coatings from the entire underwater hull from the upper edge of the boot top down, including sea chest strainer plates, sea chest interiors, fairwaters, rope guards, rudder, shaft strut, sea chest, z-drive, and thruster tunnel. The hull cleaning shall be completed before marine growth hardens within 4 hours.

8.2 Coatings

Marine fouling problem

The marine fouling phenomenon has a deep impact, since to prevent or reduce its growth which affects the ship consumption, costly drydocking for cleaning the hull and the propeller are needed and must be scheduled based on a speed loss estimation. With the large amount of information collected from the on-board sensors, is used for estimating the speed loss due to marine fouling. Ships are generally recoated every fifth year and by applying high performance coating, hull resistance can be reduced.

The hull and the propeller are subject to marine fouling, that increases the frictional resistance of the parts moving through the water and, hence, decreases their efficiency. The effects of marine fouling can be clearly observed after just a few months of operations (Demirel et al., 2017a). Marine fouling, or simply biofouling, is defined as the undesirable accumulation of microorganisms, algae, and animals on artificial surfaces immersed in seawater. On the hull, the presence of fouling increases the roughness of the surface, hence increasing frictional resistance. On the propeller, the presence of fouling increases the roughness of the blade surface, thus requiring more power to maintain the same speed (Owen et al., 2018). Fouling represents the primary cause of hull and propeller performance degradation. Over a typical 4-5 years sailing interval, inadequate hull and propeller performance is estimated to reduce the efficiency of the entire world fleet by 9-12% (CSC, 2011). This comes also as a consequence of the difficulty of identifying the actual contribution of fouling to the decrease in ship performance, and shipping companies have called for the establishment of a transparent and reliable standard for measuring hull and propeller performance

Currently, shipping companies try to mitigate the problem of hull and propeller fouling by applying anti-fouling paints on the submerged surfaces and by regularly cleaning the hull. Despite their effectiveness, such methods have some drawbacks. In spite of their prime role and effectiveness in preventing fouling growth, depending on their types, antifouling paints can be expensive and can be harmful to the marine environment (Caric et al., 2016). Moreover, the hull and the propeller are cleaned on the occasion of other drydocking maintenance events, but this practice does not ensure an optimal scheduling of the cleaning procedures (Kjaer et al., 2018).

The ISO 19030 prescribes methods for measuring changes in hull and propeller performance and it defines a set of relevant performance indicators for their maintenance, repair, and retrofit activities. Specifically, the ISO 19030 suggests comparing the measured performances with the ones obtained during sea trials in particular operating points. This comparison provides an indicator of the hull and propeller efficiency. A continuous monitoring of the efficiency provides a reliable estimation of the changes in the performances. Despite its simplicity and effectiveness, the ISO 19030 presents some limitations. The procedure requires filtering out operating points that are outside the prescribed boundaries, thus limiting the ability of the method to monitor the ship over a wide set of operating conditions. Moreover, some corrections are needed to cope with the environmental disturbances (i.e., winds, waves, and currents). Unfortunately, these corrections require the use of complex fluid dynamics models or additional sea trials (ISO 19030-1, 2016; ISO 19030-2, 2016; ISO 19030-3, 2016).

Underwater standard cleaning methods

There are a variety of methods available for cleaning the hull and niche areas. Some companies use ROVs, and others use divers. Further, some cleaners use brushes, whilst others use water jets and other types of equipment. The industry standard does not delve into the details of any specific cleaning methods and techniques, nor does it provide any form of rating. Instead, the Industry standard concentrates on the processes for relevant stakeholders that will ensure a safe, efficient and environmentally sound in-water cleaning process.

The equipment that will be used for cleaning the ship’s hull and/or niche areas such as cleaning units which houses the controls such as the remote control of ROVs, communication devices with divers, camera monitors etc. The cleaning unit can be operated by a diver using a cleaning technology or by a ROV. It removes and captures materials and is attached to the separation and treatment or storage unit by hoses.

