Athens, June 2023

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Diploma thesis

Sensitivity analysis on the monitoring of changes in hull and propeller performance with ISO 19030

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Summary

The purpose of this thesis is to implement the ISO 19030 (2016) procedure through python language programing and perform a sensitivity analysis of the resulting performance values, by altering parameters of the procedure. In addition, an effort is made to detect the effect in efficiency of a propeller maintenance event with the ISO procedure.

The ISO 19030 standard is the first international standard to provide a data-centric method to identify the impact of hull and propeller condition in performance and trigger a cost-benefit action with data analysis and not complex physical models. It has emerged in a good timing, when regulations are pushing the shipping sector in exploitation of every energy saving opportunity and the amount of data transmitted to shore is increasing. A brief review of the IMO focus of actions is presented at the beginning. After a grasp of the regulatory framework and the directions at which ISO practice could be useful, the background and scope of ISO 19030 are presented. In continuation, follows a briefing of studies which share a common ground with ISO 19030.

Chapter 2 consists an effort to summarize the procedure, as a manual, maintaining all the important points for an application. Specifically, the calculation process at each step of the procedure is outlined here, and is used as reference for the application that follows in Chapter 3.

Chapter 3 is where the implementation takes place, which concerns a bulk carrier of 81.600 dwt, with sensor measurements per minute for one year. Specifically, after the filtering and validation procedure, the reference conditions are applied with three scenarios, one for the default method, one with loosen wind speed limit and one with wider displacement margin between measured displacements and the ones in speed power reference curves. After the sensitivity analysis, focus is given to statistical characteristics of the resulting performance values before and after a propeller maintenance event. Finally, a graph of comparison is made between the performance values and a widely used performance indicator.

Σύνοψη

Σκοπός τη παρούσας διπλωματικής εργασίας είναι η εφαρμογή του ISO 19030 (2016) με την ανάπτυξη προγράμματος σε γλώσσα Python και η ανάλυση ευαισθησίας των τιμών απόδοσης με αλλαγή παραμέτρων της διαδικασίας. Επιπροσθέτως, γίνεται προσπάθεια εντοπισμού της αλλαγής απόδοσης της γάστρας και έλικας με την εφαρμογή του ISO 19030, έπειτα από δεδομένη ενέργεια συντήρησης της έλικας.

Το ISO 19030 αποτελεί την πρώτη διεθνή πιστοποιημένη διαδικασία για εντοπισμό των αλλαγών της απόδοσης της γάστρας και της έλικας, με σκοπό τη λήψη οικονομικών αποφάσεων συντήρησης, χρησιμοποιώντας τεχνικές ανάλυσης δεδομένων και όχι περίπλοκα φυσικά μοντέλα. Το ISO αυτό εμφανίστηκε σε μια ευνοϊκή περίοδο, καθώς οι κανονισμοί επιβάλλουν πολυεπίπεδη εξοικονόμηση ενέργειας λειτουργίας των πλοίων, αλλά και παρατηρείται ένας αυξανόμενος όγκος δεδομένων από αισθητήρες που μεταφέρονται στη στεριά. Αρχικά, γίνεται ανασκόπηση του κανονιστικού πλαισίου και των δράσεων του Διεθνούς Οργανισμού Ναυτιλίας για την αναγκαία πλέον αποδοτικότητα των πλοίων, με σκοπό την κατανόηση των κατευθύνσεων που το ISO 19030 μπορεί να φανεί χρήσιμο. Ακολουθεί η περιγραφή του πλαισίου υπό το οποίο κυκλοφόρησε το ISO και παρουσιάζεται ο σκοπός του, ενώ λαμβάνει χώρα και μια ανασκόπηση εργασιών και ερευνών που μοιράζονται κοινά σημεία με το διεθνές πρότυπο.

Στο Κεφάλαιο 2, γίνεται μια προσπάθεια περιγραφής και περίληψης της διαδικασίας του ISO, σαν οδηγός, και χρησιμοποιείται ως αναφορά για την υλοποίηση που πραγματοποιείται στο Κεφάλαιο 3.

Στο Κεφάλαιο 3 γίνεται η υλοποίηση, η οποία αφορά ένα πλοίο ξηρού φορτίου χύδην, χωρητικότητας 81.600 dwt, με μετρήσεις ανά λεπτό στο βάθος ενός χρόνου. Ειδικότερα, έπειτα από φιλτράρισμα και έλεγχο εγκυρότητας των δεδομένων, οι συνθήκες αναφοράς του προτύπου εφαρμόζονται για τρία σενάρια, ένα για τη βασική μέθοδο, ένα με διαφορετικό κριτήριο ταχύτητας ανέμου και ένα με μεγαλύτερο εύρος ανοχής για τη διαφορά του μετρούμενου εκτοπίσματος με τα διαθέσιμα από τις καμπύλες αναφοράς ταχύτητας ισχύος. Εν συνεχία, ακολουθούν στατιστικοί υπολογισμοί των τιμών απόδοσης που προκύπτουν για τις περιόδους πριν και μετά την δράση συντήρησης της έλικας, που συμβαίνει στο τέλος του πρώτου τριμήνου. Τέλος, γίνεται σύγκριση των τιμών απόδοσης με έναν διαφορετικό, ευρέος γνωστό, δείκτη απόδοσης.

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Chapter 1 – Introduction

The maritime industry is experiencing significant changes, because the current world population's needs for trade have been increased and are bound to increase further. The most recognizable entities and research institutes have been pursuing international solutions. Although the contribution of the shipping industry has proven only a fragment of the overall anthropogenic emissions at a rate of 2.76% in 2012 to 2.89% in 2018 (Fourth GHG Study – IMO 2020), the risks of continuing the operation of the world fleet as we have known it, have been acknowledged.

One in the industry from now on, with reference to the commercial shipping industry, should always have in mind the energy efficiency of the vessels and the reduction of pollutants emissions. According to the Initial IMO GHG Strategy published in 2018, the plan is to *"reduce GHG emissions by at least half by 2050, compared with their level in 2008, and work towards phasing out GHG emissions from shipping entirely as soon as possible in this century*", given the expected proliferation of the world fleet. In addition, the IMO GHG Strategy will be revised during this year, 2023. The assessment and further contemplation of measures is going to take place, while at the same time energy efficiency regulations, have and are further beginning to kick-in. In this respect, it should be a common effort to decarbonize shipping and the stakeholders need carefully planned pathways to meet conformity.

The necessity to change towards more efficient vessels highlighted the terms vessel performance, performance monitoring and performance prediction. Significant developments have been made towards this field of monitoring and assessing performance. The mandatory measures in combination with the benefits of technology and digitalization comes as a timing for the maritime industry to experiment with mature and advanced terms such as big data analysis, neural networks, low orbit satellites, onboard servers, cloud computing, crew training for new technologies, speed-trim optimization algorithms, optimal voyage routing, alternative fuels, on-shore power, Just-In-Time logistics, cybersecurity and the list goes on. Technology provides the opportunities and the sure thing is that more and more data, external or internal to a vessel's operation, will need to be adequately collected and managed in order to become competitive and comply to regulations.

Hull and propeller performance is a prominent part of the overall ship's performance. For the scope of this thesis, a tool and guideline will be discussed, with the aim to determine changes in hull and propeller performance of ships, the ISO 19030 – 2016 standard. ISO is an acknowledged non-governmental organization which among others, provides guidelines for shipping practices, in view of existing and new technologies. Guidelines can be used as a tool, in order to gain value in environmental impact and ensure compliance to current and forthcoming regulations. Worth mentioning that ISO standards have been integrated all along, in technical and other relevant IMO regulations.

ISO 19030 has been published in 2016, to address the market need of quantifying, in a data-driven practice, the complicated measurement of hull and propeller performance. This comes as an asset to stakeholders, such as ship owners/operators and also, but not limiting, to anti-fouling painting companies, propeller treatment and design providers. It can also be used in order to prove the benefits of retrofitting new technologies.

However, the ISO 19030 is noticed with little attention in the industry since its publication (INTERTANKO 2020). Nevertheless, it comprises a significant development for vessels performance monitoring, because of three main reasons:

1) Emerges at a good timing, when monitoring and reporting regulations have amended data acquisition systems onboard ships and on shore.

2) ISO 19030 shares the mentality of performance monitoring through Key Performance Indicators (KPIs), a well-known and developing decision-making practice.

3) Computing technology facilitates the methods of acquiring big data sets, extracting proper subsets for analysis and calculating valuable indices for decision making purposes.

1.1 IMO, Ship Energy Efficiency and ISO 19030

1.1.1 IMO shipping policies and the United Nations

The International Maritime Organization (IMO), as a specialized agency of the United Nations (UN), has undertaken the responsibility to regulate the shipping industry in a sustainable way, acting through its Committees and Sub-committees. The key Committee of IMO for pollution prevention, and subsequently, for ship energy efficiency is the Marine Environment Protection Committee, MEPC[1].

Important changes are going on regarding energy efficiency regulations, which are eventually translated in the efficiency of cargo carried per energy used, rendering the consumption of fossil fuels a key parameter. The consumption results to GHG emissions and specifically, CO_2 emissions, which lead in a reverse way to the reason of the regulations, the air pollution prevention and environment protection from ships.

Regulations are always relevant to UN Conventions and Protocols, and the main driver of IMO's strategies on air pollution can be considered the UNCCC (United Nations Framework Conference on Climate Change), operationalized from the Kyoto Protocol [2](signed 1997- into force 2005). The latter is committing industrialized countries and economies, the Members to

[1] https://www.imo.org/en/about/pages/structure.aspx

[2] https://unfccc.int/kyoto_protocol

the Protocol, to limit and reduce greenhouse gases (GHG) emissions, by adopting policies and measures to mitigate and report of emissions.

IMO has a structured strategy regarding ship energy efficiency and GHG emissions, with the ambition to decarbonize the shipping industry by the end of this century (IMO, 2018). IMO, under the remit of UN, has published the Initial IMO GHG Strategy in 2018.

1.1.2 IMO actions to decarbonization

IMO and its Committees have put a multilevel effort to achieve the objectives for the protection of the environment. At this point, an effort is made to construct an overview of milestones, regarding energy efficiency measures. Focus is in the direction to identify the measures, technical or operational, in which the use of ISO 19030 would have a positive impact on.

An important milestone to regulations has been MEPC.203(62), adopted in 2011 and implemented the first day of 2013. It represents the first-ever legally binding, energy efficiency standard for a global industry sector. An instrumental action and first global mandatory GHG-reduction regime, since the Kyoto Protocol (1997).

MEPC.203(62) between others, introduced a new Chapter 4 to MARPOL Annex VI entitled *"Regulations on energy efficiency for ships"*. This package of technical requirements, introduced the Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan I (SEEMP I), for international going ships above 400 DWT (MEPC.203(62), 2011).

Amendments have taken place up to date - 2^{nd} quarter of 2023 - and the regulatory framework has expanded. Reference is made to short-term operational measures EEDI phases, SEEMP II & III, Energy Efficiency Existing Index (EEXI), the CII Rating framework and the optional EEOI. In forthcoming MEPC 80, July 2023, the adoption of the revised IMO GHG Strategy for Reduction of GHG Emissions from Ships (2018) is to take place (MEPC 79, 2022). Table 1 presents an effort to concentrate the relative IMO resolutions and guidelines for before-mentioned measures.

EEDI

EEDI is more a medium to long term measure in IMO GHG Strategy. Essentially, it is an energy efficiency performance indicator that estimates grams of CO_2 per transport work (g of CO_2 per tonne-mile) and sets a baseline for efficiency. Applicable to ships of 400 Gross Tonnage (GT) and above[3].

The year that the vessel's contract was placed or date keel laid or the date of delivery, are the dates which determine the phase of EEDI requirements. A vessel should have an attained energy efficiency complying with the required one for corresponding ship type and size. The levels of compliance are set in EEDI phases, which are to become stricter through time. It is calculated once and during the construction of a vessel (MEPC.203(62), 2011).

[3] https://www.imo.org/en/MediaCentre/HotTopics/Pages/Cutting-GHG-emissions.aspx

Some methods to improve the EEDI of new-building ships are presented below:

- ✓ Hulls with less resistance and improved steering configurations.
- ✓ More efficient aft-ship, propeller and rudder arrangements.
- ✓ Lower energy consumption in main and auxiliary engines.
- ✓ Switch from oil to natural gas as main fuel.
- ✓ Miscellaneous technologies to reduce minor energy consumers (deck paint, pipe insulation, lighting, air conditioning, etc.)
- ✓ Zero or minimum ballast configurations (e.g., by alternative design or ship type)
- ✓ Marine fuel cells; and Hybrid ships (e.g., wind power, solar panels, and use of light materials, etc.)

EEXI

Introduction started at MEPC 75 at which draft amendments to MARPOL Annex VI, with Regulations 20A and 21A. The Energy Efficiency eXisting Index (EEXI) is essentially a technical measure for determining existing ships energy efficiency level and applies to all ships over 400 GT operating in international waters. (MEPC 75, 2020)

In the 2021 MEPC 76 and 77, the EEXI guidelines and regulations were detailed and are into force, in an entry level, from 1 January 2023 or bureaucratically, from the first endorsement of the International Air Pollution Prevention certificate of a corresponding vessel[4]. The new measures will require all ships to calculate their EEXI following technical means to improve their energy efficiency (MEPC 76, 2021).

The EEXI is related to built-in performance, however it can be influenced by modifications, but this is out of the scope of ISO 19030. One method that could be evaluated by ISO 19030, is the optimization of a propeller, or a bulb/fore end modification of the hull[5].There are cases of existing ships, under latest regulations, that a downgrade of operational speed may be necessary. Aforementioned practices may be a solution to optimize hull and propeller performance for a different than the design speed, and could be evaluated, besides other methods, with ISO 19030 and possible revisions.

SEEMP

The Ship Energy Efficiency Management Plan (SEEMP) was also firstly introduced in MEPC.203(62), a mandatory requirement which entered into force on 1 January 2013. Since then, amendments have extended the scope of SEEMP, by adopting SEEMP II and III.

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[4] https://www.imo.org/en/MediaCentre/PressBriefings/pages/MEPC76.aspx

[5] https://www.dnv.com/maritime/insights/topics/eexi/advisory-service-improvement-attained-eexi-value.html

The latest amendments were adopted in MEPC 78, June 2022, with MEPC.346(78) and refer to reporting of mandatory values related to the implementation of the IMO short-term GHG reduction measure, including attained EEXI, CII and rating values to the IMO Ship Fuel Oil Consumption Database (IMO DCS).[6]

The purpose of each SEEMP part is briefly presented below:

SEEMP Part I: into force in January 2013. A document that should determine both the current status of ship energy usage and also the further actions for improvement of the ship's energy efficiency. (MEPC.213(63, 2012). Applicable to ships over 400 Gross Tonnage.

SEEMP Part II: into force on March 2018. Methodologies used to collect fuel oil consumption data. Connected with IMO Data Collection System (DCS), refer to below section. Applicable to 5000 DWT ships and above.

SEEMP Part III: into force in January 2023. This new par is currently in entry level, and is connected with the Carbon Intensity Indicator (CII), which effectively enters into force at the starting of 2024. It contains the annual CII rating (A to E) of the vessel with regards to carbon intensity, and the CII calculation procedure and reporting through IMO DCS framework (regulation 22A of MARPOL Annex VI), Fuel Oil Data Collection System. If the CII rating is D for three consecutive years or E for one year, the reasons should be identified and the corrective actions outlined into SEEMP III.

The SEEMP identifies energy-saving measures that have been undertaken, and determines how effective these measures are in terms of improving energy efficiency. In fact, it endorses using the indicator EEOI for performance assessment of existing ships.

ISO 19030 could be integrated into a SEEMP strategy, in order to evaluate the contribution of the ship's hull and propeller efficiency to the overall efficiency, identify positive hull and propeller efficiency practices and gain value in terms of upgrading the CII rating, in combination or not, with other practices.

DCS

With IMO Resolution MEPC.278(70), adopted in 2016, entered into force March 2018 and effective for year 2019, the MARPOL Annex VI – Regulation 22 was modified to integrate a mandatory Data Collection System, DCS, requiring ships of 5,000 GT and above (representing approximately 85% of the total CO_2 emissions from international shipping), to collect consumption data for each type of fuel oil they use, as well as, other specified data, including proxies for "transport work" (MEPC.278(70), 2016).

As per latest developments, MEPC 78 approved the draft amendments to Appendix IX of MARPOL Annex VI (DCS) to include more information on the ship's carbon intensity performance developed for final adoption by MEPC 80, 2023 (MEPC 79, 2022). Expected entry into force is 1 April 2024.

[6] https://www.imo.org/en/OurWork/Environment/Pages/Improving%20the%20energy%20efficiency%20of%20ships.aspx

EEOI

Energy Efficiency Operational Indicator (EEOI) is an internationally established too to obtain an index of the energy efficiency of a ship in operation. The EEOI is similar to EEDI index, defined as the ratio of mass of CO_2 emitted per unit of transport work. However, EEOI concerns more the operational variables of a specific vessel. It is not mandatory for the time being, but can serve as incentive for competitiveness. Equation 1.1 – from hereafter Eq.- represents the calculation of EEOI:

$$EEOI = \frac{\sum_i \sum_j FC_{ij} \cdot C_{Fj}}{\sum_i m_{cargo_i} \cdot D_i} \quad \left(\frac{gCO_2}{t \cdot nm}\right) \qquad (1.1)$$

where,

i: the voyage

j: the type of fuel consumed

FC_j: the mass of fuel type j consumed, in voyage i

C_{Fj}: the carbon factor for fuel type j

m_{cargo}: the cargo carried in voyage i, in tonnes

D_i: the distance travelled in voyage i, in nautical miles.

EEOI can be influenced by the technical efficiency of the ship, the amount of cargo transported per unit of time, and variations in speed. It is also possible to separate EEOI in port and at sea calculation (Parker, 2015) The ISO 19030, in combination with other planning, could be one of the tools to quantify hull and propeller performance and take steps for optimization of EEOI, especially at sea.

CII

The Carbon Intensity Indicator (CII) was introduced by MEPC 75, adopted in MEPC 76, June 21 and it is effective since 1 January 2023. The CII rating scheme, integrated in the enhanced SEEMP, are short-term measures to mitigate the carbon intensity from shipping. Ships will get a rating of their energy efficiency (A, B, C, D, E - where A is the best). A ship rated D for three consecutive years, or E for one, is required to submit a corrective action plan, to show how the required index (C or above) would be achieved.

It should be noted that a required and an attained CII are calculated. The required CII is obtained by the reference one per ship type and size, given in Eq. 1.2 and the reduction factor from given values per year, becoming stricter through time. The reference is obtained by Eq. 1.3 and the regression constants a, c from a table per ship type and size. The attained

CII is obtained by Eq. 1.4. Their division, Eq. 1.5, results in a value, which according to a table with rating boundaries per ship type, gives the rating of the vessel[7]:

$$CII_{Required} = CII_{Ref} \cdot \left(\frac{100-Z}{100}\right) \quad (1.2)$$

$$CII_{Ref} = a \cdot Capacity^{-C} \quad (1.3)$$

$$CII_{Attained} = \frac{CO_2\ emmision}{Deadweight \cdot Distance\ sailed} \quad (1.4)$$

$$rating\ value = \frac{CII_{Attained}}{CII_{Required}} \quad (1.5)$$

The most important methods to improve CII and upgrading the rate of a vessel are:

- Speed Optimization
- Alternative Fuels
- Biofouling Management

IMO GHG Studies

IMO GHG Studies have been four so far and have been published, respectively, in 2000, 2009, 2014 and 2020. Each study has been recognized as an important contribution to the understanding of emissions by a worldwide audience. Each study has also served to improve the methodologies to quantify emissions, to foresee the future of emissions and to achieve market-based mitigation measures on GHG.[8]

A summary of some important regulations and guidelines is provided in Table 1. Emphasis is given to the technical and operational measures, referred to as short term measures. The purpose is not to include the whole regulatory framework referring to ship energy efficiency measures. The summary consists of important and relative points gathered by the author, which were found relative with the energy efficiency opportunities of ISO 19030.

[7] https://www.nautilusshipping.com/carbon-intensity-indicator-cii/

[8] https://www.imo.org/en/OurWork/Environment/Pages/IMO-GHG-studies.aspx

Note: Color meaning of resolutions/guidelines: **black** for firstly introduced, **blue** for superseded/revoked/amended, **red** for lastly introduced

Table 1: Map of Resolutions and Guidelines for IMO's energy efficiency measures

EEDI	SEEMP	DCS	EEXI	CII	IMO & MEPC

Jul, 2011:
MEPC.203(62)
Adoption of energy efficiency EEDI, SEEMP regulations under MARPOL Annex VI Into force Jan, 2013
 	
MEPC.212(63) – 2012
1st Guidelines on the method of calculation the attained EEDI for new ships
// amended by
MEPC.224(64) - 2012
///superseded by
MEPC.245(66) -2014
// amended by
MEPC.263(68) - 2015
MEPC.281(70) - 2016
///superseded by
MEPC.308(73) – 2018
//amended by
MEPC.322(74) - 2019
MEPC.332(76) - 2021
MEPC.364(79) –2022
	Jul, 2011:
	MEPC.203(62)
	Adoption of energy efficiency EEDI, SEEMP regulations under MARPOL Annex VI Into force Jan, 2013
	
	MEPC.213(63) -2012
	Guidelines for the development of a SEEMP
	/// superseded by
	MEPC.282(70) - 2016
	// revoked by
	MEPC.346(78) - 2022
		***MEPC.278(70)* - 2016**
		(adopted 2016)
		Amendments to MARPOL Annex VI: DCS requires ships to collect and report ship fuel oil consumption data. Also, the SEEMP shall include a description of the methodology that will be used to collect the data required by regulation Into force 2018. Effective from Jan, 2019
		
		MEPC.349(78) - 2022
		Amendments to Appendix IX of MARPOL Annex VI to update the information reported DCS, including adding reporting for EEXI and CII values
			Jun, 2021:
			MEPC.328(76) – CII, EEXI
			Amendments MARPOL Annex VI: attained EEXI, CII to be calculated according to guidelines developed by IMO Into force Nov 2022.
			
			MEPC.333(76)
			2022 Guidelines on the method of calculation of the attained EEXI.
			// revoked by
			MEPC.350(78)
				Jun, 2021:
				MEPC.328(76) – CII, EEXI
				Amendments MARPOL Annex VI: attained EEXI, CII to be calculated according to guidelines developed by IMO. Into force Nov 2022.
				
				MEPC.336(76) – 2021
				CII Guidelines, G1
				// revoked by
				MEPC.352(78) - 2022
				
				MEPC.337(76) - 2021
				Reference lines guidelines, G2
				// revoked by
				MEPC.353(78) – 2022
				
				MEPC.338(76) - 2021
				Reduction factors guidelines, G3
				
				MEPC.339(76) – 2021
				CII Rating Guidelines, G4
				// revoked by
				MEPC.354(78) – 2022
				
				MEPC.355(78) - 2022
				CII Guidelines, G5
					MEPC 75, Nov 2020
					
					MEPC 76, June 2021
					
					MEPC 77: Nov 2021
					
					MEPC 78: June 2022
					
					MEPC 79: Dec 2022
					
					MEPC 80: July 2023
					
					2018 MEPC.304(72)
					Initial IMO Strategy on reduction of GHG emissions from ships,
					
					In July 2023, MEPC 80 will reassess 2018 Initial Strategy.

The Revised IMO GHG Strategy 2023 is expected to be adopted in MEPC 80, July 2023, and will be based on fuel oil consumption data of ships over 5,000 gross tons (IMO DCS), which began on 1 January 2019. Data collected so far under the regulations, according to IMO Initial GHG Strategy (2018), and the lessons learned by the 4th IMO GHG Study, will be examined for decisions. In the meantime, IMO's Marine Environment Protection Committee (MEPC) will review the effectiveness of the implementation of the CII and EEXI until 1 January 2026, and adopt further requirements/guidelines.

In reference to existing ships, the overview of technical and operational requirements regarding ship's efficiency is of interest, because it can determine a desired level of vessel performance compliance. The desired performance level can be fragmented in as independent as possible contributors and address them strategically. One such contributor is the hull and propeller performance, quantified in an effort in ISO 19030 Parts 1,2,3 (2016).

1.1.3 Introduction to ISO 19030 (2016)

The review of existing and forthcoming regulations for the energy efficiency of the word fleet vessels (above 400 GT and 5000 GT) has aided to understand the landscape and the directions of international action. ISO 19030 addresses the quantification of hull and propeller efficiency through relative performance assessment (not absolute), in a big data analysis approach to compensate for the complexity of the issue (Søyland, 2016).

Background

In 2011, the Clean Shipping Coalition (CSC), an international association of civil society environmental protection in collaboration with marine coatings providers, submitted to the IMO the need to for a transparent and reliable hull and propeller performance standard in December 2011 (IMO & CSC, 2012). Work on the ISO-Standard was initiated in June 2013, with a large diverse group of interested parties. The working group reached consensus in 2016 with ISO 19030.

Hull and propeller performance is defined as "the relationship between the condition of the hull and propeller and the propulsion power required to move the vessel through water at a given reference speed". (ISO 19030-1, 2016).

By definition, deterioration in hull and propeller performance relates to resistance increase, viscous and pressure, and reduced propeller thrust due to changes in flow/wake field. Many efforts for an analytical approach prove it is extremely difficult to eliminate all interfering factors and solely assess the effects of hull and propeller condition.

The main reasons for the development of ISO 19030, which had been acknowledged, was:

- Complexity to quantify the effect of the deterioration of the condition of hull and propeller, together and/or separately.

- The second and third IMO GHG Study (2009) disclosed the potentials of hull and propeller maintenance.

- The lack of a reliable standard for measuring the effects of new developing anti-fouling systems and retrofit technologies on hull and propeller performance.

- Lack of incentives for investing in hull and propeller performance technologies because of non-transparent and biased methods to prove competitiveness and make decisions.

- Due to the above two, no incentive for neither Charterers nor ship owners/ operators to invest in hull and propeller performance.

Scope of ISO 19030

It should be stated that ISO 19030 scope at its current version, is to monitor a trend in changes of hull and propeller performance in a ship specific and relative way. In fact, in the latest guidelines on the development of a SEEMP MEPC.346(78), endorses "technology-coating systems, possibly in combination with cleaning and docking intervals", assessment of which is the purpose of the standard under discussion.

ISO 19030 is a big data approach based on generally available and recognized applications, to overcome the complexity of an analytical approach. It specifies the measuring equipment and sensor requirements, data manipulation including various filters and corrections, and finally outlines how to calculate a set of four performance indicators with limited uncertainty. All that to assess a "new" performance of hull and propeller, compared to a reference performance (sea trials or other).

