Operational data-driven energy efficiency and effectiveness assessment of a hybrid propulsion equipped naval vessel

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Synopsis

Ship designers hardly ever receive feedback from the actual operation of their designs apart from sea acceptance trials. This results in decisions based on assumptions that lack accounting for the diversity of actual operational conditions. Similarly, crews operating the vessels do not receive a clear picture on the energy efficiency, effectiveness and environmental footprint of different options. This paper proposes an energy assessment method using operational data from continuous monitoring, in order to provide insight on the impact of design and operational decisions and assist in taking better advised and weighted ones.

Keywords: data; energy; efficiency; effectiveness; hybrid; ship

1 Introduction

The Intergovernmental Panel on Climate Change has concluded that greenhouse gases together with other anthropogenic factors are extremely likely to be the main cause of global warming and climate change (IPCC, 2014). Future economic growth and transport demand indicate that maritime carbon dioxide emissions will increase between 50% to 250% by 2050 compared to the 2012 level (IMO, 2014). At the same time, new policy on energy efficiency enhancement and emissions will result in a carbon dioxide concentration decline, within the same time interval, only in the most conservative and strict scenario.

Mitigation of the environmental problem requires an improvement in fuel consumption, unless ships run on non fossil fuels like hydrogen, ammonia (Bicer and Dincer, 2018) or synthetic fuels (Horvath et al., 2018). There is a plethora of different strategies in reducing fuel consumption and proportionally greenhouse gas emissions (Psaraftis, 2012) for a specified vessel geometry, such as applying optimal routing (Hinnenthal and Clauss, 2010) and loading algorithms (Coraddu et al., 2017). Advanced control strategies and alternative power system configurations described in (Geertsma et al., 2017b) and (Dedes et al., 2012) can offer significant gains too. When the configuration has already been selected, optimal component sizing and interaction must be considered. Ultimately, crew behaviour is also a significant influencing factor.

One of the main challenges ship designers come across when examining different options is the uncertainty regarding propeller thrust requirement. Among the factors influencing its value are weather conditions, which show strong geographical and seasonal variation, loading conditions, fouling level, acceleration phases and manoevring activity. Aiming to capture the extent of this issue, a number of resistance curves can be considered as demonstrated in (Geertsma et al., 2017a, 2018). Another crucial challenge, according to (Georgescu et al., 2018) and (Jafarzadeh and Schjølberg, 2018), is the prediction of vessel speed profile. Unfortunately, this knowledge is not available at an early stage of the ship design process and its estimation can prove to be difficult, especially for naval vessels. Finally, most assessment indices introduced, like EEDI, refer to only one design point, and do not account for changes of energy performance over the range of operational conditions and speeds (Vassalos et al., 2014), hence lack many benefits from using multiple points as discussed in (Baldi et al., 2015).

This paper introduces an operational data-driven methodology on the energy assessment of ships. It demonstrates the actual operational profile of the vessel and uses well-established and accurate models to derive and describe the behaviour of required propeller thrust. It also proposes mean energy effectiveness and other mean values from continuous monitoring, as opposed to low frequency sampled data, as an important tool in evaluating actual energy performance. In this way it provides the missing feedback to designers and users as seen in Figure 1.

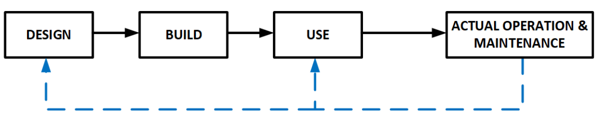

Figure 1: Missing feedback to designers and users in maritime industry addressed in this paper.