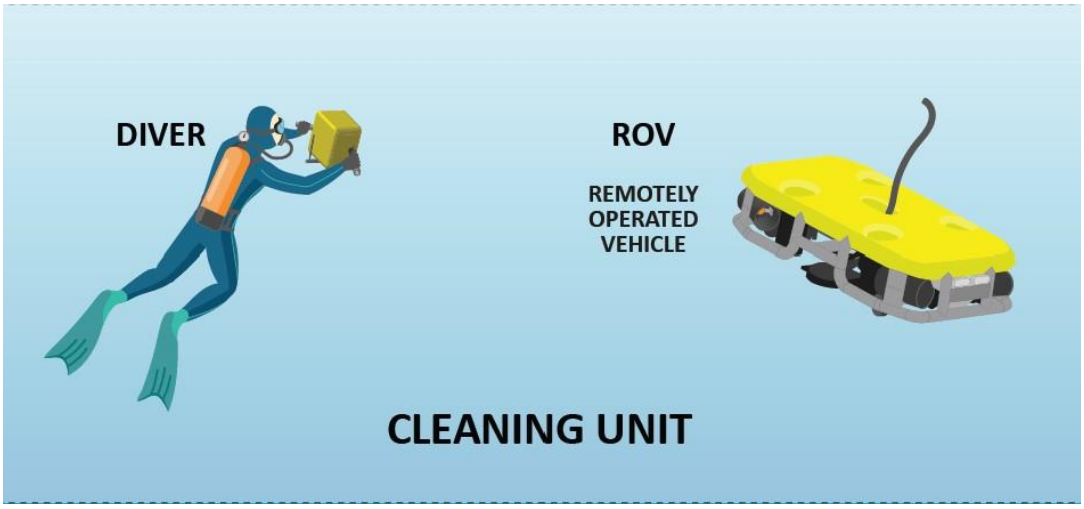


Figure 8.1 Industry Standard On In-Water Cleaning With Capture source: International Chamber of Shipping

The results of the cleaning operation shall be accurately documented in the cleaning report, and shall be retained on board the ship, along with the biofouling record book. Cleaning reports shall be retained for a period of two years on board the ship and thereafter with the shipping company until at least five years have elapsed since the date of the cleaning.

Underwater robotic cleaning

In a special session, HullPIC 2018 covers the latest developments of robotic underwater inspection and cleaning. It describes how remotely controlled robots remove fouling while the ship is loading and unloading. Since the first in-water trials in 2015, the service has been rolled out to all Dutch ports reflecting its increasing popularity with ship operators. The underwater drone can be controlled by the crew itself and sends video images in real-time allowing web-based telepresence for customers virtually without delay on the screen. Using e.g., smart-phones, ship owners can then monitor and guide the inspection without having to leave their location.

Regulation clarity

Regulations have been set out in order to control substances that are used in paints and coatings for the maritime market. The IMO's AFS convention sets out clear guidelines for the amount and usage of chemicals that are used to make paints and coatings. The most popular way of preventing fouling in the maritime industry continues to be biocide-based antifouling paints. When it comes into contact with seawater, the paint releases toxic biocides which prevent marine growth. However, the negative impact of those biocides cannot be denied. The worldwide prohibition of antifouling coatings which contain tributyltin (TBT) in 2008 was a first step the IMO took towards a more environmentally friendly antifouling. Today, the new EU biocide regulation, which came into force in 2013, is setting new standards.

All biocide-based products must now be approved before their introduction into the European market. However, only products whose substances have already been authorized can be approved in this two-stage process. It is assumed that with this regulation, that became valid in 2019, will cause a drastic decline of new products and an increasing demand for alternative antifouling coatings.

Alternative uses of coating

Since the end of tributyltin (TBT) being used in paints and coatings the maritime world has endeavored to use more environmentally considerate alternatives. Tributyltin comes under the umbrella term of organo-tin compounds and was found to have detrimental effects on ocean life. TBT was released into the marine environment by its leaching out of the paint applied to ships' hulls. Not only did this affect sediments and organisms that came in direct contact, but also other marine species further up the food chain that consumed these organisms.

Further development is needed both from manufacturers and from the IMO for modern paints and coatings to make them truly effective and environmentally friendly. The latest solutions in environmental coatings focus too much on the use of silicones, which may present more issues when it comes to maintenance. »Silicones are extremely weak substances and there's nothing that holds the matrix of the coating. Also with a silicone coating, extra care needs to be taken when cleaning a hull as it can become easily damaged (Boud van Rompay, CEO Hydrex).