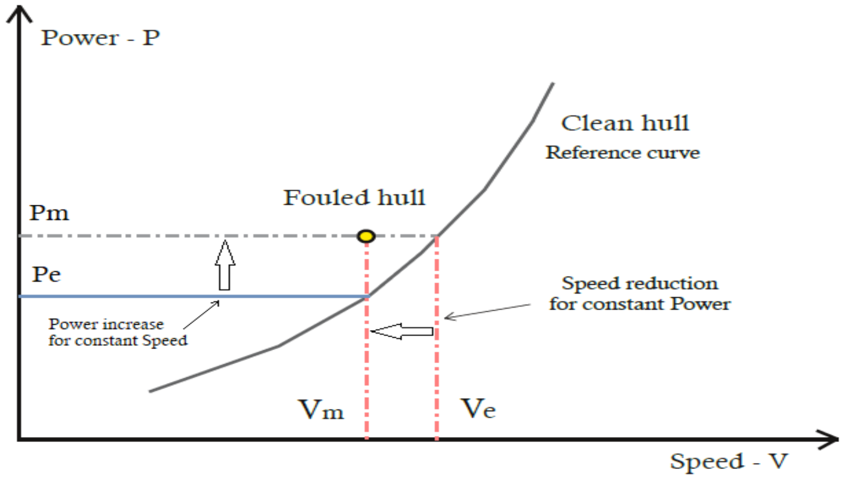


Figure 1: ISO 19030 principle for performance indicators

Consequently, ISO application could yield interesting results in the following cases:

- ✓ after deterioration of the condition of hull and propeller through time (fouling, roughness, paint loss);
- ✓ after cleaning and/or painting;
- ✓ hull or propeller damage repairs;
- ✓ retrofit activities or application of a new-technology;
- ✓ modifications on the hull form or propeller characteristics;
- ✓ benchmark performance of sister ships or even compare different type of ships;
- ✓ benchmark dry dock's effect on hull and propeller performance for sister vessels.

Companies which invest in big data, already make use of software and programming routines and import desired data sets to manipulate, visualize and predict various efficiencies. A branch of such a data strategy, a program routine, could be the use of ISO 19030.

1.2 Critical review of similar studies

The IMO has previously estimated that the deterioration in hull and propeller performance of the world fleet is accountable for 9 ÷ 12% of GHG emissions (IMO, 2009). The Clean Shipping Coalition (MEPC 63/4/8), estimated that poor hull and propeller performance represents around 10% of world fleet vitality cost. A large body of research has been made to assess the financial and environmental effects caused by fouling and the deterioration of condition in general. Hull fouling, a primary contributor, can be considered as the undesirable accumulation of microorganisms, algae, and animals on artificial surfaces immersed in seawater (*Flemming, 2002*).

In Figure 2, fuel oil consumption is divided in components based on a study on tanker vessels data (INTERTANKO 2020). It is clear that hull and propeller condition is proven a main contributor for the fuel consumption. For this reason, hull and propeller maintenance consists one of the main grounds for research and optimization. In fact, it has been predicted that up important operational costs could be cut after effective maintenance and cleaning of hull and propeller (*Coraddu et al., 2019a*).

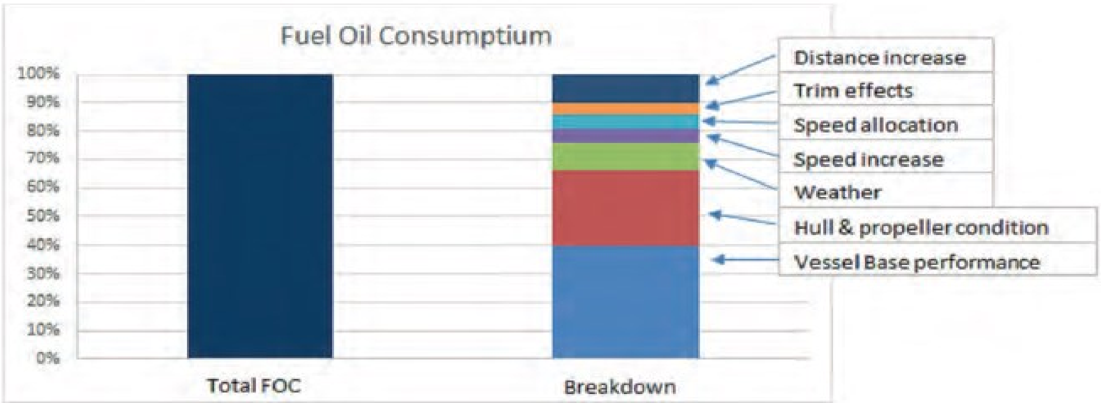


Figure 2: Main contributors to total Fuel Oil Consumption (INTERTANKO 2020)

To this day, an international standard (ISO 19030, 2016) and plethora of numerical methods have been published to quantify aspects of hull and propeller performance. An interesting review of relevant numerical methods is presented in (*Vlachev et. al 2022*). The methods are grouped based on three main modelling approaches: Physical Models (PMs), Data-Driven Models (DDMs) and Hybrid Models (HMs).

The ISO 19030 at its first revision, has attracted criticism for some aspects of the procedure, for example inadequate filtering or gross rejection of data from stated reference conditions. However, it should be viewed as a significant starting point. It is endowed with the promising concepts of high-frequency big data, digitalization and assessment through elimination of external factors. Moreover, it allows estimation with inexpensive and widely common practices, such as noon reports and other daily logs.

Noon reports have been widely exploited by researches to assess the impact of hull and propeller condition on the overall performance, displaying promising results (*Pedersen and Larsen, 2009a*). One proposed method using noon reports during a 4,5 years dry-docking interval, detected a time frame for a cost-benefit maintenance action, following the ISO 19030 procedure. The performance indicator in that case is the deviation of fuel oil consumption from reference values. (*Koboević et al. 2018*). Manual reporting is a remaining practice which results in low frequency data and with added the factor of human error. If the influence of human error is minimized, then uncertainties of manual reporting can be limited to 5% (*Aldous et al, 2015*).

Due to the growing global shipping environmental footprint, state-of-the-art methods are needed, in order to provide enhanced numerical procedures with lower uncertainty for hull and propeller performance assessment. In a review of numerical methods developed for the assessment of biofouling state by (*Vlachev et. al, 2022*) the most promising are the Hybrid Models, HMs, which combine simplistic physical models and data-driven practices. They boast accuracy, speed and flexibility for addressing real-world maintenance decision making. ISO 19030 can be considered a hybrid approach.

There are also software development attempts, like the subject thesis, which try to automatize the assessment of changes in hull and propeller performance. The proliferation of sensor data has allowed a variety of methods to emerge, which drive results either by using the ISO 19030 standard procedure and its performance indicators, either by utilizing it partially and proposing amendments, either follow their own analyses. A software development with hybrid logic (physical and data-driven practices), can prove a cost-effective way to identify performance decay patterns. An example is a monitoring software developed for ISO 19030 application, which gathers sensor data, and can display current situation based on reference ones, or detect long term speed loss by the procedures of ISO (*Papageorgiou N., 2020*). Worth noting that on one case an LNG was spotted with yearly speed loss of more than 4 % and on another case a vessel showed speed loss of 11.7% over 2.5 years, compared to its out-docking condition.

ITTC has offered numerous studies and guidelines and played an important role in developing ISO 15016 (2015). ISO 15016 has been a benchmark to mitigate weather effects and also to establish standard reference performance of a vessel at sea trials. ISO 19030 has been significantly influenced by the ISO 15016. These ISO standards share the same approach with ITTC study (2017).

1.3 Scope of the study

The scope of the study is summarized in the following bullet points:

- Develop a program in python programming language for the automation of ISO 19030 procedure.
- The application of ISO 19030 as close as possible to the default method, with auto-logged data during one year of a bulk carrier's operation, with sampling frequency of one measurement per minute
- The observation of the data processing procedure during the filtering and validation stage
- A sensitivity analysis of the Performance Values, PVs and PPVs[9], to the reference conditions that the validated data should comply with. For this purpose, the effect of three different scenarios on the final data and on PVs and PPVs is examined.
- The assessment, with ISO 19030, of a propeller maintenance event which took place at the end of the first quarter of the year and the sensitivity of the results to different reference conditions than the default method.

[9] Performance Values, PVs, refer to speed loss percent due to changes in hull and propeller performance and Power Performance Values, PPVs, are similar in concept but refer to power increase.

Chapter 2 - ISO/DIS 19030: Ships and marine technology – Measurement of changes in hull and propeller performance

2.1 ISO 19030 – Part 1: General principles

In this International Standard Part 1 the general principles and four performance indicators are presented for the evaluation of hull and propeller maintenance, repair and retrofit activities. The analysis about the uncertainty of the results is detailed in Annex A of this part describes the method used for uncertainty estimation concerning the resulting Performance Indicators.

2.1.1 General Principles

Hull and propeller performance is related with hull resistance and propeller efficiency. The condition of the hull deteriorates over time due to fouling, small deformations or paint loss. Consequently, the flow of water around the hull is affected and the ship's overall resistance is increased, especially frictional resistance. At the same time, the deterioration of the condition of the propeller and the modification to the wake field of the propeller due to changes in hull flow contributes to changes in propeller efficiency. The result is the gradual increase of the delivered power required to move the ship through water at a given speed, or equivalently, the decrease of the achieved speed through water at a given delivered power.

Hull and propeller performance model is based on the concepts of ship propulsion efficiency and ship resistance. In this light, delivered power can be expressed as:

$$P_D = \frac{R_T \cdot V}{\eta_Q} \qquad (2.1)$$

where R_T is the total ship resistance [N], V is the ship speed through water [m/s] and η_Q is the quasi-propulsive efficiency [-].

Total resistance consists of several parts and can be described as:

$$R_T = R_{SW} + R_{AA} + R_{AW} + R_{AH} \qquad (2.2)$$

where R_{SW} is still water resistance, R_{AA} is added resistance due to wind, R_{AW} is added resistance due to waves and R_{AH} is the added resistance due to changes in hull condition (fouling, mechanical damages, bulging, paint film blistering, paint detachment, etc.), all in [N].

In addition, quasi-propulsive efficiency is equal to:

$$\eta_Q = \eta_O \cdot \eta_H \cdot \eta_R \qquad (2.3)$$

where η_O is open water propeller efficiency, η_H is hull efficiency and η_R is relative rotative efficiency.

As a result, the added resistance due to changes in hull condition can be written as:

$$R_{AH} = \frac{P_D \cdot \eta_Q}{V} - (R_{SW} + R_{AA} + R_{AW}) \qquad (2.4)$$

Eq. 2.4 indicates that hull resistance and/or propeller efficiency can be quantified by measuring the variations of the speed-power relationship, if it is possible to collect the necessary information and minimize the varying influences.

In this respect, ship speed through water and delivered power are the **primary parameters** when measuring changes in hull and propeller performance. Ship speed V can be measured directly, while delivered power must be approximated. Two methods for power approximation are presented in ISO - Part 2 with small difference in accuracy. One is based on measurements on shaft torque and shaft revolutions and the other on measurements of the fuel being consumed and the SFOC reference curves.

The variations of speed-power are monitored for the specific ship over set periods, together with other parameters. The vessel during service operates under varying operational profiles (e.g. speed, loading, trim) and environmental conditions (e.g. wind speed, water depth, currents). Two periods are established: the **reference period** and the **evaluation period**.

Measurable parameters are specified which can be used to minimize the influence of environmental and operational variations in speed and power measurements. These are the **secondary parameters** of the method. They are the bases for the filtering and normalization procedures necessary to make the reference and evaluation period adequately comparable.

In Part 2 of this International Standard a “minimum set” of measurement sensor signals and signal quality for the default method are specified. In Part 3 of this International Standard more flexible approaches are defined, concerning alternative measurement systems and sensor signals that are generally available and an estimation of their effect in expected accuracy is provided.

2.1.2 Performance indicators, PIs

Performance indicators (PIs) stemming from the measurements and calculations can be used for the evaluation of hull and propeller maintenance, repair and retrofit activities. Four performance indicators are presented for estimating changes in hull and propeller performance, and can be seen in Table 2 below.

Table 2: Basic hull and propeller Performance Indicators, PIs

PI	Purpose	Corresponding periods
Dry-docking performance	Determine the effectiveness of the dry-docking (repair and/or retrofit activities	*Evaluation period*: Following present out-docking *Reference period*: Previous following out-dockings
In-service performance	Determine the effectiveness of the underwater hull and propeller solution (including any maintenance activities that have occurred over the course of the full dry-docking interval)	*Evaluation period*: A period to the end of the dry-docking interval *Reference period*: A period following out-docking
Maintenance trigger	Trigger underwater hull and propeller maintenance, including propeller and/or hull inspection	*Evaluation period*: Any chosen period between two dry-dockings *Reference period*: At the start of the dry-docking-interval
Maintenance effect	Determine the effectiveness of a specific maintenance event, including any propeller and/or hull cleaning	*Evaluation period*: After a maintenance event *Reference period*: Before a maintenance event

Illustrations of intervals regarding each PI for better understanding are given in Annex A.

2.1.3 Uncertainty and accuracy of the Performance Indicators

Appropriate use of Performance Indicators depends on understanding to what extent uncertainty influences the accuracy of PIs.

Sources of uncertainty can include:

- Measurement uncertainty which relates to sensor accuracy (both the uncertainty that occurs during laboratory tests and also uncertainties because of sensor installation maintenance and operation)
- -Uncertainty due to the use of samples, average, aggregate values of parameters that are variable with time
- Uncertainty due to the use of formulas which simplify relations to improve feasibility and counter imperfect information.

The aim of this standard is to define standard procedures for meaningful deployment of the PIs for decision making purposes, reducing the above uncertainties as much as practicable. Different availabilities of sensors and hardware are taken into account, the accuracy of which is made transparent.

2.2 ISO 19030 – Part 2: Default method

This part defines the default method for measuring changes in hull and propeller performance. As mentioned earlier, changes in hull and propeller performance translates to the changes in delivered power required to move the ship through water at a given speed, or equivalently changes in speed at a given delivered power, under the same environmental conditions and operational profile, with no changes in transmission efficiency.

2.2.1 Measurement parameters

Primary and secondary parameters must be measured with the appropriate signal sensors and suggested sensor accuracies.

The **primary parameters** are speed through water and delivered power. Delivered power must be approximated either according to Annex B, from measurements of shaft revolutions and shaft torque, or if not possible, by measurements of fuel flow and the SFOC reference curves of the engine, defined in Annex D. This way the delivered power can be approximated through the brake power.

The **secondary parameters** must be measured to ensure adequately comparable reference periods through filtering and normalization procedures. Thus, environmental factors and the ship's operational profile must be measured.

Table 3 shows the parameters, minimum sensors and accuracy required for the application of the default method.

Table 3: Minimum sensor requirements for measured parameters

Parameter	Acceptable measurement device/source	Unit
Vessel Speed	**Speed log** - minimum sensor accuracy of ±1% at 1σ (confidence interval of 66%), or ±0,1 knots at 1σ, whichever is greater	[knots]

Delivered Power	**As per Annex B** **Torsion meter** - minimum sensor accuracy for torque of ±0,5 % (1σ) **Pick-up, optical sensor, ship revs counter** - minimum sensor accuracy of ±0,5 % (1σ) **As per Annex C** **Flow meter** - minimum sensor accuracy of ±0,5 % for the full working range **Thermometer** - minimum sensor accuracy of ±(0,3+0,005t) %, where t is °C	[kW]
Relative Wind Speed and Direction	**Ship anemometer** - minimum sensor accuracy of ±1m/s, ±5°	[m/s], [°]
Speed over ground	**(D)GPS**	[knots]
Ship heading	**Gyro-compass, or compass-DGPS**	[°]
Shaft revolutions	**Pick-up/optical sensor, ship revs counter** - minimum sensor accuracy of ±0,5%, 1σ	[rev/min]
Static draught fore / aft	**Information from loading/stability computer or equivalent sources** Preference for observed draft – when available	[m]
Water depth	**Ship echo sounder** minimum sensor accuracy of · ±0,5m on the 20m range scale · ±5m on the 200m range scale, or · ±2,5% of the indicated depth, whichever is greater	[m]
Rudder angle	**Rudder angle indicator** -minimum sensor accuracy of ±1°	[°]
Seawater temperature	**Thermometer**	[°C]
Ambient air temperature	**Thermometer**	[°C]
Air pressure	**Barometer**	[Pa]

Notably, if ambient temperature and air pressure are not measured, the values to be used are 15 °C and 101,325 kPa (1 atm), respectively. The same set of sensors must and the same sensor settings have to be used in the reference and evaluation periods. They should be installed, maintained and calibrated as per manufacturer specification.

2.2.2 External information

Specific external information is needed to be made available for the default method. If the information is not available, alternative sources can be but the information source and procedure followed must be documented. Data from the same approach must be used for the whole operational range and for both the reference and evaluation periods.

The default method requires the following types of external information to be acquired for the ship in question:

1. Speed-power data or speed power reference curves
2. Displacement tables and/or formulae
3. Quantities for the correction for wind resistance

1. Speed-power data may originate from full-scale speed trials according to ISO 15016, from towing tank tests or from computational fluid dynamics (CFD) simulations. The range of the reference speed-power data should cover the range the ship operates.

Speed-power reference curves refer to standard displacements. The difference between reference and actual displacements is addressed with correcting speed and/or power values according to Admiralty formula. Moreover, with same formula, additional speed-power data can be extracted for different displacements:

$$V_2 = V_1 \left(\frac{\Delta_1^{\frac{2}{3}}}{\Delta_2^{\frac{2}{3}}} \right)^{\frac{1}{3}} \qquad (2.5)$$

where V_1 is speed at measured displacement, V_2 is speed at reference displacement, Δ_1 is measured displacement and Δ_2 is reference displacement.

2. Displacement tables and formulae are mainly used to convert measured draught and trim into displacement. They should cover the actual operational loading conditions of the vessel in question. If a significant operational change occurs, e.g. irregular slow steaming, or trim optimization, high resolution speed-power-draught-trim data should be obtained.

3. Quantities needed for wind correction include:

- Transverse projected area and centroid above water level
- Wind resistance coefficients based on beforementioned area
- Anemometer height above sea level at reference condition
- Ship width

Wind resistance coefficients from wind tunnel tests of the vessel in question should be used. If these coefficients are not available, the wind resistance coefficients according to ISO 15016 should be used. It should be noted that in its current revision, the added wave resistance and correction is not taken under consideration.

2.2.3 Procedure to obtain Data for the Performance Values, PVs calculation

Measurement procedures refer to data acquisition, data storage and data preparation. Once data are stored and retrieved, they are processed. The aim is the final data to be as accurate as possible the calculation of Performance Values, PVs, used subsequently for the calculation of Performance Indicators, PIs.

2.2.3.1 - Data Acquisition

Data should be continuously collected from the data acquisition system onboard. Data sampling frequency should remain unchanged over the whole measurement period. The parameters and the minimum acquisition frequency, can be seen in Table 4.

Table 4: Data acquisition frequencies for the default method

	Parameter	Minimum Data acquisition rate
Primary	Vessel speed through water	Once every 15 seconds (0,07Hz)
	Delivered power	Same as for vessel speed and same timestamp as vessel speed
Secondary	Shaft revolutions	Once every 15 seconds (0,07Hz)
	Relative wind speed and direction	Once every 15 seconds (0,07Hz)
	Speed over ground	Once every 15 seconds (0,07Hz)
	Ship heading	Once every 15 seconds (0,07Hz)
	Rudder angle	Once every 15 seconds (0,07Hz)
	Water depth	Once every 15 seconds (0,07Hz)
	Static draught fore and aft	Whenever loading condition changes
	Water temperature	Once every 15 seconds (0,07Hz)

2.2.3.2 - Data Storage

Data should be stored in the data acquisition system and should be retrievable at any time. Data are stored with time stamps as time offsets of Universal Time Coordinated (UTC), indicating the moment of collection in time. A backup facility is recommended.

2.2.3.3 – Retrieved Data Set

The retrieved data should be compiled in a tabular format and sorted sequentially based on the coinciding time stamp of the primary parameters. The time stamp (UTC) serves as the Unique Identifier, UI. The UI combined with a set of one measurement for each parameter at a point in time is referred to as a "**data point**".

Data from signals with higher or lower acquisition frequencies should be compiled to attain the same frequencies as the primary parameters. Data with higher frequencies should be averaged over the relevant time interval, while data with lower frequencies should be duplicated over the relevant time interval. The **Retrieved Data Set** refers to the complete retrieved set of data with sorted and unique timestamps, in fact a set of "data-points'.

2.2.3.4 – Validated Data Set

The Retrieved Data Set needs filtering, validation and correction for environmental factors. The **Validated Data Set** is the data set that remains when all invalid data points are excluded from the retrieved data set, according to filtering procedures and Chauvenet's criterion, in Table 6.

The steps of the filtering in ISO 19030 are outlined below:

1) Firstly, the raw data are grouped in consecutive blocks with 10-minute time-span. As a result, with the available sampling frequency, ten (10) data points are accumulated in each block.

2) Secondly, data points with at least one missing parameter value are rejected.

3) For each block the mean, the standard deviation, the maximum and the minimum values are computed. If the standard deviation of the filtering parameters in Table 5, surpasses the corresponding limits, the whole data block is considered invalid and all data points in the block are rejected. The purpose is to ensure steady conditions, by neglecting data which indicate an operational transition, which can be inferred by the following parameters standard deviation.

Table 5: Conditions for the standard error of the mean for measured parameters

Parameter	Limit for std
RPM	3 min^{-1}
Speed through water	0,5 knots
Speed over ground	0,5 knots
Rudder angle	1 degree

4) Finally, for the remaining blocks, the probability of the occurrence of each parameter value in each data point, multiplied by the number N of data points inside the block/group, is calculated. If same is greater than 0.5, the data point is considered an **outlier** and all parameter values of the data point are rejected.

Table 6 below presents the necessary Formulae to detect outliers, according to Chauvenet's criterion:

Table 6: Chauvenet's criterion during the filtering procedure

Parameter unit:	Not in angles	In angles
Statistics:		
Mean μ	$\mu = \frac{1}{N}\sum_{i}^{N} d_i$	$\mu = atan2\left(\frac{\sum_{i=1}^{N}\sin d_i}{N}, \frac{\sum_{i=1}^{N}\cos d_i}{N}\right)$
Difference $\boldsymbol{delta_i}$	$delta_i = \lvert(d_i - \mu)\rvert$	If $r_i = mod(\lvert(d_i - \mu)\rvert, 360) > 180\ degrees$, $delta_i = 360\ \text{deg} - r_i$ Else, $delta_i = r_i$
Standard error of the mean $\boldsymbol{\sigma}$	$\sigma = \sqrt{\frac{1}{N}\sum_{i}^{N} delta_i^{\ 2}}$	
Probability of occurrence $\boldsymbol{P(d_i)}$	$P(d_i) = erfc\left(\frac{delta_i}{\sigma\sqrt{2}}\right)$	
Chauvenet's Criterion	If $P(d_i) \cdot N < 0.5$ the datum is considered an outlier	

where,

d_i , is the parameter value in a data point

$atan2(\cdot\ ,\ \cdot)$, is the arctangent function with two arguments;

$mod(x, y)$, is the modulo of two entries x and y;

$P(d_i)$, is the probability of occurrence of the value d_i within the block with N data;

N, is the number of parameter values in each block/group;

$erfc$, is the complementary error function;

$P(d_i) \cdot N < 0.5$, is the limit below which the datum is an outlier.

2.2.3.5 – Corrected Data Set

The delivered power of the data points in the Validated Data Set should be corrected for wind resistance, according to Annex G of ISO 19030. The calculation for corrected power is done through wind coefficients which stem from external information, wind tunnel tests or other. Wind coefficients are usually determined from relative wind direction at the reference height. The wind speed and the direction at the reference height of the wind tunnel tests is calculated as per ISO 19030 Annex E. If the reference height at wind tunnel tests is not available, a reference height of 10 meters shall be used.

After wind resistance coefficient is determined, for each data point, the Delivered Power P_D is corrected as per ISO 19030 Annex G, according to Eq. 2.6:

$$P_{D,corr} = P_D - \Delta P_W \qquad (2.6)$$

where:

$$\Delta P_W = \frac{(R_{rw} - R_{0w})v_g}{\eta_{D0}} + P_D \left(1 - \frac{\eta_{DM}}{\eta_{D0}}\right) \qquad (2.7)$$

$$R_{rw} = \frac{1}{2} \cdot \rho_\alpha \cdot {v_{wr}}^2 \cdot A \cdot C_{rw}(\psi_{wr,ref}) \qquad (2.8)$$

$$R_{0w} = \frac{1}{2} \cdot \rho_\alpha \cdot {v_g}^2 \cdot A \cdot C_{0w}(0) \qquad (2.9)$$

ΔP_W: wind correction factor [W]

R_{rw}: wind resistance due to relative wind [N]

R_{0w}: air resistance in head wind condition [N]

v_g: ship speed over ground [m/s]

v_{wr}: the relative wind speed at reference height [m/s],

C_{rw}: wind resistance coefficient, dependent on direction of relative wind $\psi_{wr,ref}$ [-]

C_{0w}: wind resistance coefficient for head wind (0o wind direction) [-]

ρ_α: air density [kg/m^3]

A: transverse projected area in current loading condition [m^2]

$\psi_{wr,ref}$: the relative wind direction at the reference height (0° for head winds, 90° for wind from abeam [°]

η_{D0}: the propulsive efficiency coefficient in calm condition [-]

η_{DM}: the propulsive efficiency coefficient in actual voyage condition [-].

The transverse projected area, A, at current loading condition is approximated as follows:

$$\Delta T = T_{des} - T \qquad (2.10)$$

$$A = A_{des} + \Delta T \cdot B \qquad (2.11)$$

ΔT: difference between design draught and current draught, in m

T_{des}: design draught, in m

T: current draught, in m

A_{des}: transverse projected area in current loading condition, in m^2

B: ship width, in m

2.2.3.6 – Performance Values and Prepared Data Set

A Performance Value, PV, is calculated for every Data point of the Corrected Data Set, and the union of those two is called the **Prepared Data Set**.

The PVs are the percentage speed loss and are calculated as the relative difference in per cent between the measured vessel speed through water, V_m and an expected speed through water, V_e, as shown in Eq. 2.9:

$$V_d = 100 \cdot \frac{V_m - V_e}{V_e} \qquad (2.9)$$

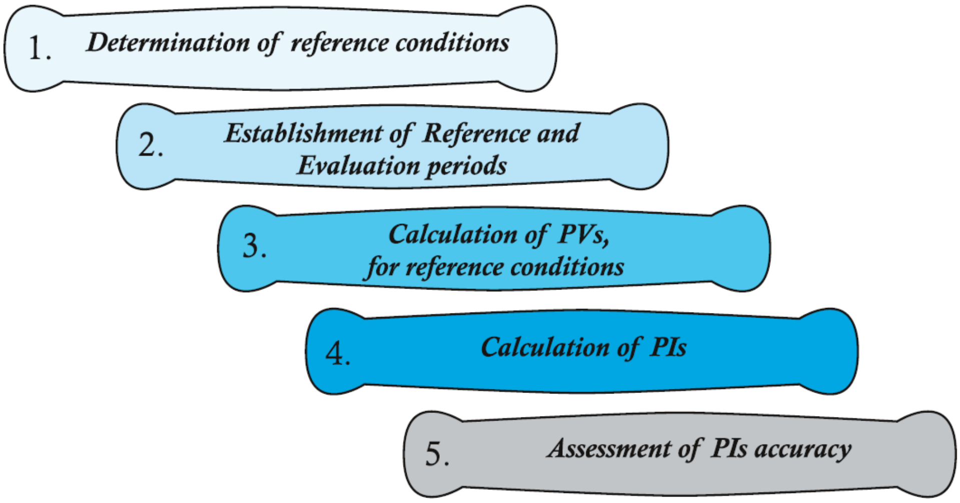
The representation of formula 2.9 is shown in Figure 1, in Chapter 1. The expected speed through water is read from a speed-power reference curve at the corrected delivered power and at the measured displacement and trim. Displacement is computed by the displacement tables and the static draught and trim.

The Performance Values, PVs can be calculated also in terms of power, according to ISO Annex K. In this respect, they are referred to as Power Performance Values, PPVs, and are the relative difference in per cent between the measured corrected delivered power, P_m, and the Expected delivered power, P_e. The equation for power is same as Eq. 2.9 with P_m, P_e.

2.2.4 Calculation of the Performance Indicators, PIs

Four performance indicators are defined in this International Standard, as previously mentioned. Illustrations of Reference and Evaluation periods to be set appropriately for each performance indicator are presented in Annex A**.** The calculation of PIs is performed in five (5) steps and are shown in Figure 3:

Figure 3: Steps for PI calculation, after validation and correction, as per default method



2.2.4.1 - Reference Conditions

These are the same for all PIs and they are met when simultaneously all of the following is true:

- Water temperature is above +2ºC and the vessel is not trading on ice;
- Wind speed is between 0 – 7,9 m/s (BF 0 and BF 4);
- Water depth is greater than the larger of the values obtained from the two formulae:

  $h = 3\sqrt{B \cdot T_M}$ and $h = 2{,}75\frac{{V_S}^2}{g}$ (2.10) & (2.11)

  where h is water depth [m], B ship's breadth [m], T_M draught at midship or mean draught [m], V_S ship speed [m/s], g is gravitational acceleration, 9,80665 m/s^2;
- Absolute rudder angle value is smaller than 5º;
- Delivered power is within the range of available speed-power reference curves
- Displacement is within ±5% of the displacement values for the available speed-power reference curves

- If delivered power is approximated through brake power, the estimated delivered power has to be within the range of power values covered in the available SFOC reference curve.

The reference conditions defined are criticized as strict. This is done for maximizing the accuracy of the PVs and PIs by rejecting a usually extent number of data, to preserve only the data which represent adequately or satisfyingly comparable Reference and Evaluation periods. In this respect, Reference and Evaluation periods might be discontinuous.

2.2.4.2 – Reference and Evaluation Periods

For Dry-docking performance periods Reference and Evaluation periods should both have a duration of one year.

For In-service performance both periods should have the duration of one year.

For Maintenance trigger both periods should be of minimum three months length.

For Maintenance effect both periods should be of minimum three months length.

2.2.4.3 - Calculation of the Performance Indicators, PIs

The Performance Indicators, PIs are obtained by the PVs when the latter are calculated for each of the reference and evaluation periods. At this point, the PIs can be calculated as follows:

$$k_{HP} = \bar{V}_{d,eval} - \bar{V}_{d,ref} \qquad (2.12)$$

where $\bar{V}_{d,ref}$, $\bar{V}_{d,eval}$ are the average percentage speed losses over the Reference and Evaluation periods respectively, and are calculated from the respective data sets as follows:

$$\bar{V}_{d,ref} = \frac{1}{k}\sum_{j}^{k}\frac{1}{n}\sum_{i}^{n} V_{d,j,i} \qquad (2.13)$$

where k: number of Reference periods

j: reference period counter

n: number of Data points in the Processed Data Set under reference conditions in the Reference period j

i: counter Data points in Reference period j

$V_{d,j,i}$: percentage speed loss for Data point i in reference period j

and

$$\bar{V}_{d,eval} = \frac{1}{n}\sum_{i}^{n} V_{d,eval,i} \qquad (2.14)$$

where n: number of Data points in the Processed Data Set under reference conditions of the Evaluation period

$V_{d,eval,i}$: percentage speed loss for Data point i in a Data set of the evaluation period

Following the above formulae, PIs result in terms of speed. Calculating PIs dimensioned in terms of power is possible and a method is defined in Annex K of the ISO standard. PPVs instead of PVs should be calculated and a replacement of speed by corrected delivered power in above formulae. The Power Performance Indicator, PPI, as in ISO Annex K, would be calculated by Eq. 2.15.

$$k_{HP-P} = \bar{P}_{d,eval} - \bar{P}_{d,ref} \qquad (2.15)$$

2.2.4.4 - Accuracy of the Performance Indicators, PIs

Appropriate use of the PIs for decision-making purposes is dependent on understanding to what extent uncertainty influences the accuracy of each. An approximation for the expected accuracy is presented, based on calculations, simulation parameters and assumptions, as presented in Part 1 of the standard. The procedure takes into account representative assumptions of the ship types and sizes for which the default method is intended. However, when specifications of an individual ship are more unique, one must ensure the applicability of the key assumptions.

The quantification of accuracy, presented below in Table 7, offers guidance on achieved accuracy when all requirements of this Part of this International Standard are met.

Table 7: ISO 19030 method's expected accuracy for each Performance Indicator

Performance indicator (PI)	**Estimated uncertainty in % of PIs, to within a 95% confidence interval**

Dry-docking performance	± 0,3% *assuming one Reference period
In-service performance	± 0,3% **assuming one year evaluation period / 2 years dry-docking interval
Maintenance trigger	± 0,5%
Maintenance effect	± 0,5%

2.2.5 Annexes

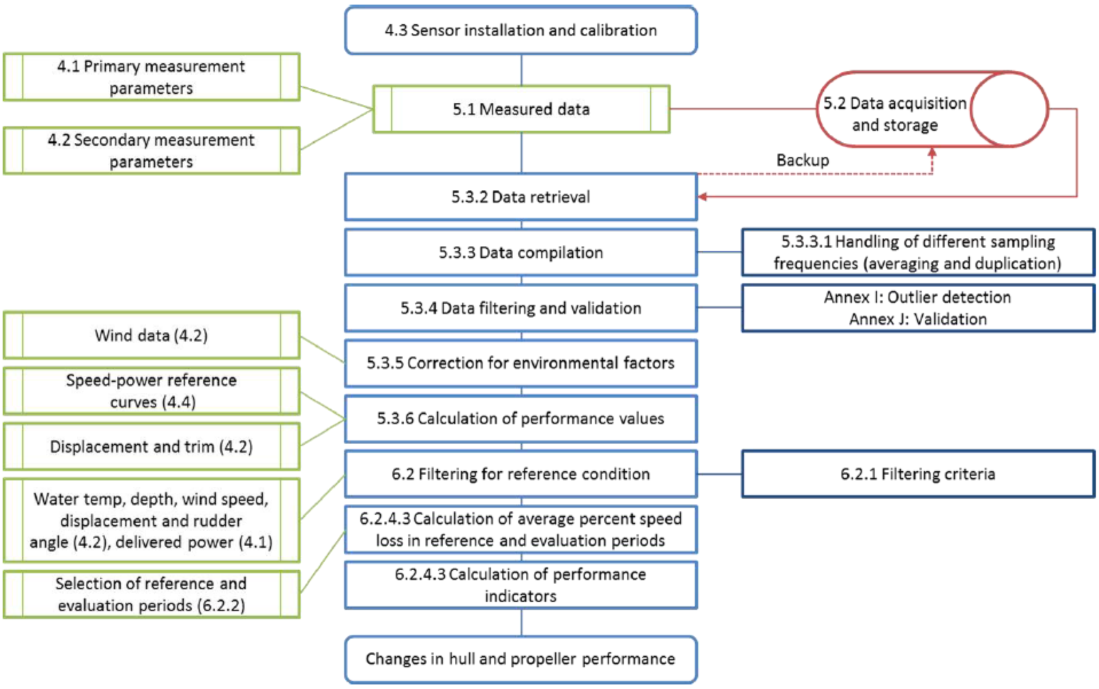
The Annexes of Part 2 of this International Standard consist of procedures used throughout the implementation of the default method for measuring changes in hull and propeller performance.

Table 8: List of the Annexes in ISO 19030 - Part 2

Annex	Title
Annex A	Process ISO 19030-2
Annex B	Approximating Delivered power based on calculations of Shaft power
Annex C	Approximating Delivered power based on calculation of Brake power
Annex D	SFOC reference curve
Annex E	Calculation of true wind speed and direction
Annex F	Procedure to obtain ship specific power-speed-draught-trim databases
Annex G	Correction for wind resistance
Annex H	Protocol to export data from data logger
Annex I	Outlier detection (Chauvenet's criterion)
Annex J	Validation (of data blocks)
Annex K	Method for calculating Power Performance Values, PPV, and Power Performance Indicators, PPI

Annex A of ISO provides a comprehensive diagram of the procedure, shown in Figure 4:

Figure 4: The flow chart of ISO 19030 - Part 2



2.3 ISO 19030 – Part 3: Alternative methods

This Part of the International Standard proposes alternatives to the default method. The use of proxies and alternatives will ease the use of ISO 19030, however accuracy will be reduced, in a tolerable way or not.

2.3.1 Alternatives for measurement parameters

The alternatives (proxies) for primary and secondary parameters are presented here. Instruments, automated equipment and sensors must be installed, maintained and calibrated in accordance with Part 2. The proxies can be used in case it is not possible or practical to meet the minimum requirements for the default method.

2.3.1.1 - Primary parameters proxy

Speed through water can be approximated by speed over ground measurements (GPS or navigation system) and should be as accurate as possible. In this case, the PVs and PIs should be calculated from speed over ground instead of speed through water. When automatic recording systems are not available (speed log, GPS speed over ground), speed of the vessel can be calculated by distance travelled per period of time. The procedure must be legitimate and should be documented.

Delivered power can be approximated according to Annex B, C, that is from break power from fuel consumption data, using mass or volumetric flow meters. This method assumes 1) Conventional propulsion system 2) two-stroke directly coupled to propeller (no gearbox) 3) no shaft generator. The fuel consumption is measured for the main engine alone and must not include consumption by auxiliaries, boilers or returns. The equation used is:

$$P_B = f\left(M_{FOC} \times \frac{LCV}{42.7}\right) \qquad (2.16)$$

where M_{FOC} is mass of consumed fuel oil by main engine (kg/hour), LCV is lower calorific value of fuel oil (MJ/kg) and f is SFOC reference curve.

The uncertainty of this proxy can be considerable, because of the influence of changes in fuel quality, the accuracy of the fuel mass sensor and the influence of changes in SFOC over time due to engine degradation. The impact of uncertainty is outlined in Part 1 of this International Standard, Annex A. As far as measurement of fuel consumed is concerned, needed for brake power calculation, when automated systems are not available, the choice of measurement method depends on the available equipment on the vessel.

Manual readings, either by the physical sounding of tank or by taking manual meter readings, the frequency must be the most practical, but not less than daily. Taking into account effects of trim and list for sounding corrections has to be documented. Also, corrections must be applied for temperature and density for both volumetric flow meters and sounding measurements.

Sources of uncertainty associated with obtaining measurements of the mass of fuel are presented in Part 3. Some are errors due to ship motions, trim and/or list, due to manual recording or calculation of total fuel consumed, uncertainty in the dimension of the tank etc. Uncertainty of the flow meter measurement and errors in correction calculation and error propagation due to calculating fuel consumption from differences of inflow and outflow of fuel.

2.3.1.2 - Secondary parameters proxy

Proxies can be used to isolate comparable reference conditions and to enable filtering and normalization procedures, if measurement of those parameters and/or sensor requirements set in the default method in Part 2 cannot be followed. In some cases, one may have to modify the reference condition criterion or modify the analysis procedure. Such modifications must be fully and transparently documented and justified. The alternatives/proxies for some secondary parameters can be seen in the Table 9:

Table 9: Measurement alternatives for secondary parameters

Parameter	*Proxy measurement*
Wind speed:	Anemometer with lower accuracy than as specified in Part 2
Draught:	Observed directly or derived from observed draught in port
Water depth:	Calculated from electronic nautical charts and the ship track from (D)GPS
Rudder angle:	Not taken into account (None)

For wind speed, lower accuracy sensors may be used if the requirements of default method cannot be met. If it is done manually, the measurements must not be less than daily and reflect representative wind conditions of the period in question. Draught can be recorded from a loading computer. The values must reflect vessel's condition at the beginning of sea passage and may be derived from observed draught and trim in port. If there is a significant change in displacement, draught values must be updated. A clear procedure of personnel's readings must be documented. Water depth, when automated logging system is not available, must be obtained from electronic nautical charts and recorded alongside other secondary data.

2.3.2 Alternatives for measurement procedures

2.3.2.1 - Data acquisition

The default method in Part 2 of this International Standard, suggests data acquisition frequency of 1 signal every 15 seconds (0.07 Hz). If an available system for data collection cannot achieve such high frequency, a lower frequency (e.g. noon data) is permitted to be used alternatively. Generally, high frequency data collection reduces uncertainty. If data are collected manually, there is the probability of human error.

2.3.2.3 - Data preparation

Generally, the procedure as in Part 2 of this International Standard should be followed. If reliable measurements of wind speed and direction, for wind resistance correction as in Part 2 Annex G, are not available, this step has to be omitted. In case the speed-power reference curves from external sources do not cover the range of the vessel's operation, additional curves should be estimated by interpolation or by generally acceptable power estimation approaches and the procedure must be documented.

In case there is no external information about speed-power reference curves, they could be extracted from in-service data following one of the below methods:

- Conducting "permanent trial trips" as detailed in ISO Part 3, Clause 5.3.1.2.1
- Collecting data by "passively monitoring" the vessel as it operates as, detailed in ISO Part 3, Clause 5.3.1.2.2

For data collected in each loading condition, a speed-power curve should be fitted and this curve is to be used as a speed-power reference curve for the loading condition in question. The mathematical approach should be documented. As an example, a curve fitting approach is presented, with model linearization by taking algorithms as follows:

$$P = a \cdot V^{b} \qquad (2.17)$$

Where P is delivered power and a, b are unknown constants to be calibrated from the data. By taking logarithms:

$$\log P = \log a + \mathrm{b} \cdot \log V + \varepsilon \qquad (2.18)$$

Now the parameters log(a), b, can be obtained by fitting a line using the linear least squares method. Epsilon ε is the measurement error. Generally, a coefficient of determination (R^2 – value) for the generated speed-power curves must be above 0.8. The R^2 value is calculated based on the formula:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(P_m^i - P_e^i\right)^2}{\sum_{i=1}^{N}\left(P_m^i - P_\mu^i\right)^2} \qquad (2.19)$$

Where P_m are the measured (wind corrected) delivered power readings, P_e are the expected power readings from created curve, P_μ is the mean observed delivered.

2.3.3 - Alternatives for Reference and Evaluation periods

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If the duration of the period is less than a year, the Reference and Evaluation periods should be chosen so that they reflect a full range of operational and environmental conditions or a part of defined ranges. The uncertainty is affected by the length of the periods, so an analysis and comparison of three (3) different durations is presented (3, 6 and 12 months). The calculation of the PI is done with the Performance Values, PVs of the Reference and Evaluation periods, that fulfill the reference conditions.

2.3.4 - Accuracy of the Performance Indicators, PIs

The effect of multiple alternatives on the accuracy of the Performance Values, PVs, thus also PIs, is presented through the combination of four scenarios. The total combined resulting uncertainty for PIs, coming from accumulative uncertainties is presented. For the quantification of the uncertainty, the Monte Carlo method is used, as described in Part 1, Annex A of this Standard.

The aim of the examples presented is to be used as indications or as **reference** and easy to compare real case scenarios, generally common for the ship types and sizes for which this Standard is intended. If the technical and operational specifics of an individual ship differ a lot from the assumptions considered, the uncertainties presented may be misleading. The four cases/scenarios are as shown in Table 10. They differ in measurement procedures and parameters:

Table 10: Four case studies-baselines for the accuracy of PIs alternatives, in ISO Part 3

Method	Speed	Del. Power	Sampling Frequency	Trim/ draught	Water depth	Rudder angle	Wind Speed and Direction
3-1	Speed log	Part 3 Fuel consumption (proxy)	Every 15s	From loading computer or from draught mark readings	Echo sounder	Rudder angle indicator	Anemometer
3-2	Speed over ground (as per Part 3)	Torque meter and rpm meter	Every 15s	From loading computer or from draught mark readings	Echo sounder	Rudder angle indicator	Anemometer
3-3	Speed log	Torque meter and rpm meter	Daily (as per Part 3)	From loading computer or from draught mark readings	Echo sounder	None (as per Part 3)	Anemometer
3-4	Speed over ground (as per Part 3)	Part 3 Fuel consumption (proxy)	Daily (as per Part 3)	From loading computer or from draught mark readings	Echo sounder	None (as per Part 3)	Anemometer

Note: *where as per Part 3 is not mentioned, it is as per Part 2 default method.*

In order to calculate the uncertainties, according to Part 1, Annex A, there are simplifications to be made, to make a practical and controllable modelling. The assumptions made for the calculation are shown in Table 11 below:

Table 11: Assumptions for the baseline uncertainties provided in ISO Part 3

Assumption	Effect on PI (bias/precision/both)	Included?
Sample size	Precision	Yes
Sensor precisions	Precision	Yes
Sensor bias	Both	No
Sensor drift	Both	No
Speed variability/day	Bias	No
Operational profile	Bias	No
Time-dependent P increase	Bias	No
Time-dependent V loss	Precision	No
Model error	Both	No
Human error	Both	No

Note: *The justification of the assumptions is presented in Table 4, Clause 7.2 of Part 3*

Two main justifications for the assumptions are:

- The proximity of uncertainty estimate using Monte Carlo with the uncertainty estimate by inspecting measured data, as presented in (XX) - Aldous et al. (2015),
- The assumptions are common for Reference and Evaluation periods and the fact that the PIs reflect relative performance rather than absolute.

The results of the uncertainties underlying the four standard variations are shown in Table 12, expressed as the uncertainty to a 95% confidence interval, referring to methods in Table 10.

Table 12: Comparison of PI uncertainties for alternative cases in ISO 19030 Part 3

	3 months period	6 months period	12 months period
Part 2 method	0,38 %	0,27 %	0,19 %
Part 3 – 1	0,50 %	0,36 %	0,25 %
Part 3 – 2	0,57 %	0,40 %	0,29 %
Part 3 – 3	3,40 %	2,46 %	1,76 %
Part 3 – 4	6,30 %	4,57 %	3,25 %

The total uncertainty of the PI is calculated from the combined estimates of the uncertainty in each of the Reference and Evaluation periods, as in Eq. 2.20:

$$u_{k_{HP}} = \sqrt{{u_{\hat{V}_{d,eval}}}^2 + {u_{\hat{V}_{d,ref}}}^2} \qquad (2.20)$$

where $u_{k_{HP}}$ is the uncertainty of the estimated PI value, $u_{\hat{V}_{d,eval}}$ is the uncertainty of the calculated percentage speed loss during the evaluation period, $u_{\hat{V}_{d,ref}}$ is the same but corresponding to reference period. (all three to 95% confidence interval).

The main inferences of the uncertainty analysis are that absolute uncertainty is reduced if any of the following occur:

- ✓ Increasing accuracy of sensors and measurements of the PI calculation's inputs;
- ✓ increasing the frequency of measurements (i.e. the sample size);
- ✓ Increasing the time period of the reference and/or evaluation periods.

Furthermore, the user may use it as a guide towards an expected uncertainty and have an indication of the sensitivity of the uncertainty to variations of methods. The International Standard does not dictate a minimum level of uncertainty in the PI. Different levels of uncertainty may be appropriate to different applications, depending on the criticality or risk associated with the decision.

Chapter 3 - Application of ISO/DIS 19030

3.1 Vessel and Data Description

The data were available in excel format. They are measurements from an automatic monitoring system and correspond to a vessel during the operation of one (1) year. The sampling frequency is one measurement per minute. The vessel is a **bulk carrier** built in 2020 with carrying capacity of **81600t DWT**. The characteristics of the vessel are shown in Table 13:

Table 13: Characteristics of the vessel in ISO 19030 implementation

Main Particulars		
Length between particulars	$L_{BP}, [m]$	225,5
Length over all	$L_{OA}, [m]$	229
Breadth	$B, [m]$	32,26
Depth	$D, [m]$	20,05
Draught scantling	$T_{sc}, [m]$	14,45
Draught design	$T_d, [m]$	12,20
Lightweight	$W_{LW}, [t]$	13.800,11
Main Engine		
Type	MAN B&W	
Model	6S60ME – C8.5 – Tier II	
S.M.C.R	9.930 kW @ 90,4 rpm	
N.C.R	7.110 kW @ 80,9 rpm	
Propeller		
Diameter	$D_P, [m]$	6,95
Number of blades	N of blades	5
Shaft diameter	$d_s, [mm]$	540

Table 14, displays the measured parameters from the data collection system, divided in the primary and secondary parameters according to ISO standard.

Table 14: Primary and secondary measured parameters in ISO 19030 implementation

PRIMARY parameters	
Speed-Through-Water	knots
Propeller-Shaft-Power	kW
SECONDARY parameters	
Speed Over Ground	knots
Vessel Heading	deg
Relative Wind Speed	m/sec
Relative Wind Direction	deg
Draft Aft	m
Draft Fwd	m
Draft Mean	m
Trim	m
Significant Wave Height	m
Mean Wave Direction	deg
Shaft Torque TRQM	kN·m
M/E Shaft RPM TRQM	rpm
Water Depth Relative to the Transducer BRG ECHO	m
ME FO Consumption	mt/day
LCV of Fuel	kJ/kg
Fuel Index Position	n/a
ME RPM AMS	rpm
Shaft Thrust TRQM	kN
Cargo Carried	tn
ME Loading Percent	%
Ballast Condition	(-)

The raw measured values of parameters in Table 14 are stored in a tabular format in python, with the time-stamp as the row index, and are named the **Retrieved Data Set**.

3.2 Program for ISO 19030 application

A program in Python programming language was developed for the scope of this thesis. The program is structured upon the procedural steps of ISO 19030 that were encountered during the implementation. The main libraries of python in use are Pandas, Numpy and Matplotlib. Pandas is the go-to library for data analysis, which facilitates storing and manipulating data, in dataframes[10]. Numpy is a core numerical library and is used for quick and vectorized calculations in large data sets or chunks of data. Matplotlib is the basic library for plotting, with deep control of figures appearance and is used for visualization of results.

The program executes in modules[11] the steps of ISO 19030 Part 2. It imports the raw data in excel format, performs the filtering, validation, correction and normalization, extracts a prepared data set and calculates a Performance Indicator, PI. The sequence of the steps to be executed is determined in a main body of code. In general, the current data at each step are passed as arguments to the main functions of the modules and they return the corresponding data for further processing. It is worth noting the possibility for general use of the program, as the modular structure can be adapted at each case. The process is presented in a graph in Annex H.

3.3 Retrieved Data Set and Visualization

The raw data are initially stored in four Microsoft Excel files with each file corresponding to one quarter of the year 2021. For details of the importing data, refer to Annex D. An algorithm is used to alter the column names of the data-frame and match those names provided by ISO 19030 Part 2, default method. The process can be seen in Annex B.

The primary parameters, Propeller Shaft Power (kW) and Speed Through Water (knots), are presented in Figure 5, during the vessel's operation in the second quarter, arbitrarily, and in Figure 6, a zoomed period of ten (10) days, for a general view of the processing data set. The 10-days-time-window in Figures 5 and 6 represents a proper period for analysis, as the operational profile of the vessel is relatively steady.

The validated data, according to Chauvenet's criterion of the default method, have been displayed further below in Figure 7, for easier comparison with the retrieved data, and in Figure 8 the same 10-days-time-window. The validated data set is obtained by the procedure in Section 3.4.2.

[10] *dataframes*: object in Python's Pandas library in tabular format with indexes for rows and headers for columns.
[11] *modules:* separate portions of a program with isolated functionality.