One of the most promising alternatives to conventional paints is the use of films. For several years, the experts from, a family-owned business and international leader in the manufacture of high-quality plastic films (Renolit), have worked on a new product, which would solve the problem of toxic antifouling coatings. Based on the principle of fouling release, they developed a film which offers an alternative to conventional paints. Although a lot of shipowners are skeptical about the effectiveness of antifouling films, thorough test results have shown this skepticism to be unfounded. Some advantages according to the company are:

- Lower total cost of ownership: The roll-coating technology enables simple application, keeps surfaces clean, safe and protected. It lasts longer and thus contributes significantly to operational efficiency.

- Easy preparation: In general, the same surface preparation is needed as with paints. However, no time is wasted with masking the surrounding surfaces since there is no risk of overspray and no silicone contamination.
- Simple application: The films fit various shapes and can be applied at temperatures between 10 and 30 Celsius and in high humidity. They are easy to apply, as mixing of components is not necessary (eliminating pot life). They deliver instant functionality: one layer, no curing time.
- Timesaving: The films are easy to clean, without risk of flammability, maintenance jobs (e.g., welding) can be done in parallel. There is no drying time and repairs can be done quickly and easily using film patches.
- Better surface protection: There is good resistance to abrasion and scratches, and a double anti-corrosion barrier (adhesive and film). The films offer effective protection due to consistent thickness and quality.
- Harmless to humans and the environment: The films are biocide-free and no volatile organic compounds (VOC) are released. This enables easier Health Safety Environment (HSE) Management.

8.3 Energy Saving Devices

Rudder Bulb System with Fins

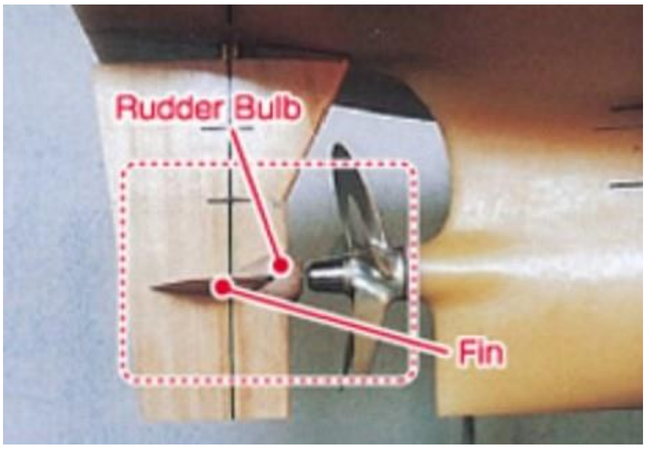


Figure 8.2 Kawasaki RBS-F

A combination of rudder bulb and rudder fins (RBFS) is one of these hydrodynamically based energy saving devices. The rudder bulb is an energy saving device (ESD) installed on the leading edge of the rudder blade at the center position of the propeller shaft. It can cut down the space of low pressure at the axis after the propeller and strengthen the rectification of rudder and decrease the circumferential velocity of propeller. It can also make the propeller wake field uniform and has the benefit of the cavitation performance of propeller. The rudder fin is a device to control water flow around hull to improve fuel efficiency and reduce vibration. It is the thrust fin fitted on both sides of the rudder and has an opposite installation angle to the direction of the inflow. While rotating the propeller, the rudder fins produce the additional thrust from the interaction between the fin blade and the wake flow from the propeller. These RBFS can be applied in both new and retrofit tanker, bulk carrier, container and Ro-Ro ships and the estimated payback time is medium (4 to 15 years).

31st International Ocean and Polar Engineering Conference, Rhodes, Greece, June 2021

The Flettner rotor

Figure 8.3 Chemical ship with 4 flettner rotos on deck

Flettner rotors (FRs) are a form of wind-based propulsion that utilizes the ‘Magnus effect’, a phenomenon exhibited by a spinning body in a fluid flow incident upon it. It is this effect that is responsible for the curving flight path of a ball in many sports, or the deviation of a spinning artillery shell in a crosswind. A FR typically comprises a cylinder with an endplate affixed to the top, mounted vertically to the deck of a ship. Through the action of a motor, the cylinder rotates in an air stream and a lift force is generated that can contribute to the propulsive needs of the ship.

The wind power technology modelled was Flettner rotors, a unique type of powered sail that has attracted more recent interest for its potential to reduce fuel consumption on ships. Consideration has been given to some of the practical limitations of retrofitting Flettner rotors to a ship, and also some negative side effects that have been incorporated into the model to attempt to give a balanced and conservative assessment of the potential benefits.