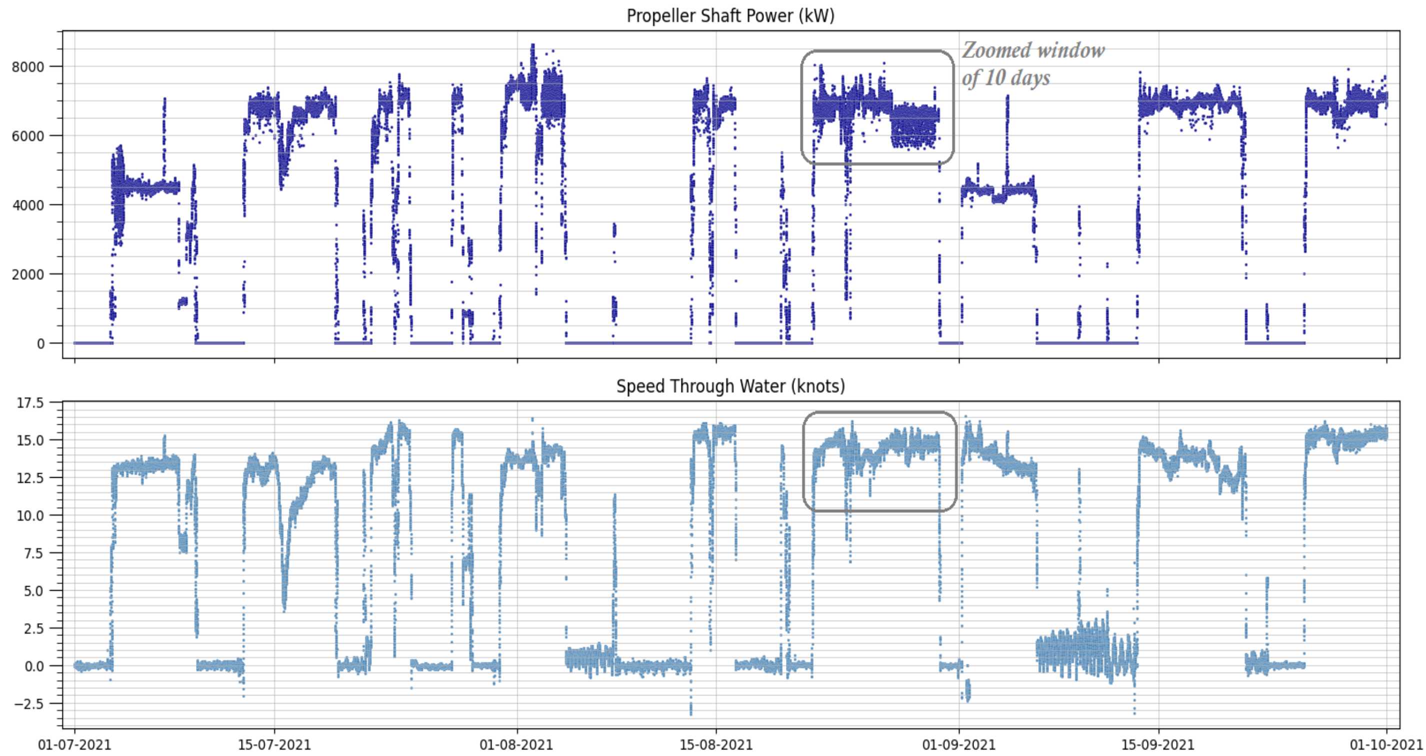


Figure 5: Retrieved Data Set visualization – 2nd Quarter of the year

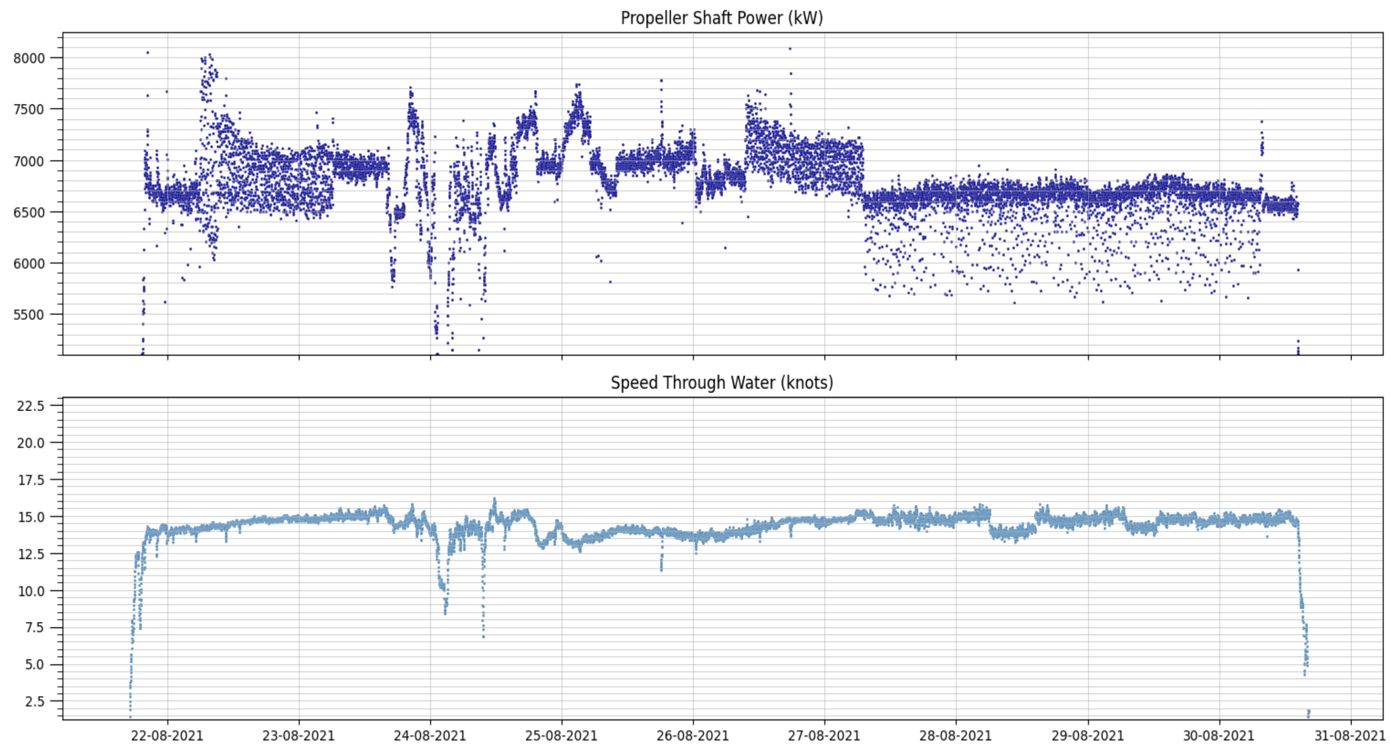


Figure 6: Zoomed 10-days-time-window of Retrieved Data Set - 2nd Quarter of the

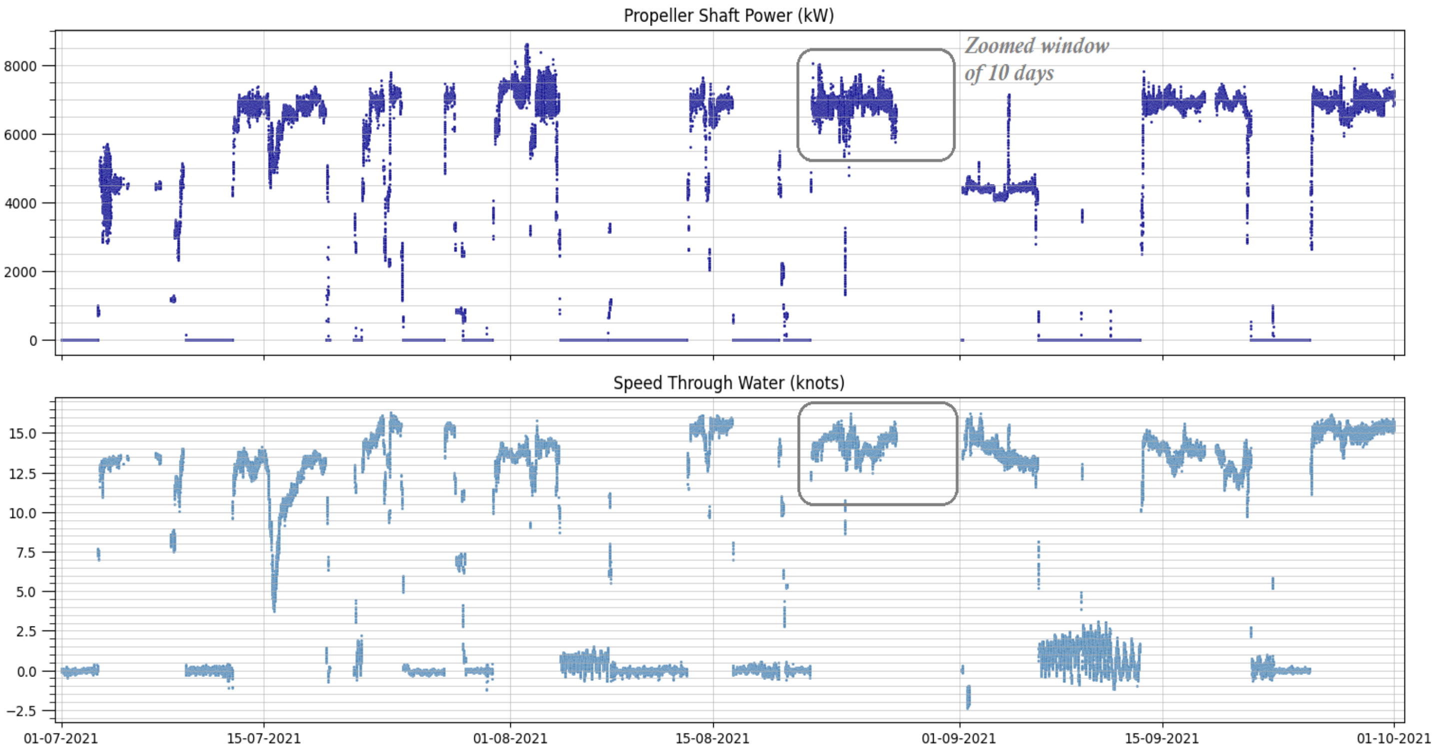


Figure 7: Validated Data representation according to Chauvenet's criterion– 2nd Quarter of the year

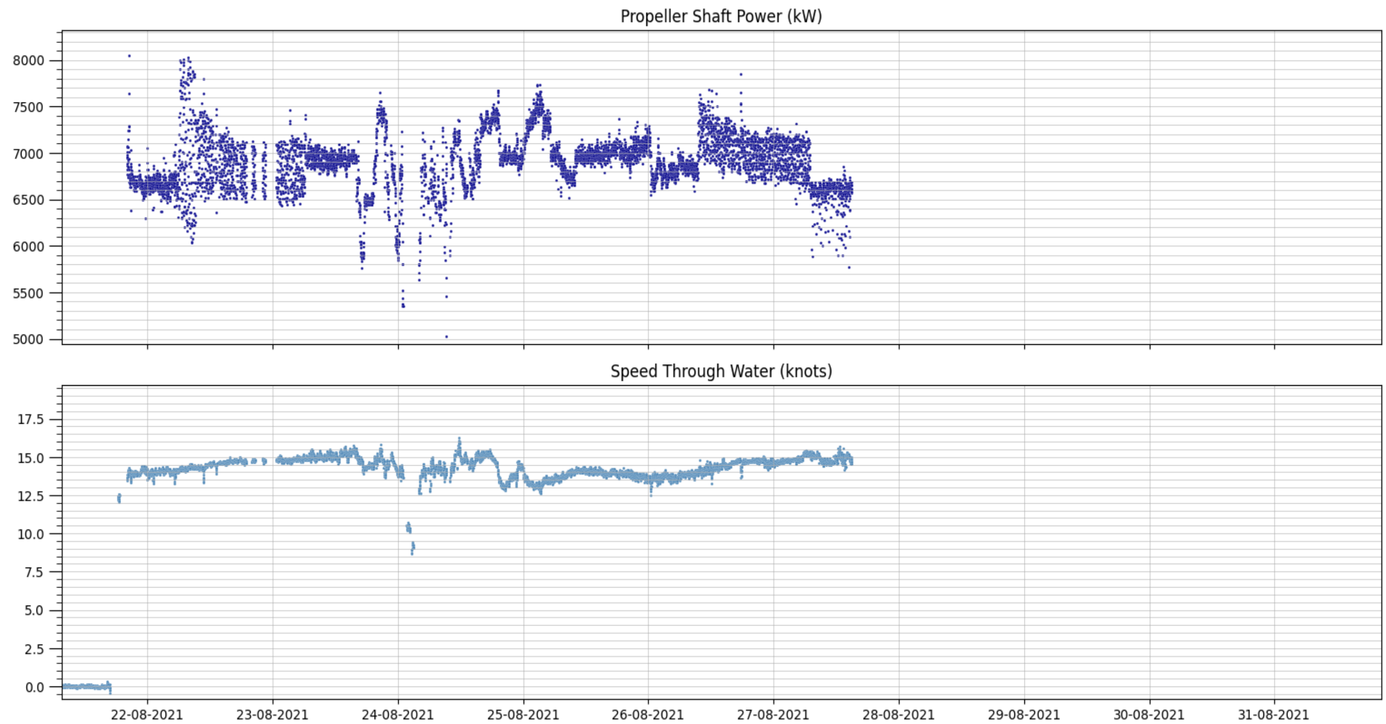


Figure 8: Zoomed 10-days-time-window of filtered data according to Chauvenet's criterion – 2nd Quarter of the year

3.4 Procedure to obtain the Validated Data Set

The Retrieved Data Set needs filtering, validation and correction for environmental factors, in order to render the Reference and Evaluation periods adequately comparable. The process is based on ISO standard and outlined in Section 2.2.3.4.

3.4.1 Filtering Tests for different frequency from Part 2: Default method

In ISO default method, a 10-minute time-span for grouping is recommended for a sampling frequency of one measurement per fifteen seconds or 0,067 Hertz. However, the sampling frequency available in this case is one per sixty (60) seconds or 0,016 Hertz. Consequently, the subject analysis is oriented towards ISO 19030 – Part 3, an alternative method for data frequency acquisition.

During the filtering procedure, blocks of ten minutes time-span should be formed for statistical validation. However, the different sampling frequency (one per minute) reduces 75% the amount of data in each block, compared to the default method (one per 15 seconds). This alternative is dealt with tests for a variety of grouping time spans regarding the consecutive blocks of the filtering procedure. Tested time spans are {10T, 20T, 30T, 40T, 50T, 1H, 2H, 6H, 12H, 24H}, where T is minutes and H hours and in Figure 9 the amount of filtered data for each time span is depicted.

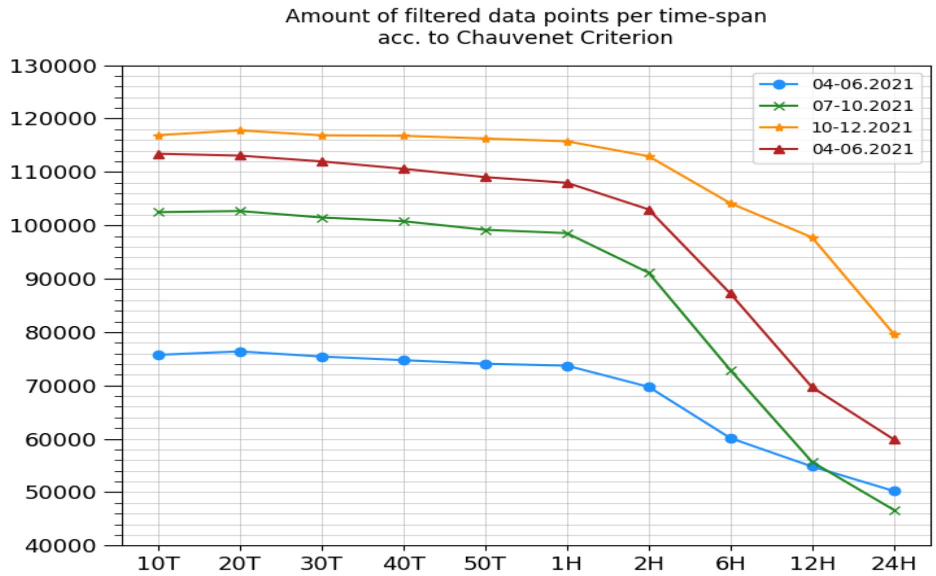


Figure 9: Amount of Filtered Data for different grouping time-spans than the default method.

The amount of raw data for each quarter, Q1, Q2, Q3 and Q4 is respectively 128.381, 130.352, 130.748 and 128.098 data points. The value that seems to have the most validated values is 20T or twenty minutes, thus this time-span for grouping and filtering will be chosen for further analysis.

It can be observed that 1st Quarter has the least approved values, while the 3rd Quarter has the most. Moreover, there is little difference between the amount of filtered data and the time-spans 10 minutes to 50 minutes. For a larger time-span, the amount seems to decrease. This is expected as more data are accumulated in each group, and by standard deviation effect, result to more data being considered outliers by Chauvenet's criterion (Table 6).

3.4.2 Validated Data Set according to Chauvenet's criterion in default method

The filtering process is presented in detail in Section 2.2.3.4 and is performed with Python's Pandas and NumPy libraries. A script module built for the scope of this thesis, with the name Filter, contains the functions used to manipulate and filter the raw data.

In Figure 10, the validated propeller shaft power and in Figure 11, the validated speed through water are presented for the four quarters of the year 2021.

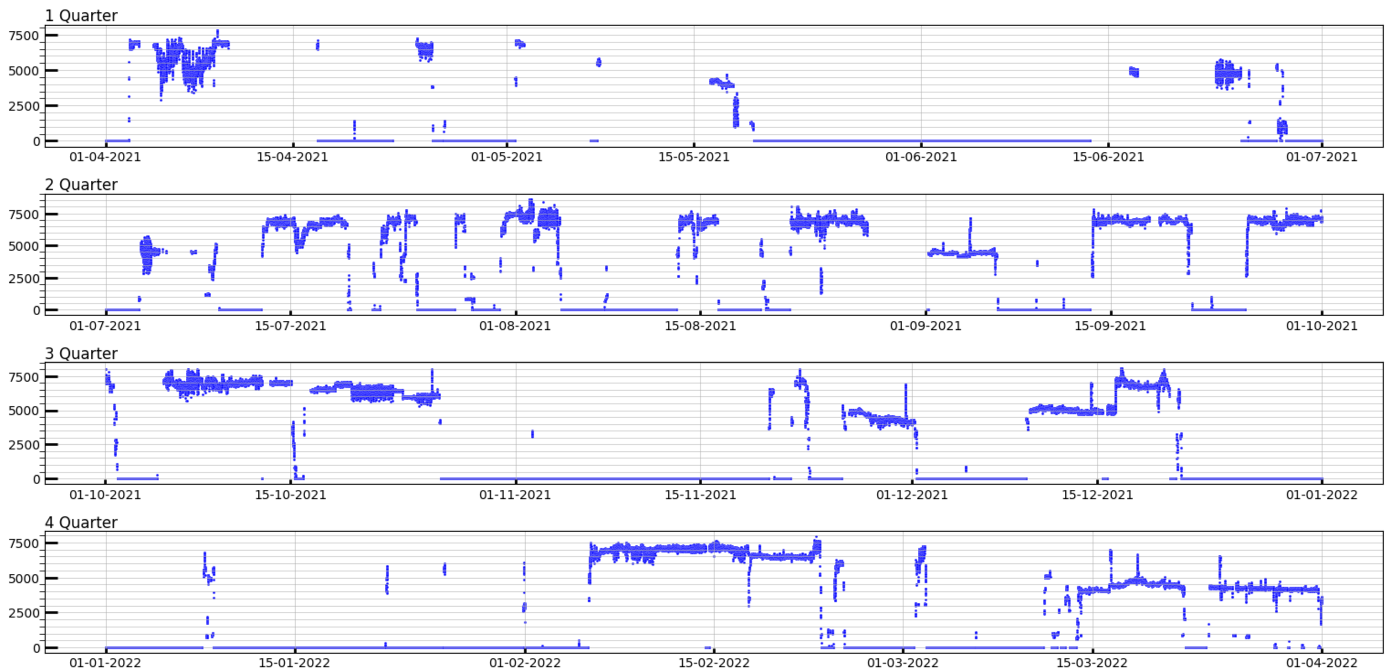


Figure 10: Validated Speed Through Water (knots) from measurements over one year

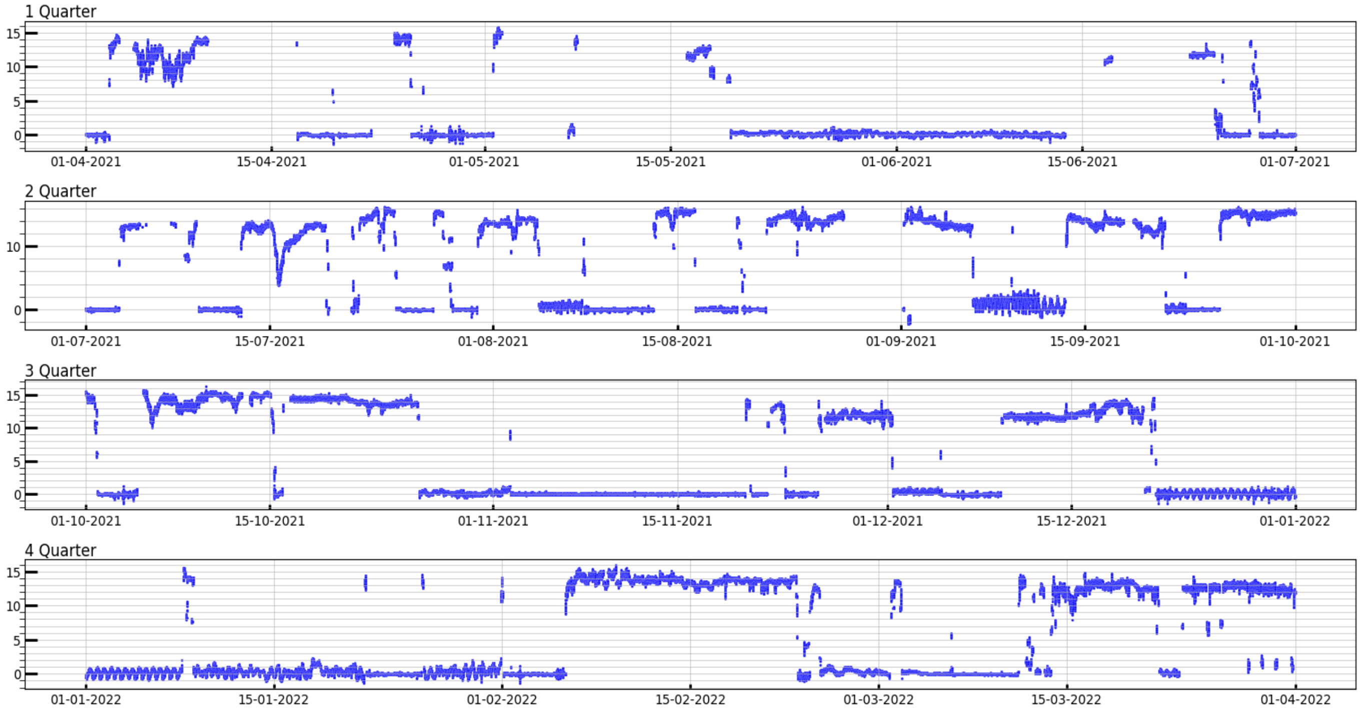


Figure 11: Validated Propeller Shaft Power (kW) from measurements over one year

3.5 Procedure to obtain the Corrected Data Set

After the Validated Data Set has been obtained, the correction of Propeller Shaft Power for wind resistance is performed. The process is described in Section 2.2.3.5. The external information needed for wind correction, as outlined in Section 2.2.2, is obtained from the Sea trials, of the bulk carrier under investigation, and from ITTC (2017).

3.5.1 Wind Resistance Coefficients for the corrections in delivered power

The added resistance due to wind is determined by the wind resistance coefficients. ITTC (2017) and ISO 15016 standard describe the best practices, but also provide standard wind resistance coefficients as measured in tests for a range of vessel shapes and types.

In ITTC *Appendix F.2* (Rev 05, 2017) the most suitable coefficients given are those for a handy-size bulk carrier, corresponding to ballast and heavy ballast conditions. The Sea Trials of the vessel under examination contain calculated wind resistance coefficients according to the abovementioned guidelines and are vessel specific.

The sign conventions for wind speed and direction, are the same in both cases and can be seen in Figure 12. Zero (0) degrees means wind coming on the bow, positive to starboard (clockwise) and one-hundred-eighty (180), coming from astern.

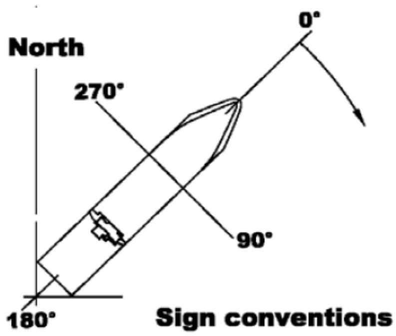


Figure 12: Sign conventions for wind measurements (ITTC 2017)

The ITTC and Sea trials wind coefficients are depicted together in Figure 13, along with a polynomial interpolation (9th order). The sea trials follow ISO normalization procedures and the STAWIND as the wind method. According to formula (2-X) in Section 2.2.3.5, the correction factor ΔP_W should be positive for negative wind impact, in order corrected power to be less than the measured power. Thus, the actual wind coefficient curve has reversed sign $C_{rw}(\psi_{wr,ref}) = -C_X$. Values are symmetrical for the other [180, 360] degrees range.

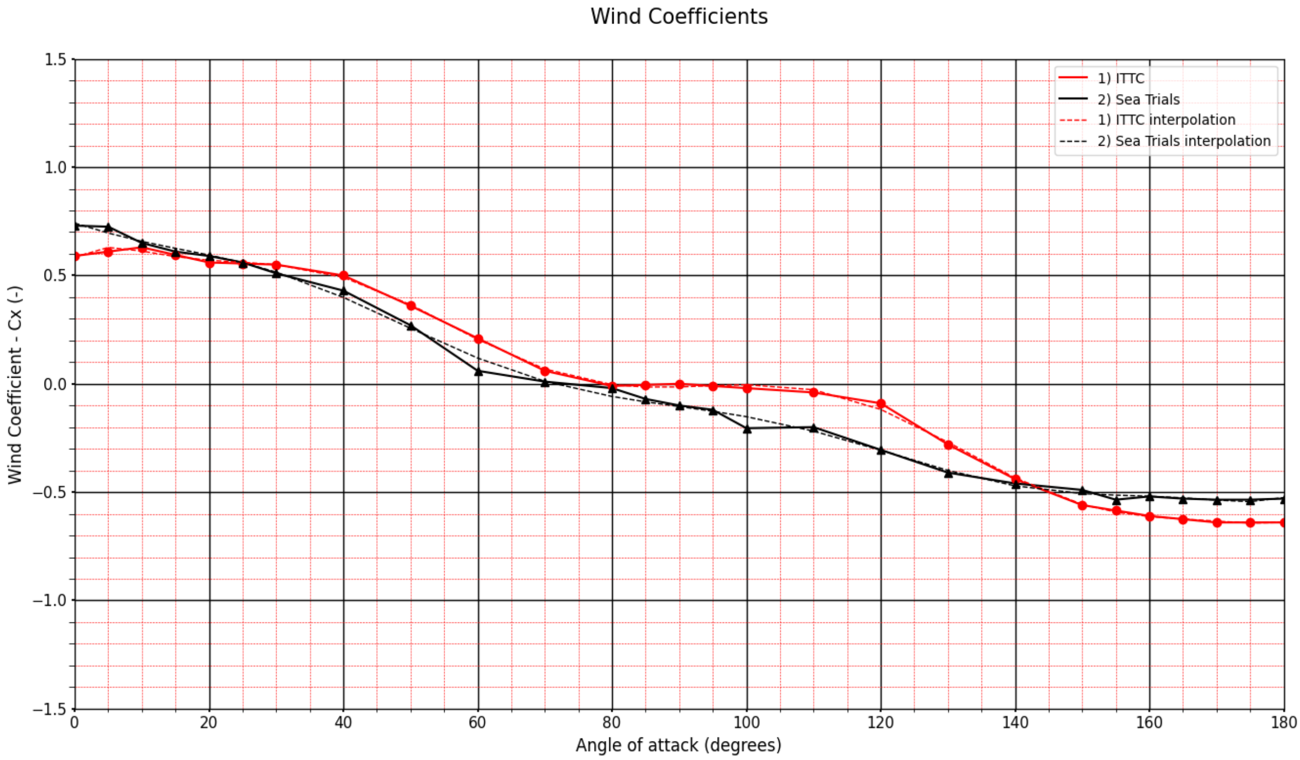


Figure 13: Wind resistance coefficients stemmed from ITTC (2017) and vessel's Sea trials.

Conclusively, the Sea trials wind coefficients are chosen for power correction analysis, because are ship specific and stem from the ITTC and ISO 15016.

3.5.2 Corrected Delivered Power for Wind Resistance

Sea trials are chosen for extracting the wind resistance coefficients information. The correction is done with the module Wind of the program of this thesis. The inputs to Wind module are the parameters Relative Wind Speed (m/sec), Relative Wind Direction (deg), Speed Over Ground (knots), Vessel Heading (deg), Draft Mean (m), Propeller Shaft Power (kW). The output is the corrected Propeller Shaft Power (kW). The calculations are described in Annex E & G of the ISO – Part 2.

According to ISO Annex B, delivered power should be approximated either by brake power or by calculations of shaft power. In our case, the shaft power is directly available. Consequently, with the assumption of maintained shafting arrangement, the Delivered Power will be the Shaft Propeller Power.

The measured and corrected Propeller Shaft Power are shown in Figure 14, during the second quarter of the year. At the same period, the wind speed and direction are shown in Figure 15.

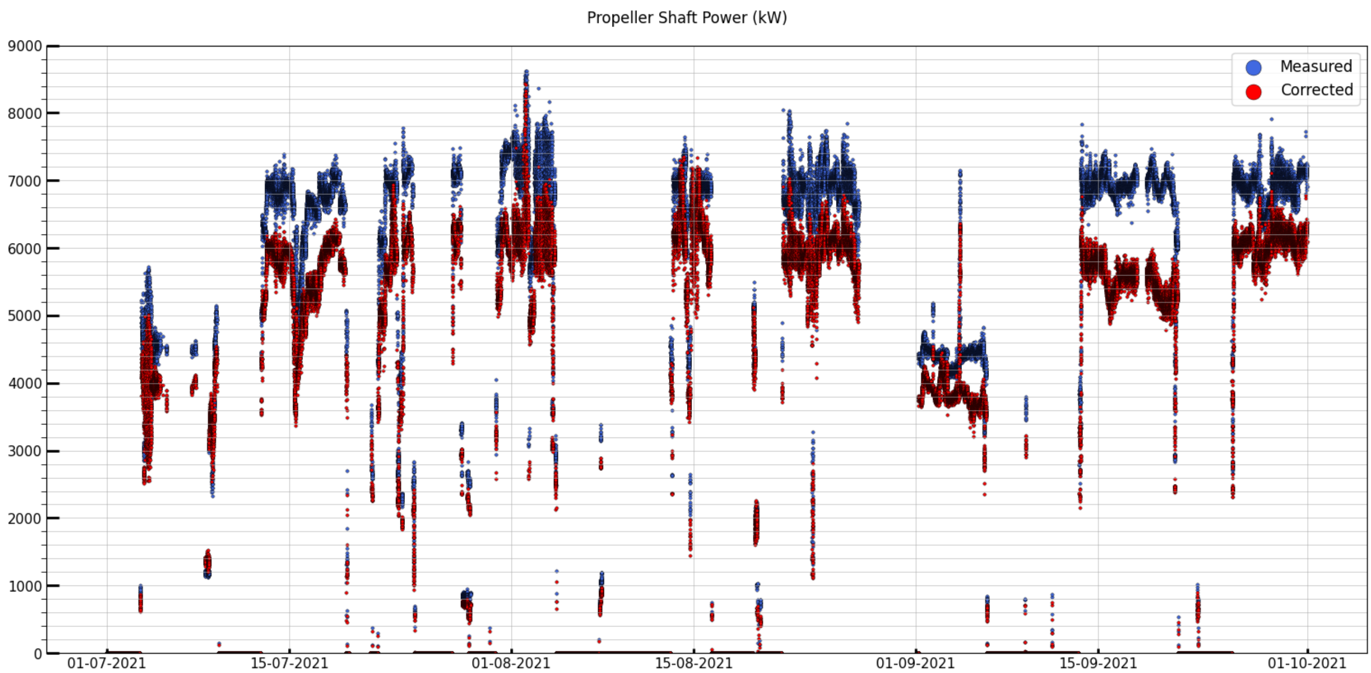


Figure 14: Validated vs Corrected Power during 2nd quarter, according to ISO 19030 correction

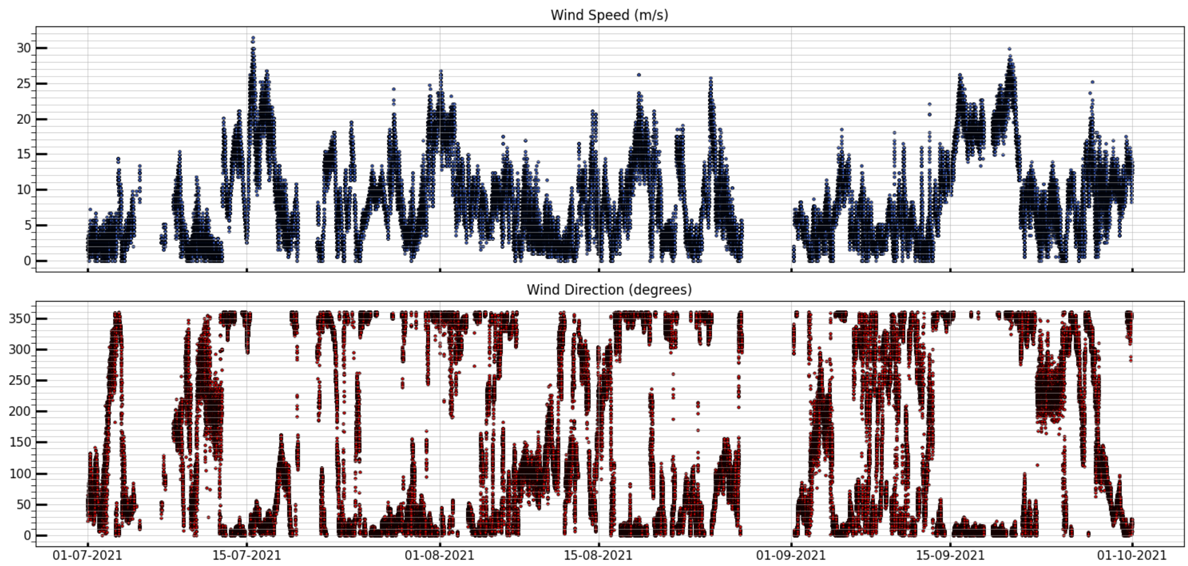


Figure 15: Wind speed and direction during 2nd quarter

3.6 Procedure to obtain the Performance Values, PVs

3.6.1 Power-speed reference curves

The sea trials reference curves can be seen in Figure 15. They provide three power speed relations for three different displacements/loading conditions:

- Scantling condition $\Delta_{scant\_ref} = 94796{,}2\ tn$ and $T_{Aft} = T_{Fwd} = T_{mean} = 14.45\ m$,
- Design condition $\Delta_{des\_ref} = 78711{,}9\ tn$ and $T_{Aft} = T_{Fwd} = T_{Mean} = 12.20\ m$
- Ballast condition $\Delta_{ball\_ref} = 40389{,}0\ tn$ and $T_{Aft} = 7.40\ m$, $T_{Fwd} = 4.90\ m$, thus having $T_{Mean} = 6.15$ and $trim = 2.5\ m$.

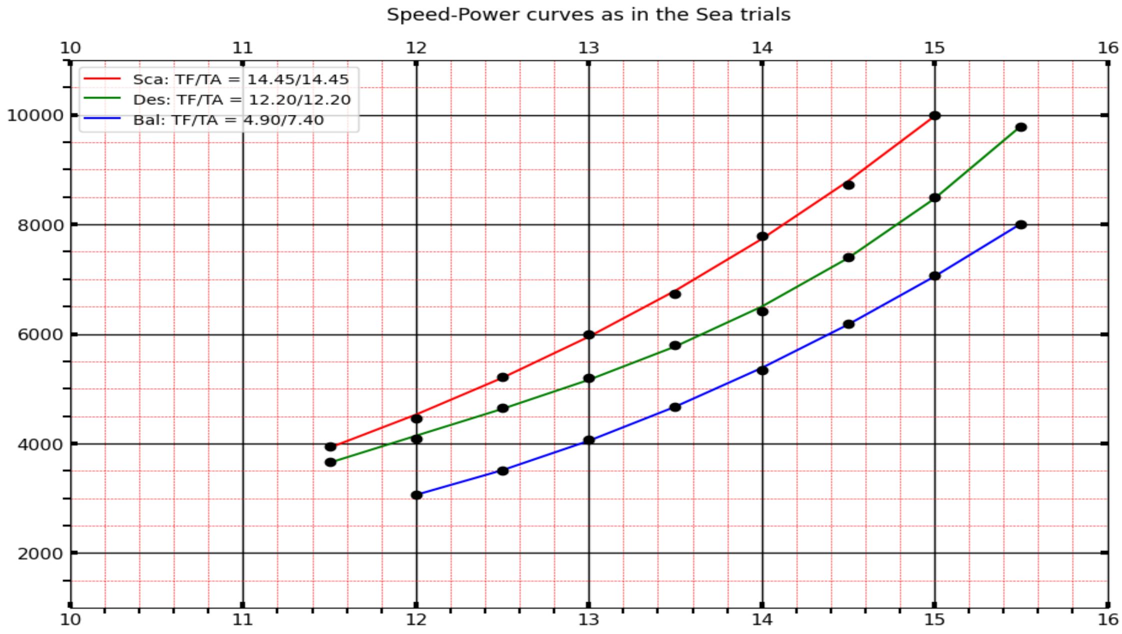


Figure 16: Reference speed power curves from Sea trials

3.6.2 Reference and Evaluation Periods of application

Reference Period

The Reference period for the scope of this thesis is set as the Sea Trials period. In this respect, the speed-loss and power-increase will be evaluated between Sea trials and the Evaluation period.

Evaluation Period

The Evaluation period is one year of available measurements from the vessel's operation, from April 2021 to April 2022. During that period, a large amount of data is accumulated, but after ISO application, a significantly smaller number of data remains for analysis.

3.6.3 Default Reference Conditions and Different Scenarios

The Validated Data Set, as per default method, needs to comply to the reference conditions. The default reference conditions can be seen in Section 2.2.4.1. The goal is to minimize the effect of environmental factors that interfere with hull and propeller performance. The default reference conditions and the corresponding application in our case can be seen in Table 15.

For the scope of this thesis, the sensitivity of the PI to the reference conditions will be examined. The different reference conditions examined can be considered as scenarios, which are shown in Table 16.

Table 15: Application of default reference conditions

A/A	CONDITION	APPLICATION
1	Water temperature with no ice	Above +2 °C, as per standard method
2	Wind speed limit	Below 7,9 m/s (or 4 BF), as per standard method
3	Water depth limit	Above the larger of indicated values, as per standard method
4	Delivered power in the range of power-speed reference curves	In the range of Sea Trials reference curves
5	Displacement close to this in power-speed reference curves	Draught as proxy,
6	Rudder angle	Not applicable
7	SFOC reference curve	Not applicable

Table 16: Scenarios for different examined reference conditions

A/a	Description	Conditions
Scenario 1	As in Table 17, default method	▪ wind speed < 7,9 m/s ▪ displacement within ± 5 % of the reference curves
Scenario 2	Different wind speed	▪ wind speed < 12 m/s
Scenario 3	Different displacement range	▪ displacement within ± 10 % of the reference curves

Condition 6 is not applicable because there are no available measurements for rudder angle[12]. Condition 7 is not applicable as Delivered Power is not calculated by Brake Power. In our case, the Delivered Power is considered equal to the directly measured Propeller Shaft Power, with the assumption of maintained shafting arrangement.

The displacement for each data point is calculated by the measured mean draught and the approximation of actual block coefficient, derived from Eq. 3.1:

$$Displacement = \rho \cdot L \cdot B \cdot T_{act} \cdot C_{b_{act}} \qquad (3.1)$$

where ρ, the density of sea water 1,025 $[tn/m^3]$, L, B are the length between perpendiculars and the breadth of the vessel, T_{act} the actual measured draught and $C_{b_{act}}$ the actual block coefficient for measured draught, calculated as:

$$C_{b_{act}} = 1 - (1 - C_{b_{ref}}) \cdot \left(\frac{T_{ref}}{T_{act}}\right)^{\frac{1}{3}} \qquad (3.2)$$

where T_{ref}, the given reference draught in speed power curves and $C_{b_{ref}}$ the block coefficient read from the Hydrostatic curves of the vessel corresponding to T_{ref} and trim. The actual displacement of Eq. 3.1 is checked to be in the range of one of the displacements in sea trials reference curves, as shown in Figure 15.

At this point, speed and power data are normalized for the deviation between actual and reference displacement. The Admiralty formula is respectively for speed and power:

$$V_2 = V_1 \cdot \left(\frac{\Delta_1^{\frac{2}{3}}}{\Delta_2^{\frac{2}{3}}}\right)^{\frac{1}{3}} \qquad (3.3)$$

$$P_2 = P_1 \cdot \left(\frac{\Delta_2}{\Delta_1}\right)^{\frac{2}{3}} \qquad (3.3)$$

where,

$V_1,\ P_1$ measured speed and power

V_2, P_2 speed and power at reference displacement

Δ_1 measured displacement

Δ_2 reference displacement

[12] Neglection of rudder angle may rise the uncertainty effect of some data

Current effect

The data remaining after the above procedure are displaying, at some points, irrational speed through water values for corresponding power. In this respect, the current effect needs also to be addressed. The current in speed terms, is considered as the absolute difference between speed through water, V_{TW}, and speed over ground, V_{OG}:

$$V_{current} = |V_{TW} - V_{OG}| \qquad (3.4)$$

The additional condition applied to the data set at this point, is $V_{current} \leq 1\ knots$

In Figure 17, the power and speed of the Prepared Data Set is displayed along with the reference curves of Figure 16. The red points are the rejected data points due to the additional condition for water current to be less than one (1) knot. They amount to 18.174 points. The water current for the whole period, stemmed from Eq. 3.4, is shown in Figure 18.

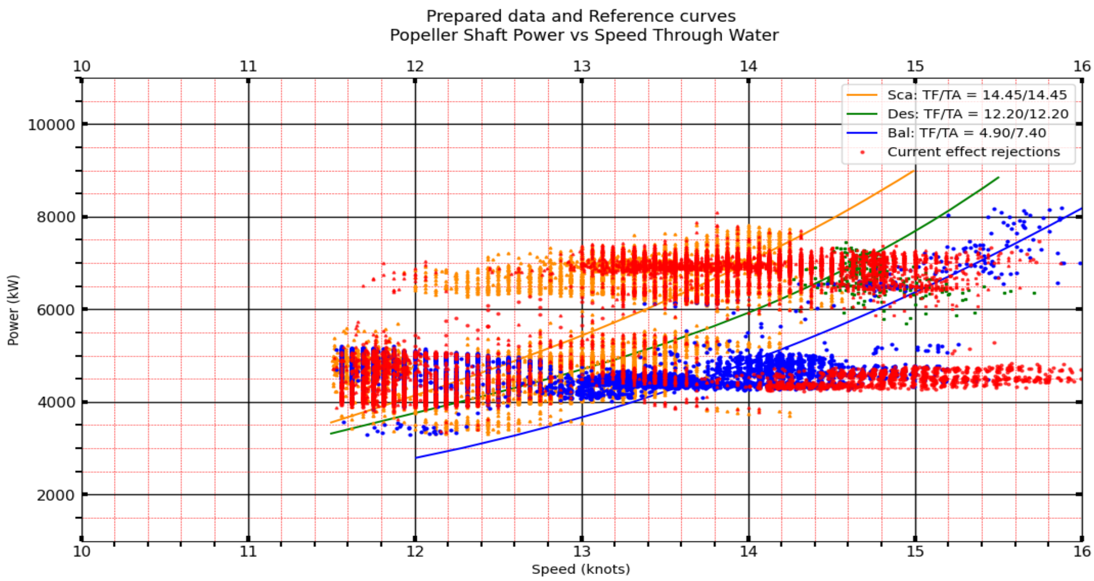


Figure 17: Amount of Prepared Data rejected by the condition water current to be below 1 knot, following the ISO default method

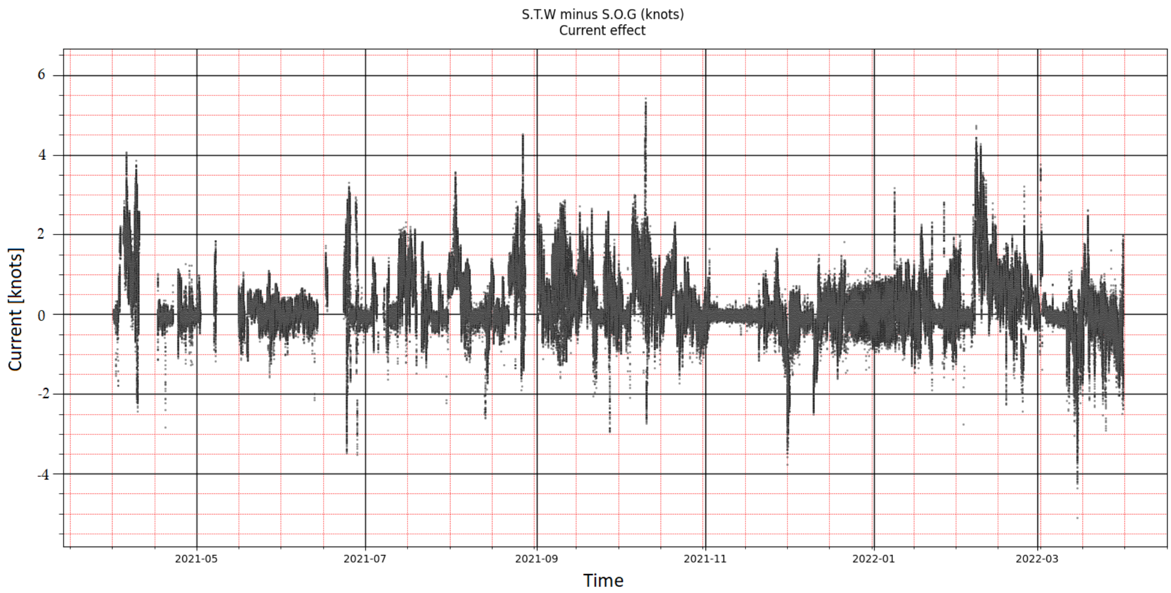


Figure 18: The measured sea water current during the one-year period

The current effect seems to have an important impact on the amount of final data and also on the resulting PVs. The current condition removes the 37 % of prepared data (figure 17) of ISO procedure (scenario 1). For more details about current impact on PVs refer to next section

The final power and speed values of the prepared data, following the ISO procedure, which correspond to the first scenario results, can be seen in Figure 19 (refer to Table 16). The same final prepared data for the rest scenarios, can be seen in Figure 20.

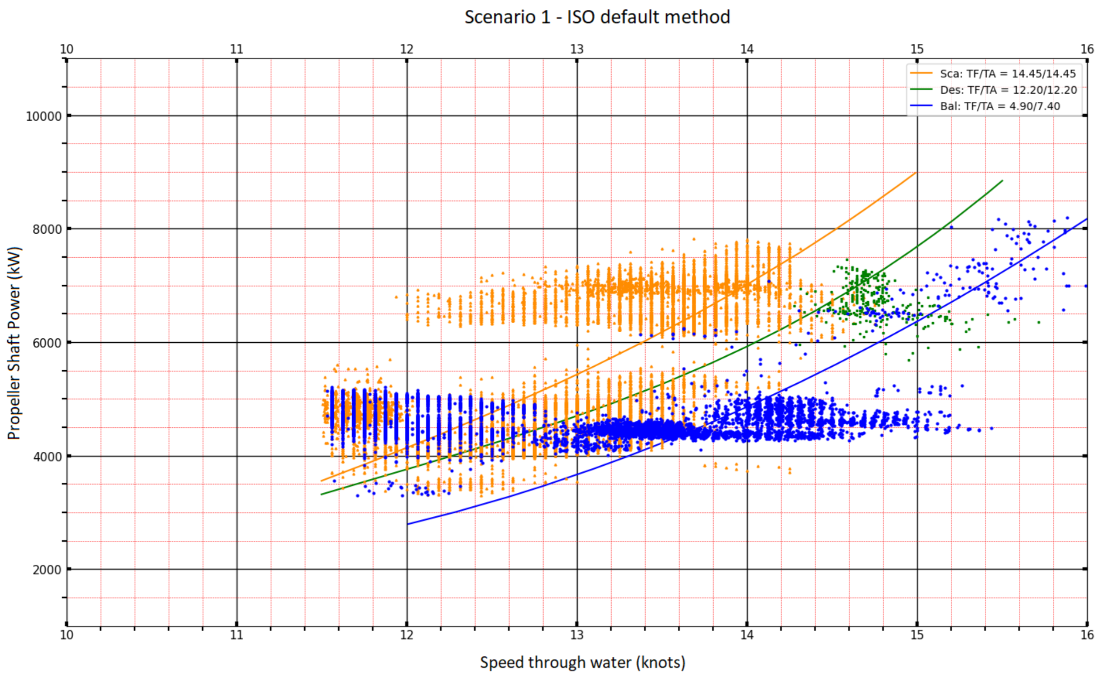


Figure 19: Prepared power and speed with reference curves, following the ISO default method

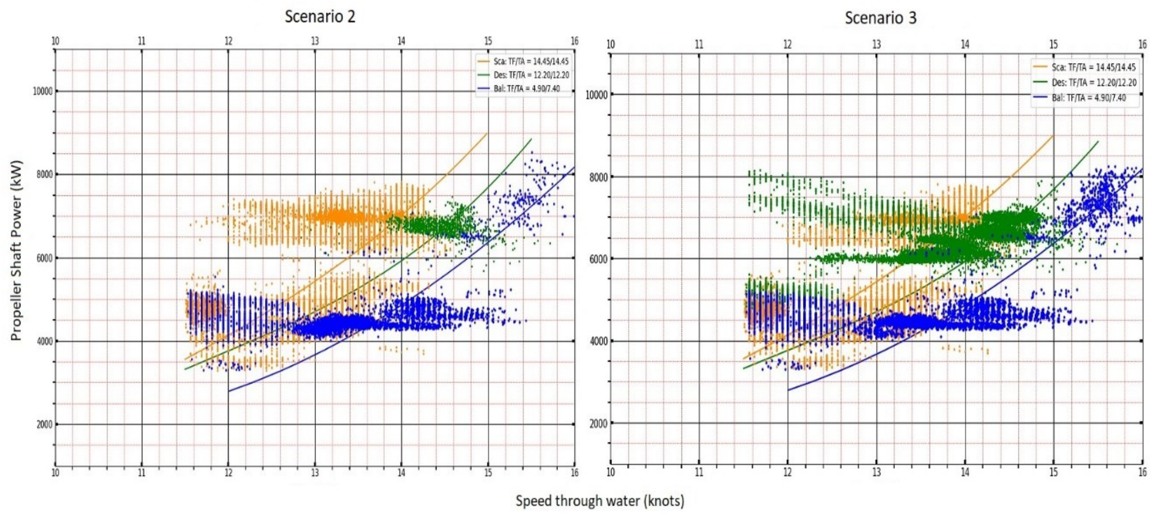


Figure 20: Prepared power and speed with reference curves, for two different scenarios than the ISO default method

3.6.4 Calculation of the Performance Values

At this point, the calculation of the Performance Values, PVs, will follow for each of the three scenarios of reference conditions, as in Table 16. Each scenario results to different amount of data to be used and subsequently to different PVs, calculated as per Section 2.2.3.6 with Eq. 2.9. The PVs are namely the speed loss % and the power increase %, which is called power performance value, PPV. The analysis of PPVs can be seen in Annex F.

The expected speed V_e is extracted from the corresponding power measurement and the correct displacement curve. In fact, data are split into three loading conditions, i.e. scantling, design and ballast, during the application of the reference condition for displacement. In this respect, the calculated PVs can also be divided to examine each loading condition results individually. The PVs of the three scenarios can be seen in Figure 21.

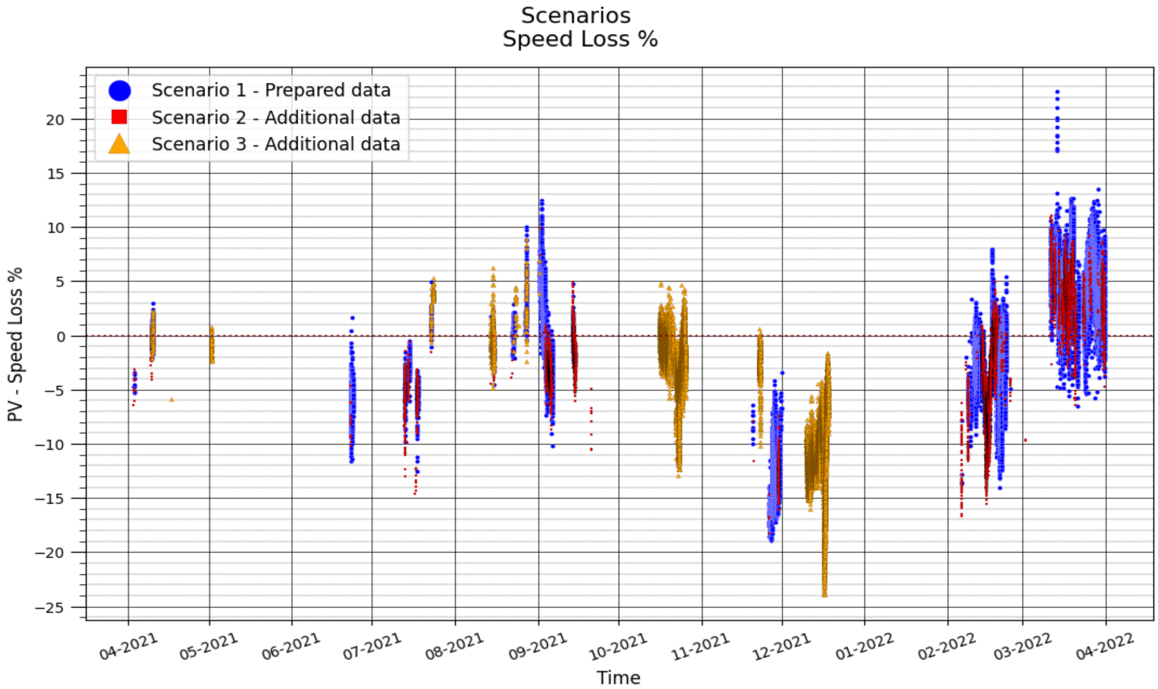


Figure 21: Performance Value speed loss % for all scenarios

3.6.5 Statistical Analysis of Results

Statistical characteristics of the PVs of figure 20 can be seen in Table 17. For each scenario, the loading condition have also been taken into account.