Wind propulsion has been a popular research topic for green shipping enthusiasts throughout the 20th and 21st century, particularly at times of high bunker prices. The potential benefits are obvious; with the promise of reducing the fuel consumption of a ship is the possibility of improved profit margins, a reduced freight rate and a reduction in greenhouse gas emissions.

Ship Selection

When beginning an assessment for the potential retrofit of FRs on a ship, it must first be ensured that the candidate ship is physically well suited to accommodate them. The ships particulars are used to define the initial dimensions and locations for FRs, and depending on the type of ship, a different logic is applied. Initial requirements are as follows:

- Sufficient clear deck space
- No immediately adjacent structure
- Suitably strong mounting points.

These requirements ultimately mean that a candidate ship must be of a type that has an open area of deck, without extensive superstructure that would inhibit air flow, or deck gear/cranes which may be obstructed by the presence of a FR.

From this approach it becomes clear that certain ship types are unsuitable from the outset. RoPax and container feeder type vessels lack the clear deck space required. For container vessels the installation would require the sacrifice of some container carrying capacity, besides the requirement for clear space around the rotor. However, other vessel types such as dry bulk carriers and tankers represent an ideal platform for the installation of FRs. Their open decks and relatively slow steaming speeds, alongside favourable operating profiles make them a more attractive proposition for the use of FRs.

The operating profile of the ship and the ships speed in different sea states are also key factors to the feasibility of a FR installation, as FRs are more effective for ships travelling at slower speeds in medium/higher winds. The best fuel-saving benefit is for ships that spend the majority of their operational time at a constant cruising speed instead of maneuvering, such as anchor handlers

Cost of implementation: The range of cost for a Flettner rotor is $400,000 to $950,000 (USD) depending on the model (size) of the rotor. Size of a typical delivery with multiple rotor sails starts from $1,000,000 to $3,000,000 (USD).

Reduction potential: The reduction potential of a Flettner motor is 3% to 15% on main engine fuel consumption depending on vessel size, segment, operation profile and trading areas. Some have reported reductions as high as 35%, but for a reduction potential in general, this is seen as high

Source: https://northsearegion.eu/wasp/our-technologies/flettner-rotor-eco-flettner/how-it-works-flettner-rotor/

Although Flettner rotors are successful in achieving their overall goal of saving fuel, the high capital cost alongside reduced bunker prices in cases means that ultimately these ships might disappoint their owners. However, with the modern focus on energy efficient design and fuel saving technologies, matched with high bunker prices, the focus has once again come round to FRs and their potential to save shipowners money, as well as improve the green credentials of a ship.

Air Lubrication Method

The air lubrication reduces the skin friction between the ship's wetted area and sea water. The dominating active method for the reduction of skin friction is the injection of air into the boundary layer underneath the hull, namely air lubrication. The use of air as a lubricant has been proved analytically, experimentally and computationally to decrease the friction between the ship and the seawater. Successful application of air lubrication to both existing and new craft would save fuel and reduce exhaust emissions

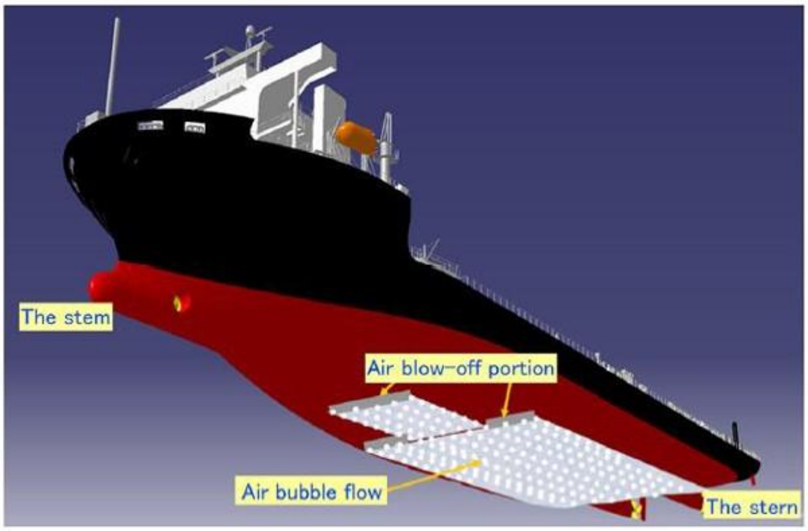


Figure 8.4 Air Lubrication Method

There are three known methods of air lubrication: Bubble Drag Reduction, Air Layer Drag Reduction and Partial Cavity Drag Reduction. It has been experimentally proved that Bubble Drag Reduction is the best method, but it is difficult to consistently create the right bubble size and maintain the bubble mattress under the hull.

Bubble Drag Reduction (BDR): The more efficient Bubble Drag Reduction uses very small or even micro-sized bubbles. The size of these bubbles is generally less than 0.1 mm. However, micro-bubbles can be difficult to produce on a full-scale ship and are less effective at low speeds due to buoyancy. As bubbles grow in size, they can no longer maintain their spherical shape, making them prone to deform in turbulent flows.

Air Layer Drag Reduction (ALDR): After many years of studying the BDR method, the focus of the air lubrication method extended to the air layer. When sufficient air is injected into the near-wall region of a turbulent boundary layer of water, the injected air will coalesce to form a continuous or nearly continuous layer of air separating the solid surface from the water flow. When the injected air increases, the coalesced air layer is able to maintain a fully continuous air layer covering a larger wetted surface and subsequently results in a greater skin friction drag reduction.

Partial Cavity Drag Reduction (PCDR): The partial cavity concept utilizes a recess or cavity on the hull bottom where air is injected from inside the hull so that an inflated air cavity is formed and persists to the rest of the hull, separating the hull from with water, therefore reducing frictional resistance. The air layer in the cavitating flow in the cavity is much thicker than the turbulent boundary layer on the ship hull and requires smaller air injection rate to maintain the air layer than BDR or ALDR.

Scientists and scholars have become interested in air lubrication technology for its potential to reduce drag resistance on the hull. In ship resistance, the three main components are frictional resistance, form resistance and wave resistance. For higher speed displacement vessels, the frictional resistance is approximately 40%, but for low-speed displacement vessels, the frictional resistance is the dominant contributor and can reach 85% of the total resistance. For low-speed vessels, a reduction on the frictional resistance would result in an even higher reduction in fuel consumption in addition to what is achieved by the traditional optimization of the ship's hull form, addressing the form resistance and wave resistance components.

Potential economic impacts

Maritime companies have started using this system in new builds. As has been proven, air lubrication contributes significantly to the performance of the ship. Therefore, there is a need for further and cheaper investigation into this system. Finally, taking the impact of maritime CO2 emissions into consideration, mechanisms such as air lubrication are needed. Taking into account that this ship travels unstoppably, we can assume the proportional economic and environmental benefits of air lubrication.

According to the current air lubrication investigations, the economic and environmental impacts of successfully implemented air lubrication could be significant, as a ship's fuel consumption may be reduced by 5 to 20% with the corresponding reduction of harmful gases.

However, the techniques have yet to be implemented on a large number of real vessels and hence the potential benefits are yet to be realized.

For the BDR and ALDR techniques, there have been two sea trials. The first one was carried out on the Pacific Seagull ship resulted in 5 to 10% net energy savings according to Hoang *et al.* (2009), while the second sea trial by Mitsubishi Heavy Industries achieved 8 to 12% net energy savings (Mizokami *et al.* 2010).

As for PCDR technique, a scale test by MARIN showed 15% net energy savings (Foeth, 2011) and a test by STENA reported resistance reduction of 20 to 25%

Bulbous

A bulbous bow is an extension of the hull just below the load waterline. The basic purpose is to create a low-pressure zone to reduce or eliminate the bow wave and reduce the resulting drag. Today the bulbous bow is a normal part of modern seagoing cargo ships. Comparative model experiments show that a ship fitted with a bulbous bow can require far less propulsive power and have considerably better resistance characteristics than the same ship without a bulbous bow.

Predominantly, ships have a bulbous bow installed to improve efficiency by reducing wave making resistance (Schneekluth and Bertram 1998). Bulbous bow forms have been optimised and bulbs developed in the recent years can reduce the resistance quite considerably. Earlier non-projecting bulbous bows decreased resistance at best by some 5 – 10 %. Modern bulbs can decrease resistance by up to 15 - 20% [Schneekluth and Bertram 1998]. This reduction in resistance translates into lower operating costs and higher profits for those merchant vessels that employ this design enhancement.