Table 17: Statistical metrics of Performance Values, PVs, for each Scenario

	Scenario 1				**Scenario 2**				**Scenario 3**			
	Sc	**De**	**Ba**	**Total**	**Sc**	**De**	**Ba**	**Total**	**Sc**	**De**	**Ba**	**Total**
Count	**22799**	**294**	**7782**	**30875**	**29610**	**1133**	**9175**	**39918**	**23209**	**15544**	**8229**	**46982**
Mean	1.74	1.80	-6.33	- 0.29	0.81	-0.48	-6.09	-0.81	1.67	-6.04	-5.98	-2.22
Std	4.49	2.37	7.27	6.37	5.03	2.44	6.87	6.18	4.50	5.32	7.23	6.58
Min	-14.03	-2.16	-18.96	-18.96	-16.69	-10.60	-18.95	-18.96	-14.03	-23.92	-18.95	-23.92
25%	-1.22	0.12	-13.02	-3.23	-2.47	-2.08	-12.57	-4.13	-1.34	-10.80	-12.80	-6.43
50%	2.01	1.14	-6.44	0.75	1.22	-0.54	-4.20	-0.05	1.89	-4.92	-4.27	-1.19
75%	5.05	3.21	-0.22	4.27	4.59	0.78	-0.91	3.75	4.99	-1.32	-0.04	2.49
Max	22.49	10.06	12.44	22.49	22.49	10.06	12.45	22.49	22.49	10.06	12.45	22.49

The information that the vessel had a propeller repair activity on about 19/07/2021 coincides with the performance values in Figure 20, as there is a visible difference in speed loss at points before and after this date. Statistical characteristics are shown in Table 18 for the two periods: before propeller repair (19/07/21) and after propeller repair:

Table 18: Statistical characteristics of Performance values before/after propeller repair, for each Scenario

	01-Apr-2021 to 19-Jun-2021			**19-Jun-2021 to 01-Apr-2022**		
	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 1**	**Scenario 2**	**Scenario 3**
Count	1302	1795	1423	29573	38123	45559
Mean	-5.08	-5.11	-4.68	-0.08	-0.61	-2.15
Std	2.40	2.41	2.66	6.40	6.23	6.65
Min	-12.50	-14.63	-12.50	-18.95	-18.95	-23.92
25%	-6.58	-6.54	-6.47	-2.67	-3.61	-6.42
50%	-5.43	-5.35	-5.22	1.03	0.26	-1.06
75%	-3.98	-3.95	-3.23	4.44	3.95	2.65
Max	3.01	3.01	3.01	22.49	22.49	22.49

From Table 18, one can observe the mean speed loss for each scenario. Noticeable is also that ISO 19030 procedures do not allow further analysis for the majority of data during the first and half quarter. All scenarios are calculating a notable upgrade in hull and propeller performance, with gains in speed loss at a range of 2 to 4.5 %.

The different outcomes of PVs of the three scenarios can also be seen with each scenario's trendline in Figure 22 In addition, the effect of the propeller maintenance has been tried to be captured by trendlines, before and after the event. The trendlines before and after the date of the event, 19/07/2021, for each scenario of reference conditions is shown in Figure 23. The corresponding graphs for PPVs, are shown in Annex F.

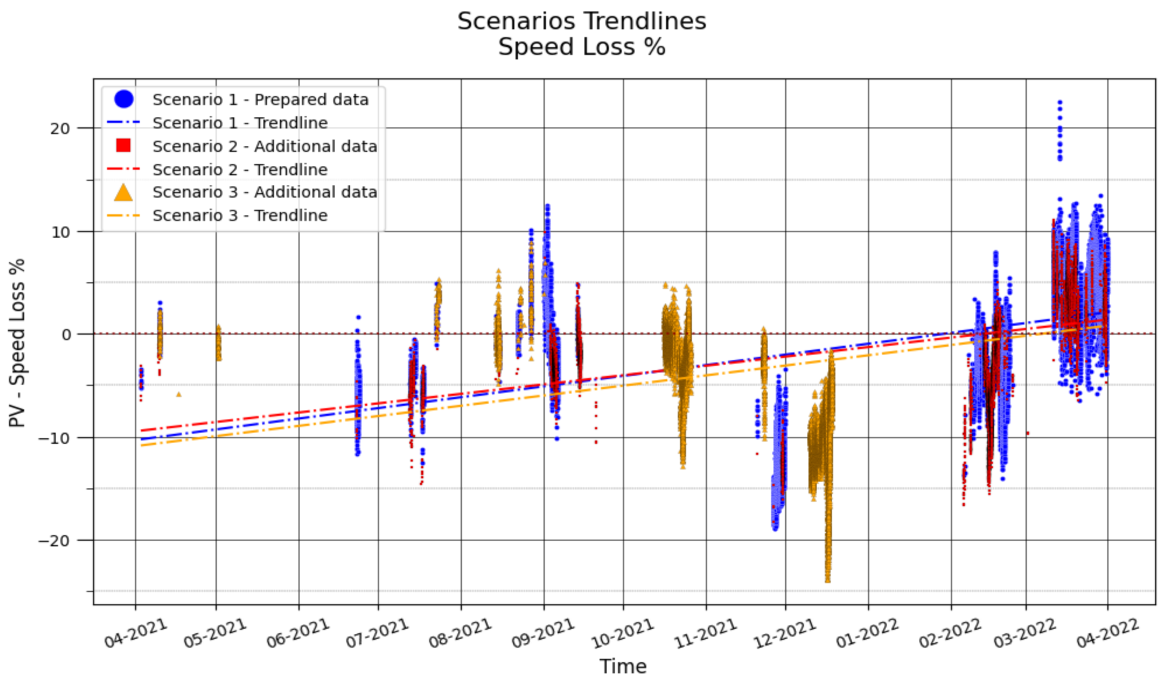


Figure 22: Trendline of Performance Values, PVs, for three different scenarios of reference conditions

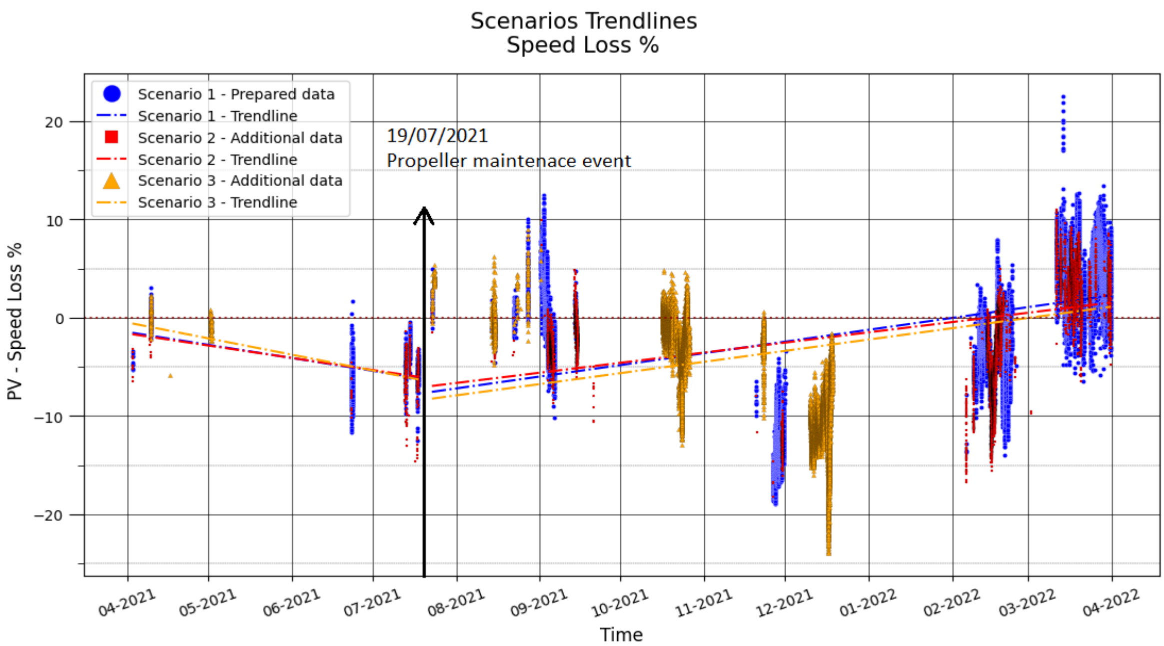


Figure 23: Trendline of Performance Values, PVs, for three different scenarios, before and after propeller maintenance event.

Additional scenario for displacement

An additional scenario has been checked, that is, instead of 10% displacement margin to consider 15% margin for measurements which can be called Scenario 4. However, it was not adopted because of the similarity with Scenario 3. The comparison between Scenario 3 and Scenario 4 is shown in Table 19:

Table 19: Additional scenario for displacement deviation from reference curves

Stats	**Period**	**Scenario 3** 10 % Displacement margin	**Scenario 4** 15% Displacement margin
Count	One year	**46982**	51856
	Before 19/07/2021	1423	1673
	After 19/07/2021	45559	50183
Mean	One year	-2.22	-1.97
	Before 19/07/2021	-4.68	-4.48
	After 19/07/2021	-2.15	-1.88
Std	One year	6.58	6.42
	Before 19/07/2021	2.66	2.62
	After 19/07/2021	6.65	6.49

3.6.6 Comparison of performance values with another performance indicator

The performance values, PVs, derived by the scenarios of the ISO procedure are now compared with a different performance indicator, PI, in order to infer the correlation of the results with the values of following indicator:

$$PI = \frac{P_{Del}}{n^3} \quad (3.5)$$

The figure 22 shows the values of the indicator during the year of vessel's operation per Scenario. In Figure the relation of the PI with the Performance values of the ISO default method. has on the x-axis the PI resulting from Eq 3.5 and on the y-axis the resulting PVs for the default method scenario.

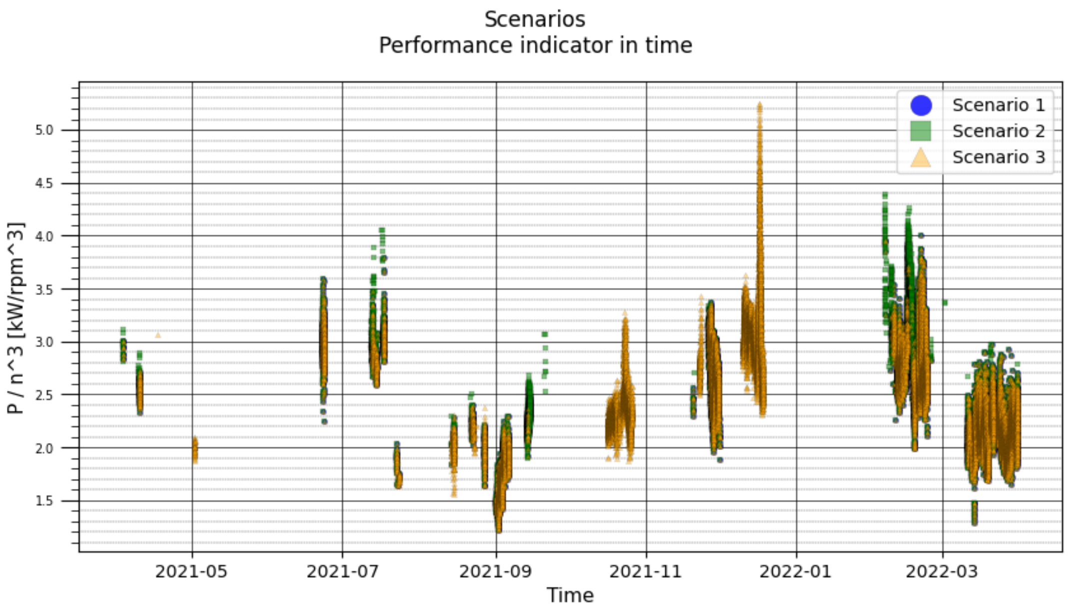


Figure 24: Additional Performance indicator in time

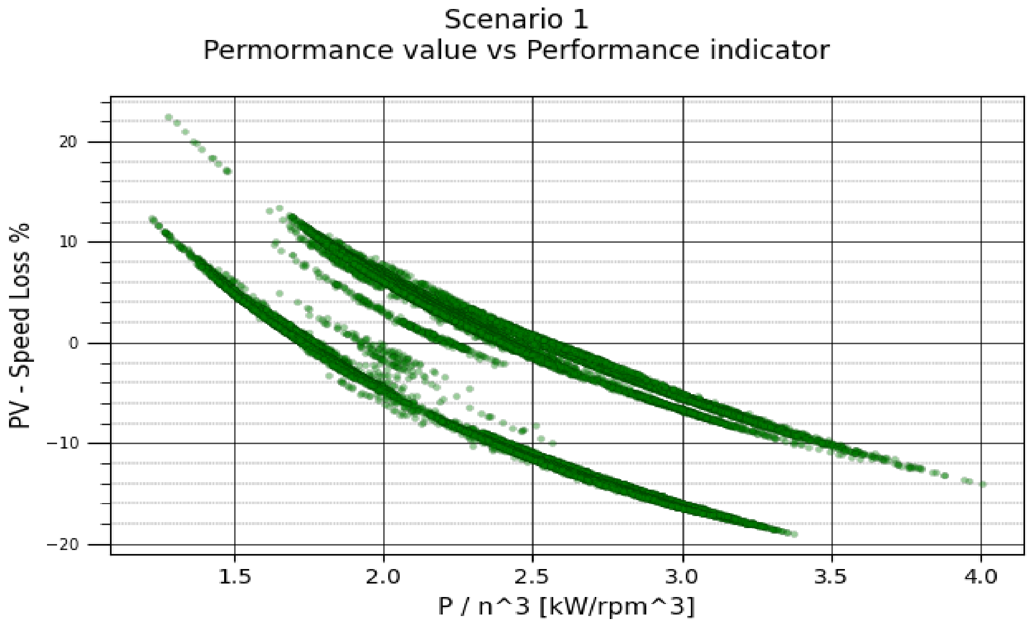


Figure 25: Performance Values of default method compared with the additional performance indicator

3.6.7 Speed Power Draught Trim of final data set

An overview of the final data set of speed, power, draught, trim of the default method is presented in the following figures, in order to have a better understanding of the results. Further below, the frequency histograms of same parameters are displayed.

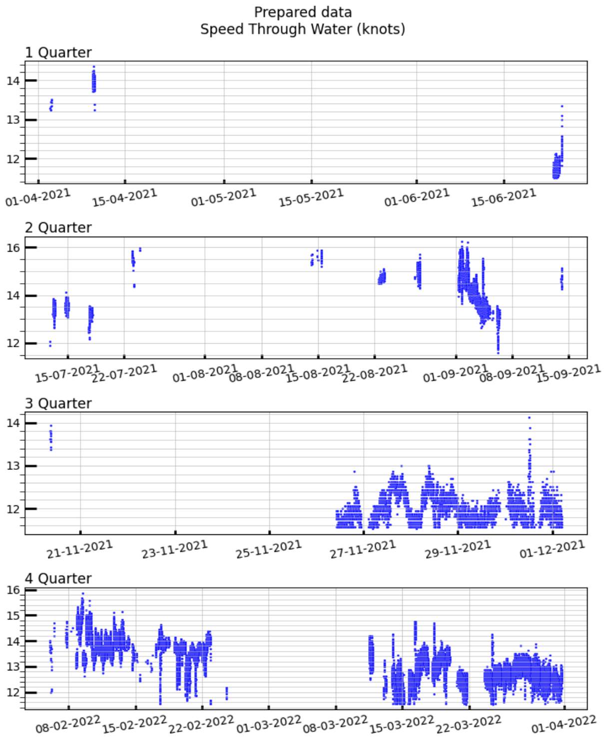


Figure 26: Final speed through water values for PVs calculation

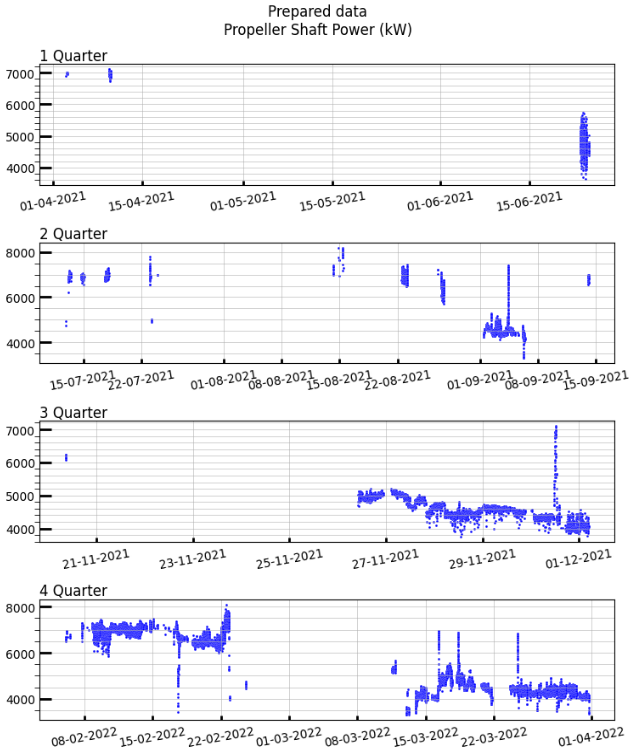


Figure 28: Final propeller shaft power for PVs calculation

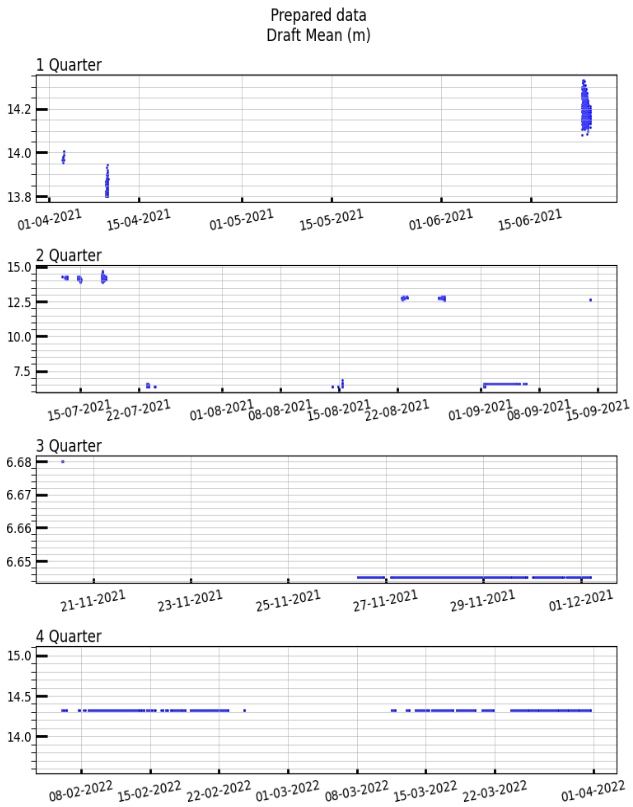


Figure 27: Final draft mean for PVs calculation

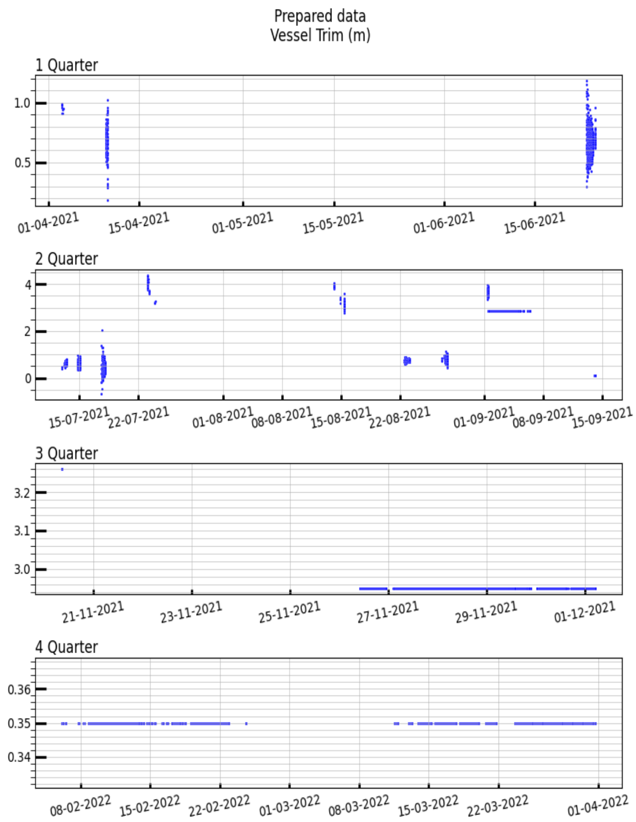


Figure 29: Final trim for PVs calculation

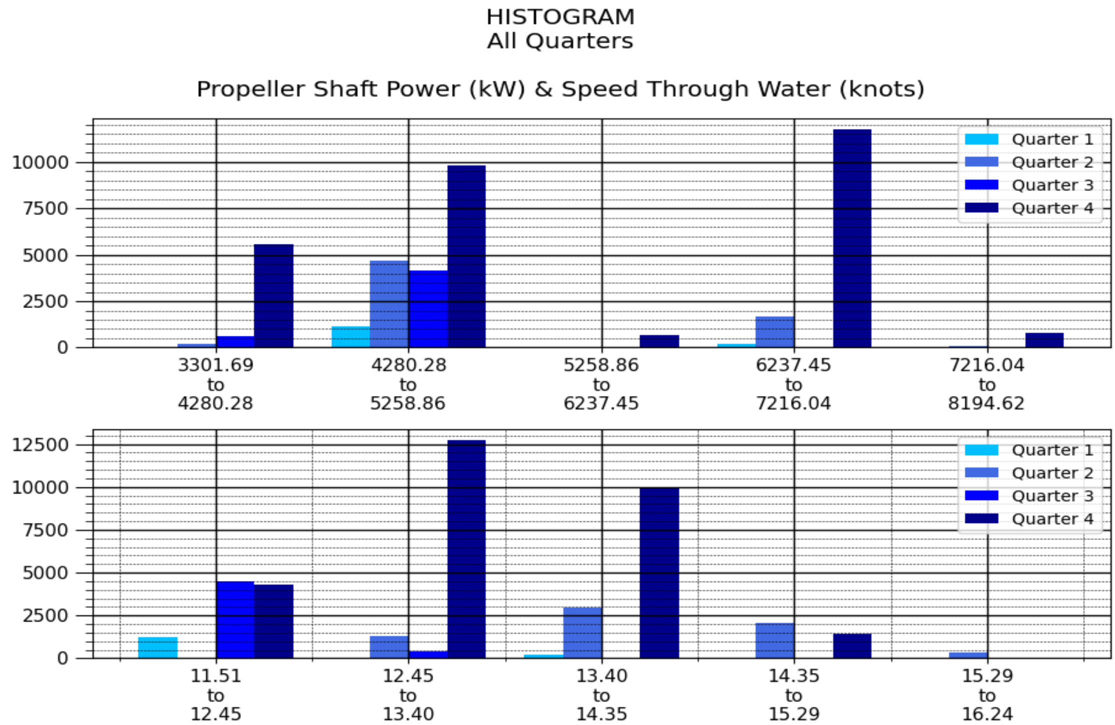


Figure 30: Frequency histograms of final power and speed values, for each quarter of the year

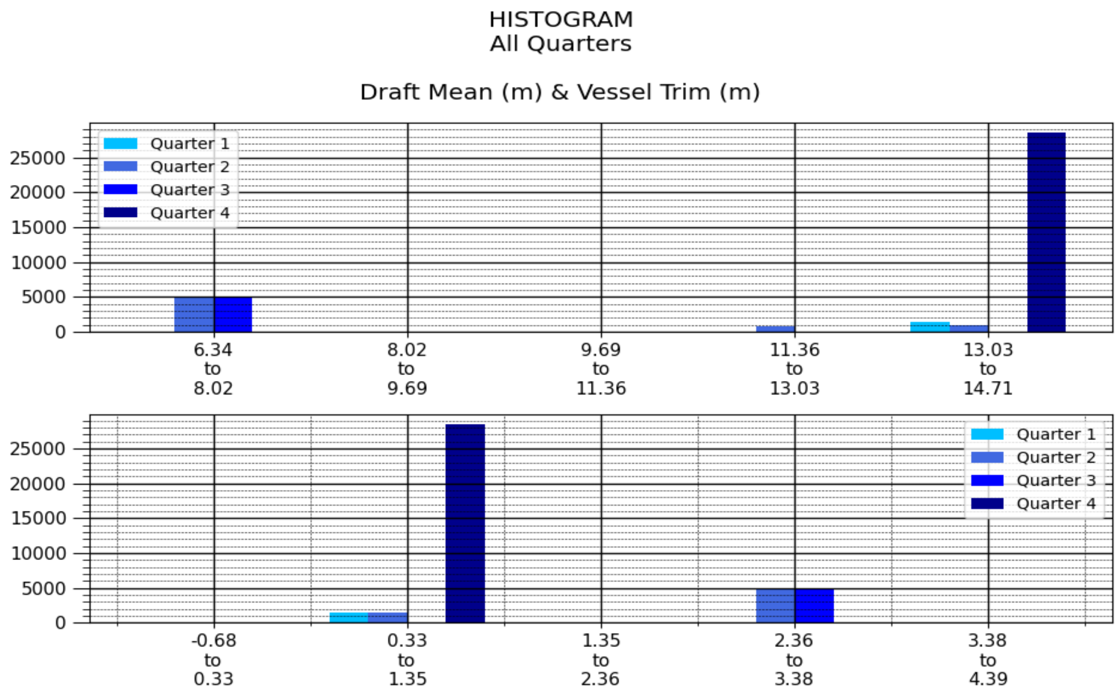


Figure 31: Frequency histograms of final mean draft and trim values, for each quarter of the year

3.7 Limitations

3.7.1 Limitations of the Case Study

- Delivered power correction for Shallow Water;
- Delivered power correction for Current;
- Delivered power correction for Difference in temperature and density of air and water;
- Delivered power correction for Resistance due to Waves (wind and swell waves);
- The effect of appendages such as rudder, propeller, sea chest, etc.
- No available rudder angle measurements which should be below 5º according to ISO standard.

The corrections undertaken are the most significant regarding the added resistance, considering that 1) final speed values are over 11 knots, which mostly excludes shallow waters and 2) reference conditions of ISO 19030 Part 2, determine a 4 BF or 7.9 m/s barrier for wind speed, which means calm weather and restricted wave resistance.