The effects of the bulbous bow are numerous including impact on resistance in a seaway (wave making and frictional), sea keeping characteristics, propulsion efficiency (due to changes in the uniformity of the flow and the thrust coefficient), course-keeping ability and the effective drag which depends on draught and trim (Schneekluth and Bertram 1998).

Fuel saving technologies adaption rate

82% of our sample have bought at least one fuel saving technology the last 5 years, some companies have adopted up to 3 of them. Hull coatings is the most common purchased fuel saving technology being followed by propeller modifications. Noteworthy is the low usage of hydrodynamic devices with only one purchase from a company which operates tanker and dry bulk vessels

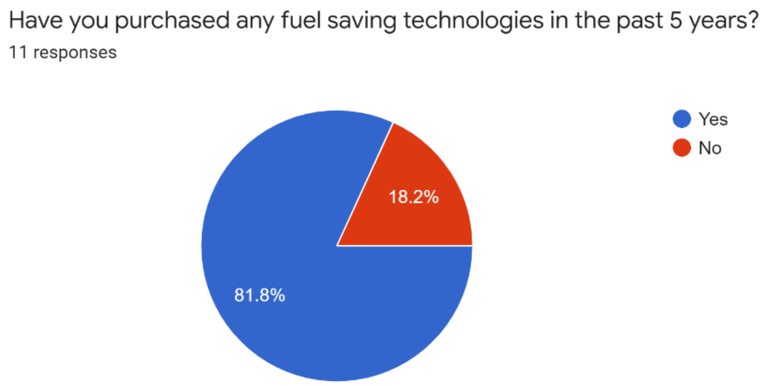


Figure 8.5 Delphi survey “Have you purchased any fuel saving technologies in the past 5 years?”

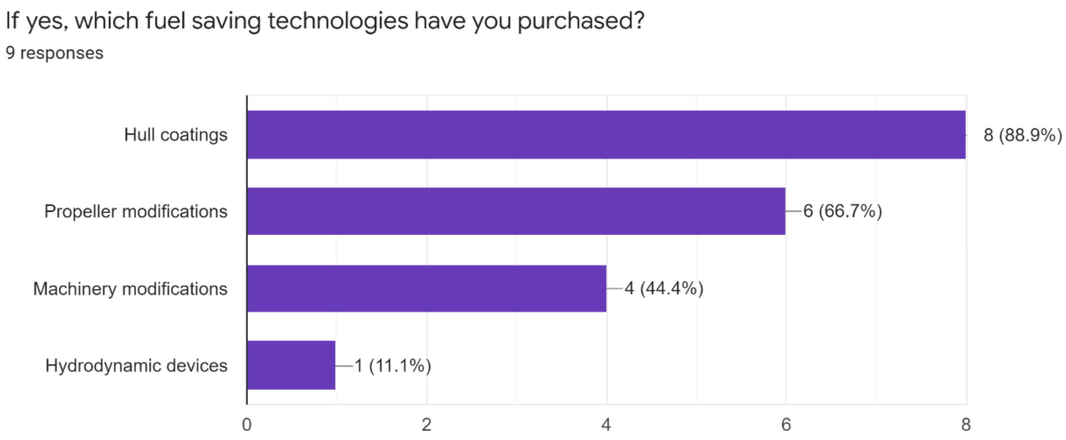


Figure 8.6 Delphi survey “Which fuel saving technologies have you purchased?”

Conclusion

Over the past years there has been a strong interest to improve ship performance. Fuel prices have risen sharply over the past years, and fuel costs have gone up. Therefore, every per cent saved in fuel consumption has a major impact on profitability for ship owners. Performance management system (PMS) plays key role in implementing operational measures for fuel saving. Thus, an onboard continuous data collection and performance system combined with an onshore analysis system, will be a valuable tool in order for ship owners to optimize the performance of the fleet, saving running costs and reducing emissions of green-house gases.

Due to resource limitation and our stringent selection criteria, eleven experts each from a different shipping company were engaged in this study. Although the small number they still well represent different perspectives. Under these circumstances, the following conclusions are formulated.

- ✓ 91% of the Greek shipping companies will move forward dynamically incorporating digitization into their fleets automating their processes and functions on board their vessels.
- ✓ Torque sensor and Doppler log are the most crucial sensors for ship performance monitoring and also the most common among the companies. The calibration of both sensors is also important to avoid misinterpretation of KPIs for performance assessments.
- ✓ This thesis recommends adding accurate fuel oil consumption measurements like the flow meters even though they are more expensive, to get the complete performance picture of a vessel.
- ✓ The SPM system uses raw sensor data, filtering and statistical analysis to give the users a clear information about actual status and its progression over time for the main performance indicators. Based on the research with the data collection systems demonstrated that the automatic data acquisition and collection of the data during constant performance are the most accurate and the way ahead for an ideal PM system. Worth pointing out that most of the companies that participated in the survey already use SPM system instead of a manually noon report one.
- ✓ The noon report and continuous monitoring comparison has demonstrated that there is an improvement in uncertainty achieved using a continuous monitoring set relative to a noon report dataset, even without including the likely significant effects of human error. 73% agree with the statement that automated systems can decrease system failures and or incidents.
- ✓ The operators asked in the survey feel that speed optimization is the most efficient method in terms of fuel economy.

- ✓ Hull coatings proved the most common fuel saving technology that has been applied recently, but this was followed closely by machinery and propeller modifications. Less popular choice was the use of Hydrodynamic devices.

Acknowledgments

I highly appreciate the experts' time participating in the survey. Furthermore, my gratitude goes out to Dr Karlis Athanasios my supervisor for his positive attitude and support to finish my thesis.

Literature list

Continuous Performance Monitoring – A Practical Approach to the ISO 19030 Standard Universidad de Cantabria by Carlos Gonzalez

Hansen, S. V. (2012). Performance Monitoring of Ships. Technical University of Denmark.

"A novel indicator for ship hull and propeller performance: Examples from two shipping segments" Dinis Reis Oliveira, Lena Granhag , Lars Larsson Department of Mechanics and Maritime Sciences, Chalmers University of Technology, Gothenburg, Sweden

IAMU Research Project 2014 "Energy efficiency of Ships through Optimisation of ship operations" By Istanbul technical University (ITU)

Antonio Gallardo Martínez Polytechnic University of Cartagena (Spain) December 2016 "Investigation of The Air–Lubrication Effect On Friction Resistance"

IMarEST (2012), Global-based approach to fuel and CO2 emissions monitoring and reporting, MEPC65/INF. 3, Institute of Marine Engineering, Science and Technology, London

Cardiff University, 2013a M. Bloor, S. Baker, H. Sampson, K. Dahlgren Issues in the enforcement of future international regulations on ships' carbon emissions Cardiff : Cardiff University, 2013

Cardiff University, 2013b M. Bloor, S. Baker, H. Sampson, K. Dahlgren Effectiveness of international regulation of pollution controls: the case of the governance of ship emissions Cardiff: Cardiff University, 2013

Bunkerspot, 2009 Vol. 6, No.1, Feb/March 2009

CE Delft, 2009 Technical support for European action to reduce Greenhouse Gas Emissions from international maritime transport

CE Delft, March (2013) ''Monitoring of bunker fuel consumption'' Author(s): Jasper Faber Dagmar Nelissen Martine Smit

Ronen D (2011) The effect of oil price on containership speed and fleet size. J Oper Res Soc 62:211–216

Dulebenets MA (2019) Minimizing the total liner shipping route service costs via application of an efficient collaborative agreement. IEEE Trans Intell Transp Syst 20(1):123–136

Bazari, Z. (2007). "Ship energy performance monitoring and benchmarking." Journal of Marine Engineering and Technology

Deligiannis, P. (2014). Ship Performance Indicator. Shipping in Changing Climates, Tyndall, 2014. Liverpool, UK

University of Exeter, 2008a C. Barbour, T. Clifford, D. Millar, R. Young Fuel flow metering preliminary report (phase 1)

Armstrong, V. N. (2013). "Vessel optimisation for low carbon shipping." Ocean Engineering.

Zhen L, Hu Y, Wang S, Laporte G, Wu Y (2019a) Fleet deployment and demand fulfillment for container shipping liners. Transp Res B Methodol 120:15–32

''The use of Flettner rotors in efficient ship design'' David Pearson January 2014, Project: Vessel Technology Assessment System (VTAS)

Fathom (2011). Ship Efficiency: The Guide. UK

Stulgis, V., Smith, T. W. P., Rehmatulla, N., Powers, J., Hoppe, J. (2014). Hidden Treasure: Financial Models for Retrofits. T. L. H. MCMAHON.