3.6.2 Limitations of ISO 19030 and further improvement

- Variable pitch propellers were excluded as they introduce added complications that the first version of this standard was unable to accommodate. Further research could make it possible to be included in later revisions of the standard.
- Hull performance is not separated from propeller efficiency/performance. If separation is desired, propeller thrust would also have to be measured and ISO should be amended for new physical models and data procedures.
- Uncertainty needs to be more adequately controlled for alternative procedures compared to the default method. Part 3 indicates uncertainty for reference alternative procedures but in limited range. Different frequency for signals and the use of averaging values of parameters and, the sensitivity of uncertainty for each parameter and the sensitivity for the averaging of each parameter. In this way, trustworthy flexibility will be added and ISO 19030 could be exploited on a wider scale in the industry. Based on the experience gained from the application

of ISO 19030, efforts can be made to reduce the inaccuracy of data sources, data filtering and data normalization processes.

- Corrections for waves for speed-power parameters should be considered in future revisions, with a view to further align with relevant standards (e.g. ISO 15016). Power and speed measurements have, in a negative way, a significant effect on the ISO performance values and thus, performance indicators.
- If vessel motion measurements are available in the future, these can be used to filter the data further to increase accuracy. The sensors for measurement of ship motions and calm-sea filtering could be introduced to a later revision of the standard.
- As current filtering and reference conditions disregard large amount of data, the final data set is discontinuous. The resulting continuous subsets could be further analyzed once obtained, in order to evaluate further their correspondence with the available speed power reference curves.

Chapter 4 - Conclusions

The application of ISO 19030 was performed with a python program developed for the scope of this thesis and the resulting Performance Values, PVs, were analyzed for their sensitivity in alternative reference conditions than those proposed by ISO default method. In addition, an effort was given, to detect through ISO procedure the effect of a propeller maintenance event which had taken place at a specific date. The case study uses the data collected from the automated monitoring system of a bulk carrier of 81600 dwt, during one year operation with one measurement per minute. The initial data set comprises 517.579 data points, and each data point comprises eighteen measured parameters at a moment in time. Rudder angle measurements were not available. The year was divided in four quarters, for easier handling of the big data sets. The python program was structured on the procedural steps of ISO 19030. The steps are categorized in modules with individual functionality and are initiated with correct sequence from the main module. There is also a plotting module for inspection of the data sets during the procedure.

The first step is the filtering and validation. The filtering by default method includes grouping the data in 10 minutes blocks, but for a four times higher sampling frequency than the available. For this reason, the relation between the number of outliers and the grouping time-span was examined and the 20 minutes time-span was chosen. Validation for the standard deviations was followed as per standard, but not for rudder angle. The second step is power correction for wind resistance, for which the wind coefficients were extracted from external information. The wind coefficients between ITTC (2017) and sea trials of the vessel were compared, thus the correction factor used the sea trials coefficient. The number of data remaining after the filtering and validation is 409.889.

The third step is the application of reference conditions for which three scenarios are considered, the first for default method's reference conditions, the second for wind speed limit 12 m/s (5.9 BF) instead of default 7.9 m/s (4 BF) and the third for displacement within ±10% of that of the reference curves (sea trials), instead of ±5% as per default method. In addition, the case of ±15 % deviation in displacement is compared with that of ±10%, inferring quite similar results. The reference curves are available for scantling, design and ballast condition. The final data set displayed irrational power speed measurements at some points and the current effect was taken into account, adding the condition the difference between speed through water and speed over ground to be less than 1 knot, resulting to rejection of additional data but enhancing their accuracy.

The resulting Performance Values, PVs, stem from the final data set. The amount of final data as a percentage of the initial data is, for each scenario respectively, 5.96%, 7.71% and 9.08%. Worth noting that the alternative scenarios, retain respectively 29.3% and 52.2% more data than the default method. However, the validation procedure and the reference conditions result in limited data, leaving whole periods of operation out of analysis. This happens in one hand due to the strict limits of the standard. However, on the other hand an important role plays the nature and fluctuations of sensors in a real environment, regarding filtering rejections, and the arbitrary parameter values, which in combination, may result in excessive accumulative data loss by application of proposed reference conditions.

The statistics of PVs and PPVs display similarity for the different scenarios for reference conditions, fact that increases the confidence to expand at some extent the restricting reference conditions and increase considerably the size of the final crucial data set, by increasing disproportionately the uncertainty of the measurements. An uncertainty analysis on the results in this case study could be the part of a further study.

Although the final data set ends up significantly limited, the method was capable to capture a hull and propeller performance pivot point, before and after a propeller maintenance activity. Different scenarios of reference conditions seem to have similar trends in this case as well. Finally, the comparison of speed loss performance value with the performance indicator (KPI) of P/n^3 results to conclude that the KPI of speed loss as derived by this study is an appropriate metric for performance monitoring.

The program developed for the scope of this study, provides repeatability and thus, it is a great opportunity to experiment with results for other vessel specific cases. In this way, more robust conclusions may derive and analysis can take place for enhancing current ISO revision filtering procedures and reference conditions. In addition, branches can be added to the program/procedure in order to examine various ideas for ISO 19030 improvement.

The current regulatory framework with regards to vessel energy efficiency is to become stricter, thus energy savings solutions should be further examined. Various and dispersed efforts can be found in the literature proposing methods for hull and propeller performance monitoring. The ISO 19030 standard is a good starting point for detecting changes in hull and propeller performance, however the efforts need to be joined to amend the ISO 19030 with another revision.

Annex A – ISO Performance Indicators periods

Time periods for the four (4) Performance Indicators

The Performance Indicators (PIs) defined in this International Standard are:

1) Dry-docking Performance, PI-1
2) In-service Performance, PI-2
3) Maintenance Trigger, PI-3
4) Maintenance Effect, PI-4

In order to calculate the desired PI, the periods and their respective data need to be clarified. In essence, the appropriate Reference period and the Evaluation period for each PI.

Below, in Figures 30 to 33, the establishment of proper Reference and Evaluation periods for each PI is presented.

PI-1

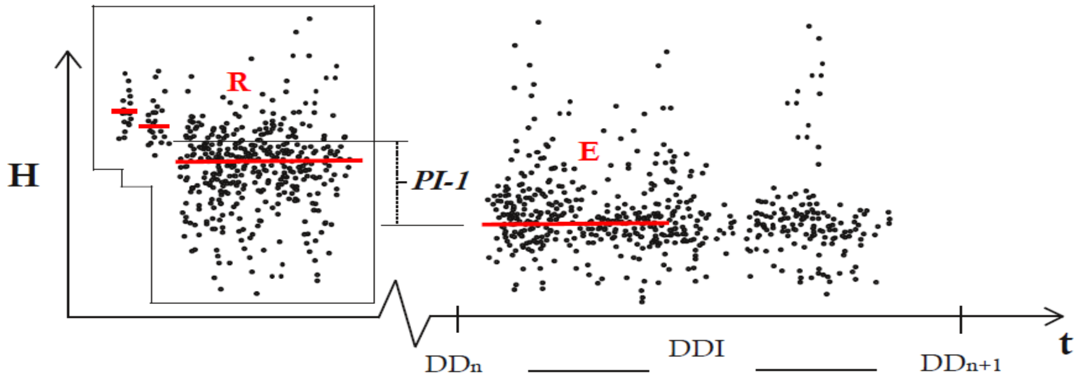


Figure 32: Periods for Dry dock performance indicator

where:

- H: Hull and propeller performance, lower H means better performance
- t: Time
- DD_n: Present dry-docking
- DD_{n+1}: Next dry-docking
- DDI: Dry-docking interval

The above are common for the rest of PIs.

Reference and Evaluation period depend on the PI. For PI-1:

- R: Reference period: average hull and propeller performance following previous out-dockings
- E: Evaluation period: hull and propeller performance following present out-docking

During a dry-docking the hull and propeller are cleaned, polished, repaired or retrofits may occur to improve the overall hull and propeller performance.

PI-1 can be used to evaluate the effectiveness of a dry-dock.

PI-2

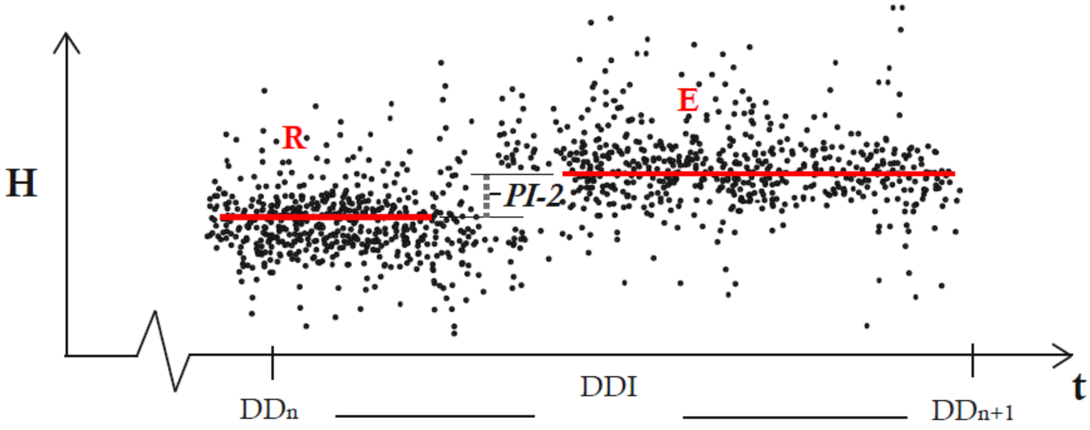


Figure 33: In-service performance indicator periods

- R: Reference period: hull and propeller performance following present out-docking
- E: Evaluation period: average hull and propeller performance to the end of dry-docking interval.

PI-2 indicator can be used to evaluate the deterioration of the hull and propeller performance during an uninterrupted period. The Reference and Evaluation Periods are inside the dry-docking interval (DDI) and other modifications to performance must be minimized.

PI-3

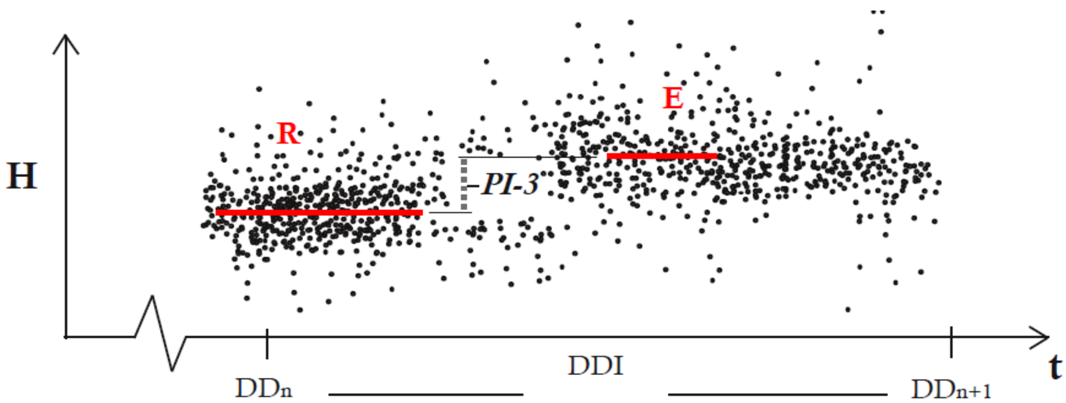


Figure 34: Periods for maintenance trigger performance indicator

- R: Reference period: hull and propeller performance following present out-docking
- E: Evaluation period: moving average of hull and propeller performance at any chosen time

PI-3 refers to changes in hull and propeller performance from the start of the dry-docking interval to a moving average at any chose time.

PI-4

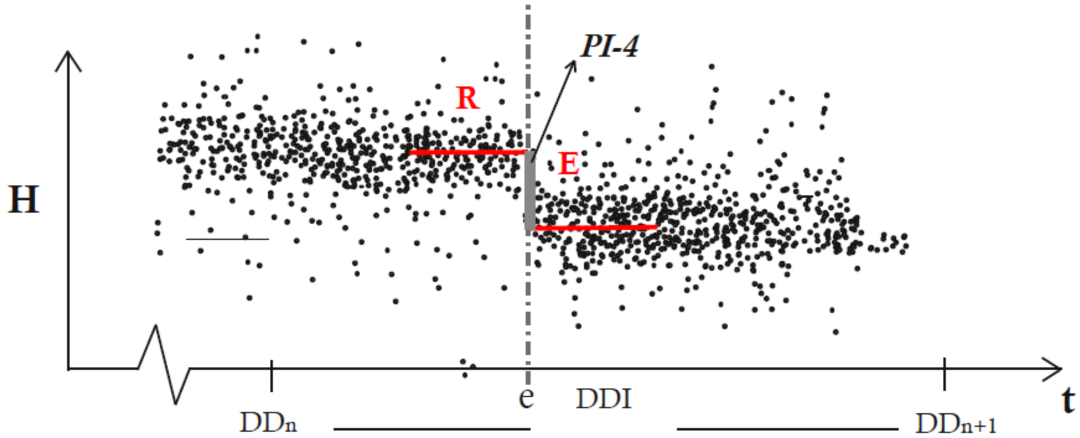


Figure 35: Figure 30: Periods for maintenance effect performance indicator

Figure A4: Maintenance effect

- e: Maintenance event
- R: Reference period: hull and propeller performance before maintenance event
- E: Evaluation period: hull and propeller performance after maintenance event

PI-4 evaluates the changes in hull and propeller performance from measurements before and after a maintenance event and can be used to determine its effectiveness.

Annex B – Data Column Algorithm

Column Standardization

The standardization algorithm is used to search through the names of the measured parameters provided in the Excel Raw Data Set and replace them with the corresponding default names of the parameter. The default names of the parameter are created in a list, at the beginning.

The algorithm is indifferent to the column names and quantity of the imported data set. It compares the words of the imported data columns with the words of ISO standard columns.

The snippet of the code displaying the algorithm is shown in Picture C1 and C2, accordingly.

```
columns_iso = ["Speed Through Water (knots)", "Propeller Shaft Power (kW)",
               "Relative Wind Speed (m/s)", "Relative Wind Direction (deg)", "Heading (deg)", "Speed Over Ground (knots)",
               "Draft Aft (m)", "Draft Fwd (m)", "Draft Mean (m)", "Vessel Trim (m)", "Water Depth (m)",
               "M/E Shaft RPM (rpm)", "Shaft Torque (kNm)", "M/E Fueil Oil Cons (mt/day)", "M/E Loading Percent (%)",
               "Fuel Oil Temperature (M/E supply) (C)", "Fuel Oil Temperature (M/E return) (C)", "Fuel LCV (kj/kg)"]



for i_old in range(0, len(data.columns)):

    old_col_name = data.columns[i_old]
    words_old_name = re.split('[- _]+', old_col_name, flags=re.IGNORECASE)

    matching = False

    for i_new in range(0, len(columns_iso)):

        words_new_name = re.split(r"\s+", columns_iso[i_new], flags=re.IGNORECASE)

        matches = 0

        for ii in range(0, len(words_old_name)):
            for jj in range(0, len(words_new_name)):
```

```
        matches = 0

        for ii in range(0, len(words_old_name)):
            for jj in range(0, len(words_new_name)):

                if words_old_name[ii] == words_new_name[jj]:
                    matches += 1

        if matches == 2:
            matching = True
            data.rename(columns={data.columns[i_old]: columns_iso[i_new]}, inplace=True)

        elif matches > 2:
            matching = True
            data.rename(columns={data.columns[i_old]: columns_iso[i_new]}, inplace=True)
            i_new = len(columns_iso) + 1

        else:
            matching = False


    if ~matching:
        print("----------------------------**********----------------------------\n",
              data.columns[i_old], "was omitted from iso columns!!!\n",
              "The column name was not similar with iso standard column names."
              "If inclusion is desired, rename the specific column."
              "----------------------------**********----------------------------\n")
```

Annex C – Raw & Filtered data according to Chauvenet's Criterion

The eighteen (18) parameters with indexes the time points are the raw data set or the Retrieved Data Set. They are specific for the subject ship, measured and attained during unbiased operation of one year duration, with sampling frequency of one measurement per minute.

The Plotting Module of the program is plotting figures with subplots of 3x3 dimension, thus, any number of measured parameters and any time-span could be provided for plotting. The ISO application program of this thesis can receive a random number of parameters for a vessel from its monitoring sensors. Usually, the more parameters measured, the more combinations and effective filters can be applied to the raw data, amending the next stage of the ISO 19030.

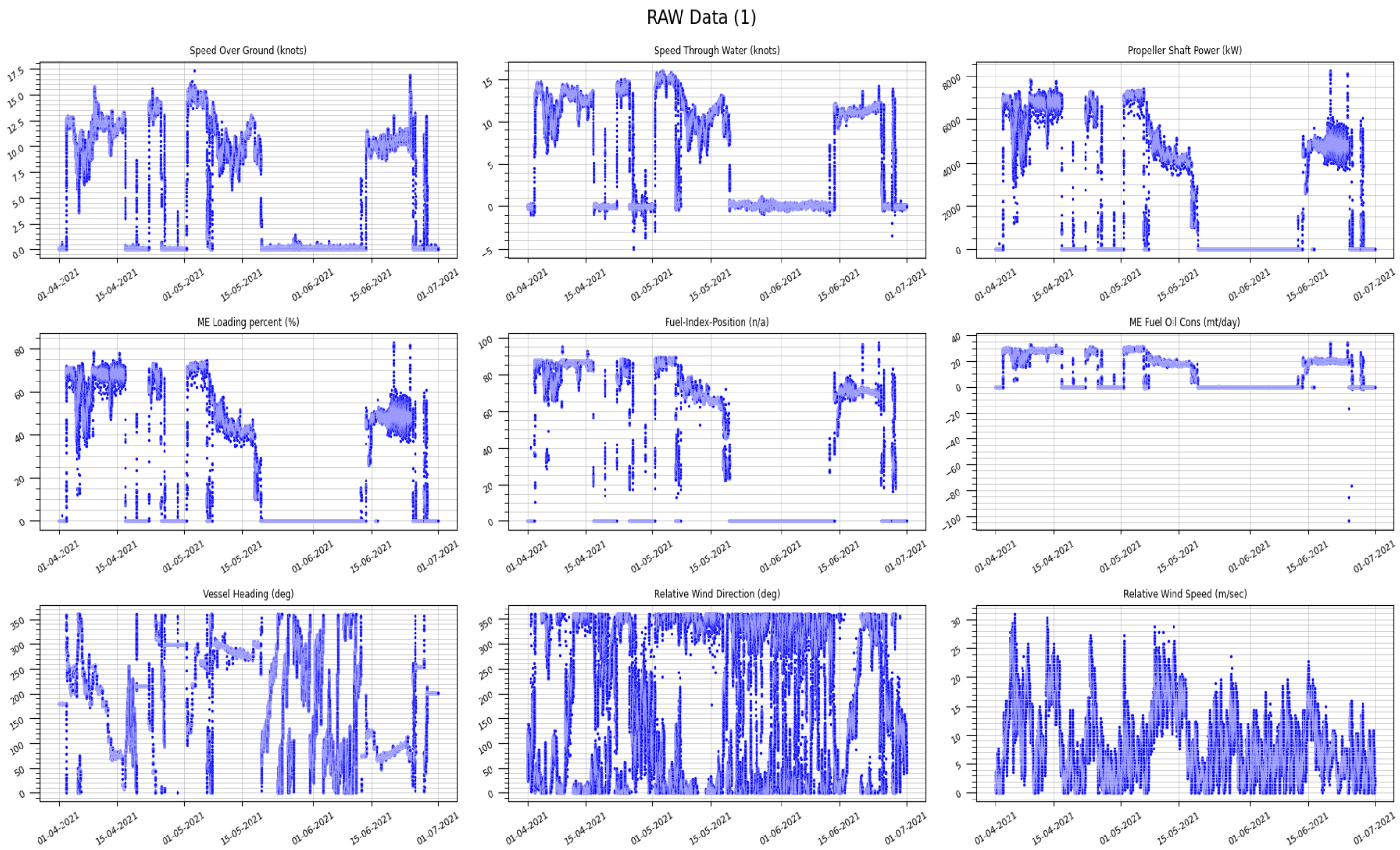


Figure 36: Raw data acquired for the 1st quarter of the year (1)

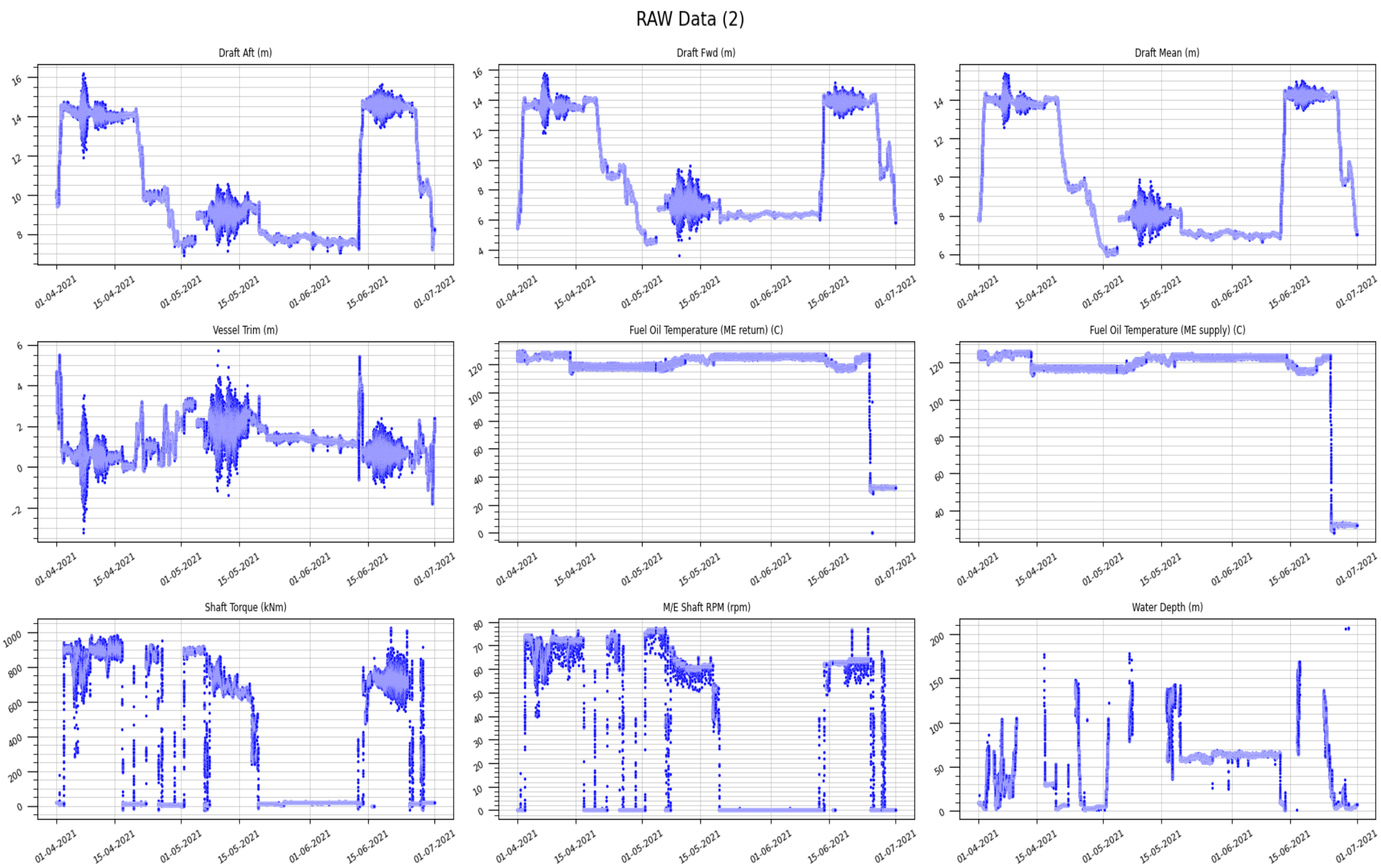


Figure 37: Raw data acquired for the 1st quarter of the year (2)

By observing the above figures important conclusions may derive, such as:

- ✓ The **Speed Through Water (STW)** and **Propeller Shaft Power (PSP)**, the primary parameters, are zero for approximately one month in the three months period – 19.05.2021 to 13.06.2021. The vessel could be at port for above period. During this period the data will not be appropriate for analysis.

- ✓ There are five (5) small periods where there are no available data. There should be some explanation, e.g. no signal for transmitting data due to bad weather or isolated sailing areas, malfunctioning of the data acquisition system of the vessel or other, but this investigation is out of the scope of this analysis.

- ✓ The Draft Mean is increased abruptly at the beginning of the reporting period, which means vessel had been loaded with cargo. Then, within a period of two weeks, from 02.04.2021 to 16.04.2021, the parameters come out within a restricted range of values. This could mean that the vessel was operating under a subset of operational profiles which could be considered similar, under laden condition and relatively small changes in above parameters. Also, the Water Depth parameter, after loading seems to be higher than 20 meters, except during a small sub-period in which goes close to zero. Probably a cargo operation at a port. The data corresponding in aforementioned two weeks period is a suitable part for further analysis.

The filtered data by following the Chauvenet's criterion are presented in the figures in the following pages.