Davidson, I.C., Scianni, C., Hewitt, C., Everett, R., Holm, E.R., Tamburri, M., Ruiz, G.M., 2016. Mini-review: assessing the drivers of ship biofouling management – aligning industry and biosecurity goals. Biofouling 32, 411–428. https://doi.org/10.1080/08927014.2016.1149572.

Demirel, Y.K., Uzun, D., Zhang, Y., Fang, H.-C., Day, A.H., Turan, O., 2017a. Effect of barnacle fouling on ship resistance and powering. Biofouling 33 (10), 819–834. https://doi.org/10.1080/08927014.2017.1373279

Owen, D., Demirel, Y.K., Oguz, E., Tezdogan, T., Incecik, A... Investigating the effect of biofouling on propeller characteristics using cfd. Ocean Engineering 2018; 159:505 – 516.

Caric (2016) "Ecotoxicological risk assessment of antifouling emissions in a cruise ship port"

Kjaer, L.L., Pigosso, D.C., McAloone, T.C., Birkved, M... Guidelines for evaluating the environmental performance of product/service-systems through life cycle assessment. Journal of Cleaner Production 2018;190:666– 678.

CSC, Air pollution and energy efficiency, a transparent and reliable hull and propeller performance standard. Tech. Rep.; Clean Shipping Coalition; 2011. URL: http://bellona.no/assets/sites/3/2015/06/fil_ MEPC_63-4-8_-_A_transparent_and_reliable_hull_and_propeller_performance_standard_CSC1.pdf.

ISO 19030-1. Ships and marine technology Measurement of changes in hull and propeller performance - Part 1: General principles. Standard; International Organization for Standardization; Geneva, CH; 2016.

ISO 19030-2. Ships and marine technology Measurement of changes in hull and propeller performance - Part 2: Default method. Standard; International Organization for Standardization; Geneva, CH; 2016.

ISO 19030-3. Ships and marine technology Measurement of changes in hull and propeller performance - Part 3: Alternative methods. Standard; International Organization for Standardization; Geneva, CH; 2016.

Hull Performance and Insight Conference (HullPIC), 12-14 March 2018

Litton Marine Systems (1998). ―Navigation Echosounder LAZ 5000. Manual ‖

IMO MEPC.1/Circ.855/Rev.2 14 January 2019

Sperry Marine Inc. (1995) ―Rudder Servo Unit RCW10-440‖, Manual.

Mishra, S., Datta-Gupta, A., 2017. Applied Statistical Modeling and Data Analytics: A Practical Guide for the Petroleum Geosciences. Elsevier.

IBM, The Four V's of Big Data, 2016.

Schneekluth, H. and V. Bertram (1998). Ship Design for Efficiency and Economy. Oxford, Butterworth-Heinemann.

Svend Søyland, Nordic Energy Research, Oslo/Norway. ISO 19030 – Motivation, Scope and Development

Coraddu, A., Lim, S., Oneto, L., Pazouki, K., Norman, R., Murphy, A., 2019a. A novelty detection approach to diagnosing hull and propeller fouling. Ocean Engineering 176, 65–73.

Research Project:

2012 Seas at Risk and Transport & Environment (T&E): Summary of research carried out by CE Delft, The ICCT and Mikis Tsimplis

Internet Sites:

https://binsfeld.com/ship-performance-monitoring/

https://www.dnv.com/maritime/energy-efficiency/monitoring-ship-and-fleet-efficiency-performance-with-an-SEEMP.html

https://www.imo.org/en/OurWork/Environment/Pages/Technical-and-Operational-Measures.aspx

https://www.dnv.com/maritime/energy-efficiency/index.html *https://www.dnv.com/maritime/energy-efficiency/automatic-identification-system-data-insights.html*

https://binsfeld.com/the-ultimate-guide-to-marine-shaft-power-torsion-meters/

https://binsfeld.com/ship-performance-monitoring/

https://www.container-xchange.com/blog/slow-steaming/

https://www.insatechmarine.com/products/performance/performance-monitoring-system

https://www.jotun.com/ww-en/industries/news-and-stories/jotun-insider/performance-monitoring-critical-to-optimising-vessel-performance-and-saving-money/

www.renolit-maritime.com