FILTERED Data (1)

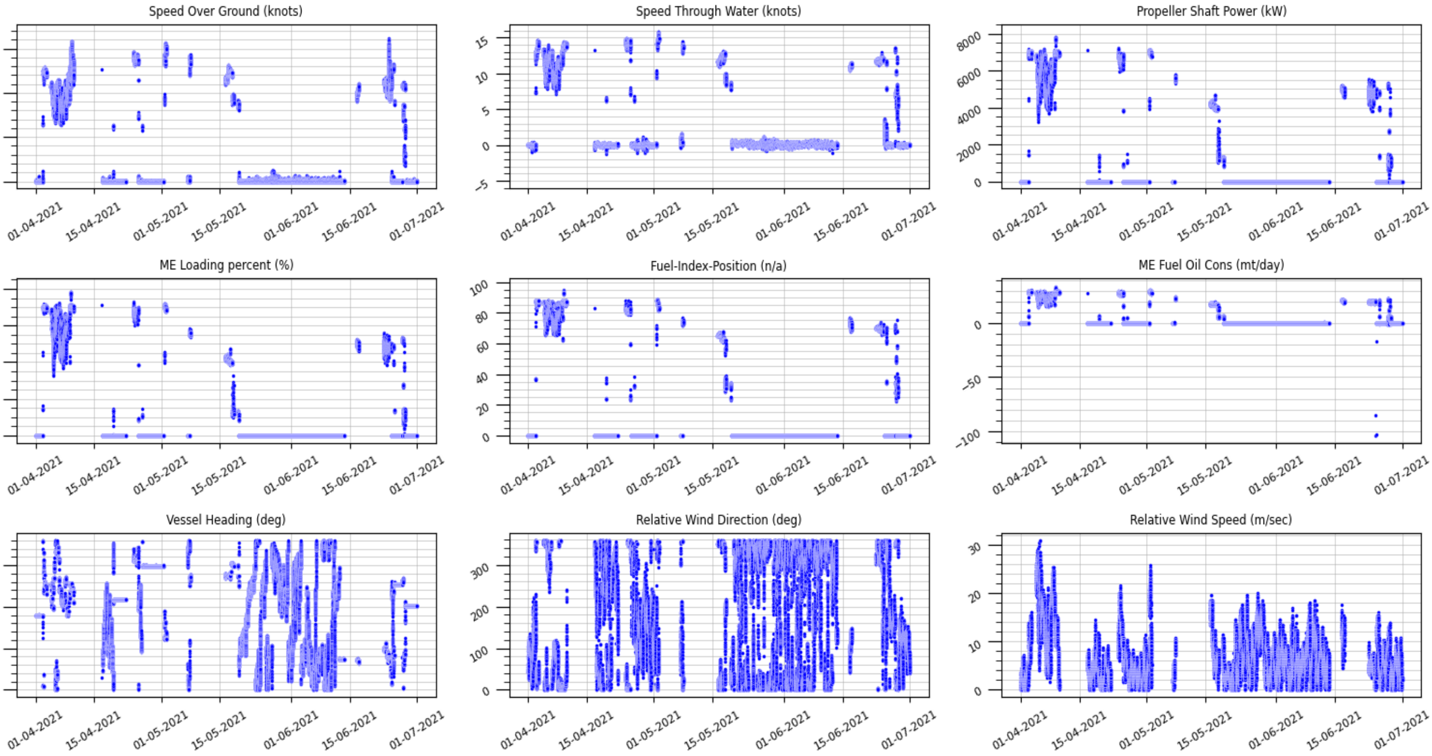


Figure 39: Filtered Data according to Chauvenet's Criterion, 1st quarter of the year (1)

FILTERED Data (2)

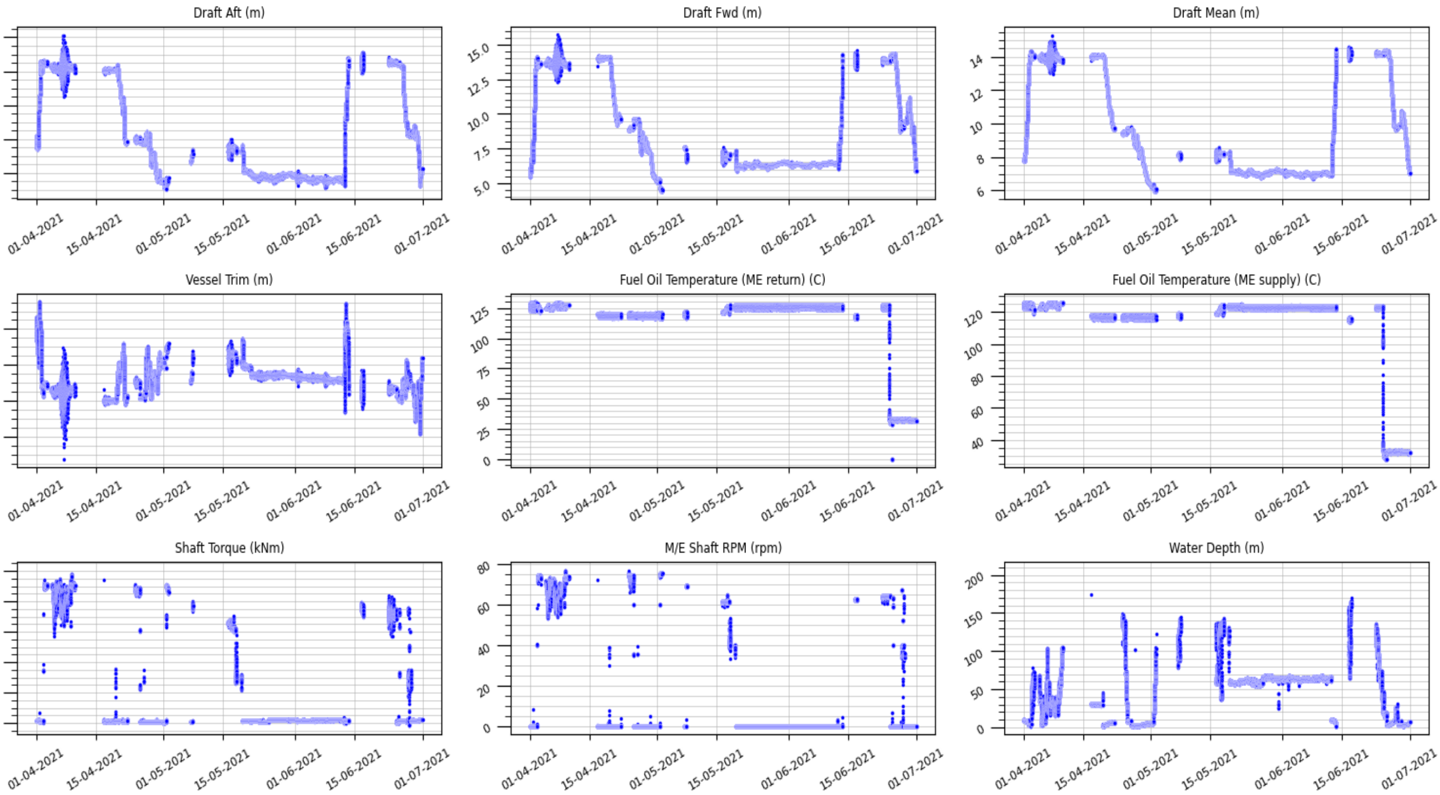


Figure 38: Filtered Data according to Chauvenet's Criterion, 1st quarter of the year (2)

Annex D – Imported Data

The procedure of importing the available raw data from an Excel sheet to Python language Data-Frames is described below.

- The first cells of the rows contain all the values;
- The first row contains the names of the measured parameters. Their sequence corresponds to the sequence of the values in below rows, resembling a table.
- The first element of each cell is the time-stamp of the measurements;
- The following elements, separated by commas "," are the parameters measured;
- Each row contains a **data-point**, which is the combination the time-stamp and the values of parameters.
- All the rows together consist the Retrieved Data Set as per the default method;

The first eight (08) sampling points are presented as an example of the format, one with no data and one filled with data.

	A	B	C	D	E	F	G	H	I	J	K	L
1	TIME,Speed-Over-Ground (knots),Speed-Through-Water (knots),Propeller-Shaft-Power (kW),ME RPM_AMS (rpm),ME-Loading-percer											
2	1/1/2021 0:00,,,,,,,,,,,,,,,,,,,,,,,,,,,,											
3	1/1/2021 0:01,,,,,,,,,,,,,,,,,,,,,,,,,,,,											
4	1/1/2021 0:02,,,,,,,,,,,,,,,,,,,,,,,,,,,,											
5	1/1/2021 0:03,,,,,,,,,,,,,,,,,,,,,,,,,,,,											
6	1/1/2021 0:04,,,,,,,,,,,,,,,,,,,,,,,,,,,,											
7	1/1/2021 0:05,,,,,,,,,,,,,,,,,,,,,,,,,,,,											
8	1/1/2021 0:06,,,,,,,,,,,,,,,,,,,,,,,,,,,,											

Figure X1: Raw data format with no values

	A	B	C	D	E	F	G	H	I	J	K	L
1	TIME,Speed-Over-Ground (knots),Speed-Through-Water (knots),Propeller-Shaft-Power (kW),ME RPM_AMS (rpm),ME-Loading-percer											
2	01/07/2021 00:00:00,0.2,-0.0099,0,0,0,0,0,201.7,60,2.0578,,,8.24,5.86,7.05,2.38,,32.0309,32.05,20,-8,0,,,7.4,1,0,42115.7072											
3	01/07/2021 00:01:00,0.1,-0.0099,0,0,0,0,0,201.7,59,2.5722,,,8.23,5.86,7.045,2.37,,32.0309,32.05,20,-8,0,,,7.4,1,0,42115.7072											
4	01/07/2021 00:02:00,0.2,-0.0299,0,0,0,0,0,201.7,49,1.5433,,,8.23,5.86,7.045,2.37,,32.0309,32.201,20,-8,0,,,7.3,1,0,42115.7072											
5	01/07/2021 00:03:00,0,-0.0498,0,0,0,0,0,201.7,57,2.0578,,,8.23,5.86,7.045,2.37,,32.0309,32.05,20,-8,0,,,7.3,1,0,42115.7072											
6	01/07/2021 00:04:00,0,-0.0698,0,0,0,0,0,201.7,55,2.0578,,,8.23,5.86,7.045,2.37,,32.0309,32.05,20,-8,0,,,7.3,1,0,42115.7072											
7	01/07/2021 00:05:00,0.1,-0.0898,0,0,0,0,0,201.7,46,1.5433,,,8.23,5.86,7.045,2.37,,32.0309,32.201,20,-8,0,,,7.3,1,0,42115.7072											
8	01/07/2021 00:06:00,0.1,0.0099,0,0,0,0,0,201.7,55,1.5433,,,8.23,5.86,7.045,2.37,,32.0309,32.102,20,-8,0,,,7.3,1,0,42115.7072											

Figure X2: Raw data format with values, collected from automatic monitoring system on vessel

The actual text in the first cell of the first row (headers/columns names) is:

Index: *0,1…130900*

0: *TIME*

1: *Speed-Over-Ground (knots),*

2: *Speed-Through-Water (knots),*

3: *Propeller-Shaft-Power (kW),*

4: *ME RPM_AMS (rpm),*

5: *ME-Loading-percent (%),*

6: *Fuel-Index-Position (n/a),*

7: *ME-FO-Cons (mt/day),*

8: *Vessel-Heading (deg),*

9: *Rel-Wind-Direction (deg),*

10: *Rel-Wind-Speed (m/sec),*

11: *DTN_AIR_TEMPERATURE_10M_ ACTUAL (oC),*

12: *DTN_AIR_PRESSURE_MEAN_SEA _LEVEL_ACTUAL (mbar),*

13: *Draft-Aft (m),*

14: *Draft-Fwd (m),*

15: *Draft-Mean (m),*

16: *Vessel-Trim (m),*

17: *DTN_SEA_TEMPERATURE_0M_ ACTUAL (oC),*

18: *Fuel Oil Temperature (ME return) _ TRQM (C),*

19: *Fuel Oil Temperature (ME supply) _ TRQM (C),*

20: *Shaft Torque_ TRQM (kNm),*

21: *Shaft Thrust_ TRQM (kN),*

22: *M/E Shaft RPM_ TRQM (rpm),*

23: *DTN_SIGNIFICANT_WAVE_HEIGHT (m),*

24: *DTN_MEAN_WAVE_ DIRECTION (deg),*

25: *Water Depth Relative to the Transducer_ BRG_ ECHO (m),*

26: *Ballast-Condition (-),*

27: *Cargo-Carried (tn),*

28: *Fuel-LCV (kJ/kg)*

After column standardization – Annex B – the varying names result in standard names, by word-to-word comparison. In this way, the exact names of the columns are known and better manipulation can take place. Finally, the column "TIME" is appointed as the index of the rows in the tabular Dataframes. The standard names, which supersede the random names of varying import cases, are:

Index: **"TIME"**

0: **"Speed Through Water (knots)"**,

1: **"Propeller Shaft Power (kW)"**,

*2:***"Relative Wind Speed (m/sec)"**,

3: **"Relative Wind Direction (deg)"**,

4: **"Vessel Heading (deg)"**,

5: **"Speed Over Ground (knots)"**,

6: **"Draft Aft (m)"**,

7: **"Draft Fwd (m)"**,

8: **"Draft Mean (m)"**,

9: **"Vessel Trim (m)"**,

10: **"Water Depth (m)"**,

11: **"M/E Shaft RPM (rpm)"**,

*12:***"Shaft Torque (kNm)"**,

13: **"ME Fuel Oil Cons (mt/day)"**,

14: **"ME Loading percent (%)"**,

15: **"Fuel Oil Temperature (ME supply) (C)"**,

16: **"Fuel Oil Temperature (ME return) (C)"**

17: **"Fuel LCV (kJ/kg)**

Annex E – Sea trials reference conditions

Table 20 presents the important physical and operational quantities during the Sea trials, from which the wind resistance coefficient was obtained.

Table 20: Sea trials period characteristics, in regards to wind correction of power

Sea trials			
Operational		Environmental	
Draft mean	6.15 *m*	Air temp	0.7 °C
Displacement	36119 *t*	Air pressure	99900 *Pa*
Draft aft	7.40 *m*	Air density	1.271 kg/m^3
Draft fwd	4.90 *m*	Water temp	13 °*C*
		Water density	1.023 t/m^3
Transverse area	832 m^2	Wind scale	5 *BF*
Prop. coefficient	0.813 (-)	Weather	*Sunny*

Annex F – Power Performance Values, PPVs, for each scenario of reference conditions

The complementary performance value, PPV, is the power increase needed to move the vessel through water at a given speed, according to the ISO standard. The graph and the statistical characteristics of PPVs for each scenario, with reference to Table 16 in section 3.6.3., are presented in Figure and Table.

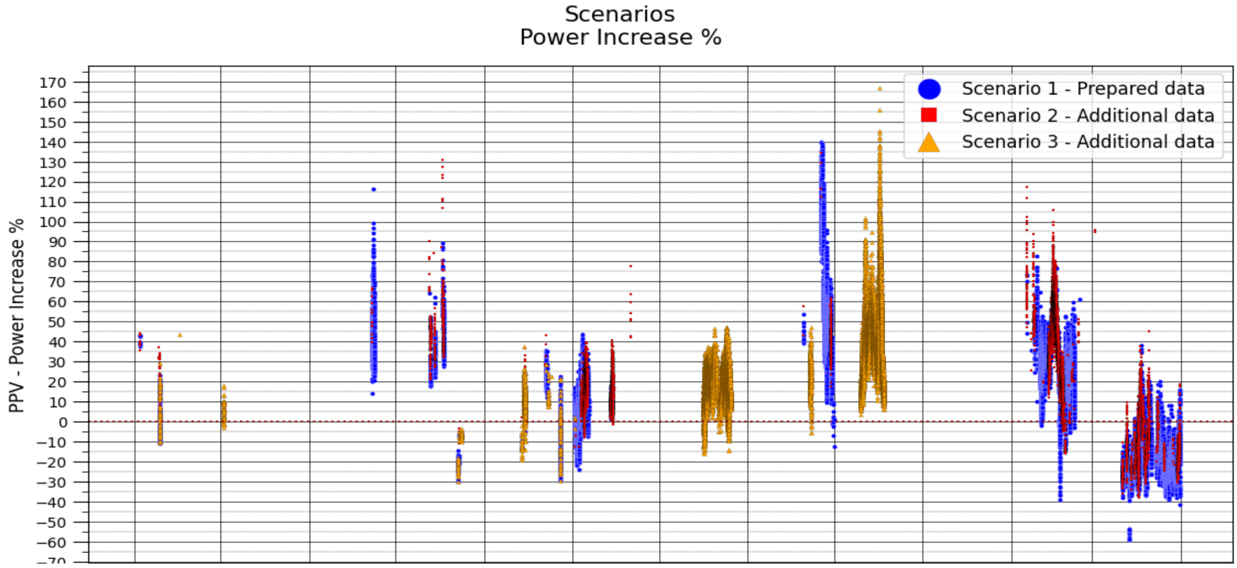


Figure 40: Power Performance Values, PPVs, power increase % for all scenarios

Table 21: Statistical metrics of Power Performance Values, PPVs, for each Scenario

	Scenario 1				**Scenario 2**				**Scenario 3**			
	Sc	**De**	**Ba**	**Total**	**Sc**	**De**	**Ba**	**Total**	**Sc**	**De**	**Ba**	**Total**
Count	**22799**	**294**	**7782**	**30875**	**29610**	**1133**	**9175**	**39918**	**23209**	**15544**	**8229**	**46982**
Mean	-0.51	8.90	30.50	7.70	5.34	13.77	29.16	11.05	-0.15	29.80	29.13	14.89
Std	23.95	17.76	31.45	29.27	27.74	12.43	29.62	29.61	23.94	19.48	31.22	28.29
Min	-59.12	-29.30	-30.18	-59.12	-59.12	-29.30	-30.18	-59.12	-59.12	-29.38	-30.18	-59.12
25%	-21.11	-5.50	5.77	-17.63	-19.20	7.59	6.94	-14.69	-20.97	17.26	5.28	-7.90
50%	-6.95	14.99	22.93	2.63	-1.37	13.85	21.95	8.43	-6.32	25.34	20.07	15.52
75%	20.67	22.92	51.32	26.43	26.72	21.51	47.88	30.20	20.97	40.24	50.05	31.12
Max	116.07	35.70	139.72	139.72	131.01	77.60	139.72	139.72	116.07	166.68	139.72	166.68

Table 22: Statistical characteristics of Performance values before/after propeller repair, for each Scenario

	01-Apr-2021 to 19-Jun-2021			**19-Jun-2021 to 01-Apr-2022**		
	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 1**	**Scenario 2**	**Scenario 3**
Count	1302	1795	1423	29573	38123	45559
Mean	39.26	40.34	36.44	5.99	9.67	14.21
Std	18.07	17.80	19.78	28.87	29.34	28.25
Min	-10.94	-10.94	-10.94	-59.12	-59.12	-59.12
25%	29.11	30.58	26.76	-18.24	-15.52	-8.87
50%	37.48	38.72	35.37	0.89	6.50	15.80
75%	50.69	50.30	49.19	24.25	28.00	30.16
Max	116.07	131.01	116.07	139.72	139.72	166.68

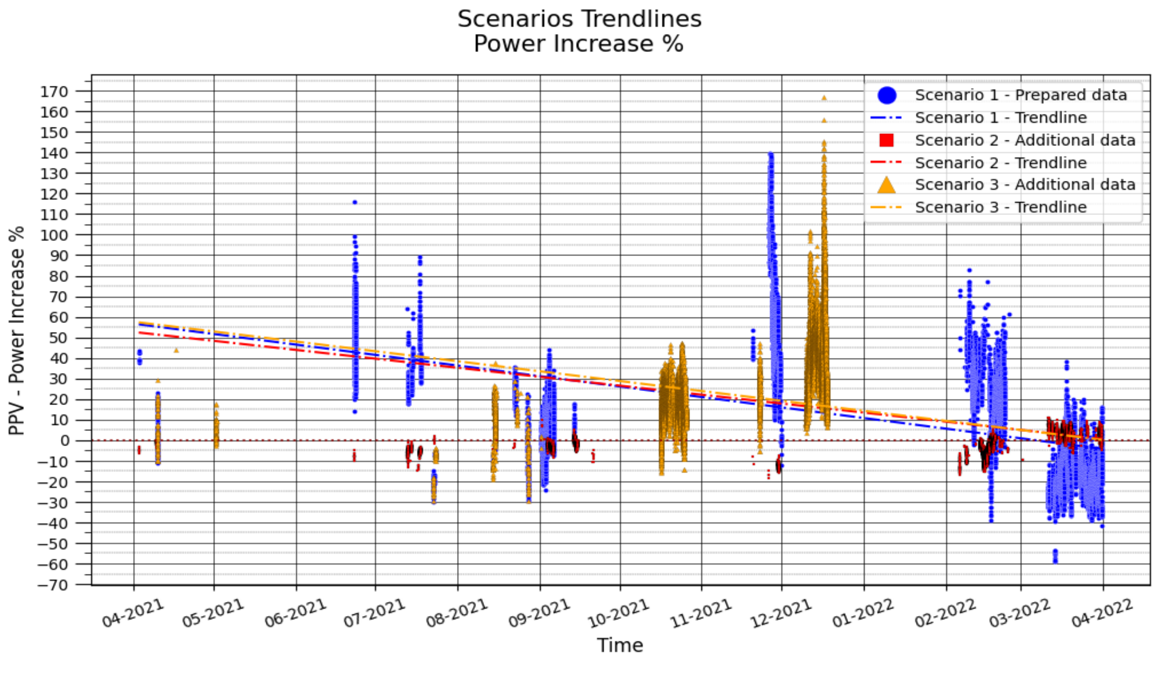


Figure 41: Trendline of Power Performance Values, PPVs, for three different scenarios of reference conditions

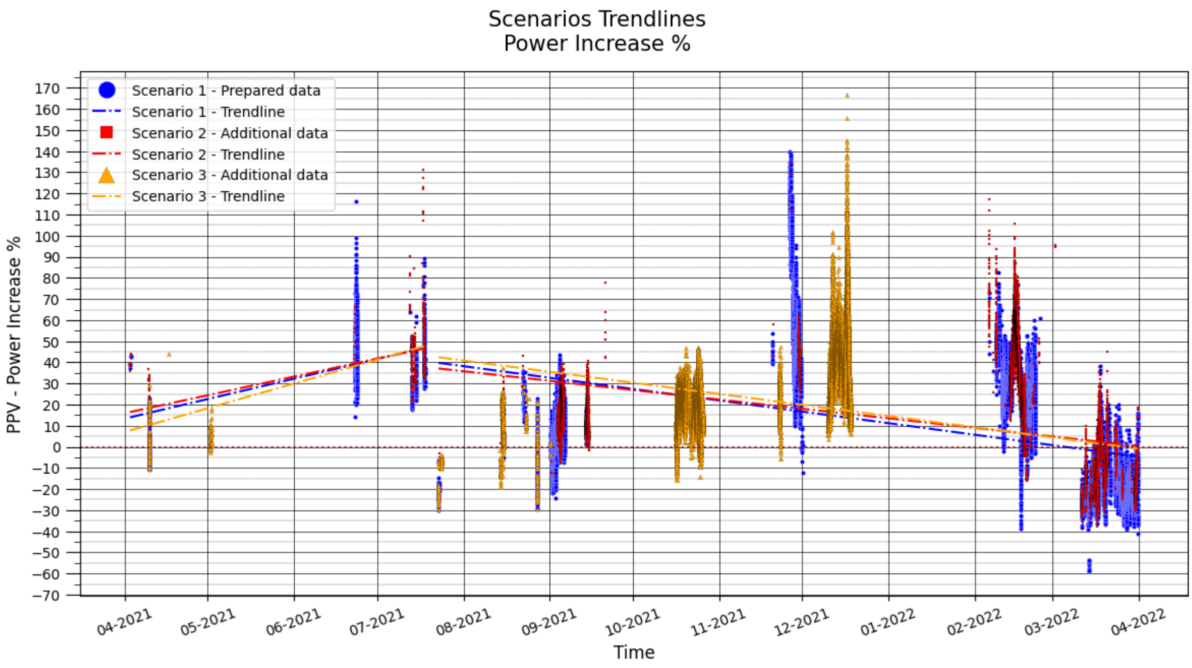
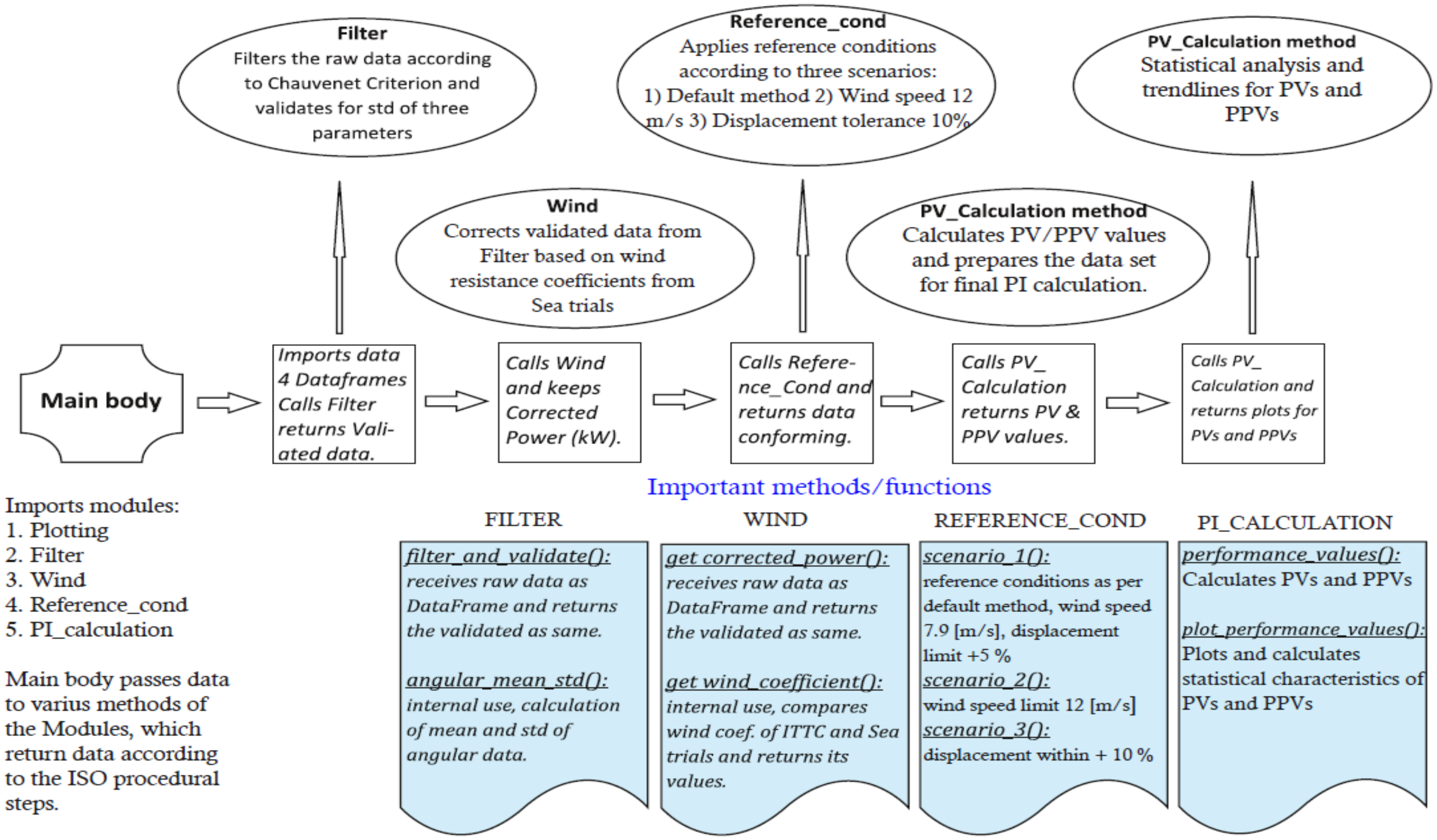


Figure 42: Trendline of Performance Values, PVs, for three different scenarios, before and after propeller maintenance event.

Annex H – Python Program Structure



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