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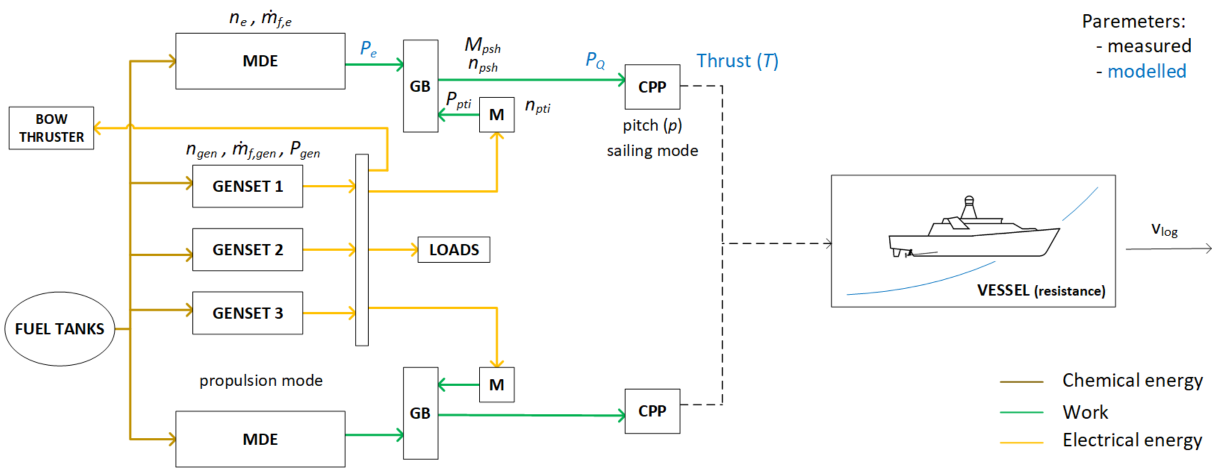

Figure 2: Depiction of vessel power system and parameters used.

2 System description

2.1 *The vessel*

The examined vessel is an ocean patrol vessel (OPV) of the Royal Netherlands Navy (RNLN). Its hybrid propulsion system architecture, seen in Figure 2, consists of two controllable pitch propellers driven either mechanically by one or two main diesel engines, or electrically by two electrical motors. Two gearboxes reduce shaft speed and electrical generation is achieved with three diesel generator sets. Component rating and characteristics can be found in Table 1. Finally, a number of propulsion and sailing modes can be selected, as seen in Table 3. Choosing the optimal mode, accounting for a number of influencing factors, can be challenging.

Table 1: Maritime power system components.

Main diesel engines		**Gearboxes**		**CPP Propellers**	
nominal power	5,400 kW	reduction ratio (MDE)	4.355	diameter	3.25 m
nominal speed	1,000 rpm	reduction ratio (PTI)	17.880	number of blades	5
				pitch/diameter ratios	
Diesel generator sets		**PTI motors**		- 100% ahead	1.318
nominal power	910 ekW	nominal power	400 kW	- design	1.108
nominal speed	1,800 rpm	nominal speed	1,788 rpm	- 100% astern	-0.768

Table 2: Measured IPMS parameters used.

Parameter	Symbol
Main diesel engine speed	n_e
Main diesel engine fuel consumption	$\dot{m}_{f,e}$
Diesel generators speed	n_{gen}
Diesel generators power	P_{gen}
Diesel generators fuel consumption	$\dot{m}_{f,gen}$
PTI motor speed	n_{pti}
PTI motor power	P_{pti}
Propeller shaft speed	n_{psh}
Propeller shaft torque	M_{psh}
Propeller pitch	p
Propeller virtual shaft speed	n_{virt}
Vessel speed through water	v_{log}
Propulsion mode	-
Sailing mode	-

Table 3: Propulsion and sailing modes.

Propulsion mode	Sailing mode
2 MDEs	transit
	manoeuvring
1 MDE	trailing
	shaft brake with 0-pitch
	blocked shaft with full pitch
2 PTIs	

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2.2 IPMS dataset

The Integrated Platform Monitoring System (IPMS) installed on the vessel provides continuous monitoring capabilities for a large number of operational parameters, significantly improving the accuracy of energy performance evaluation over other means, such as noon reports (Aldous et al., 2015). The dataset used in this analysis consisted of 13,276,800 measurements at a 3 seconds time step δt, corresponding to 15 months of operation. The 13 parameters included in this analysis are listed in Table 2. In order to clean the data, the dataset was split into a number of voyages rejecting data corresponding to periods that the vessel was out of operation. Some of the voyages were rejected too for containing periods of faulty sensor functioning. This resulted in processing a total number of 3,400,686 measurements per parameter or about 4 months of actual sailing operation.

2.3 Dataset restrictions

The available dataset does not include parameters for propeller thrust, main diesel engine power and power delivered to the propeller as seen in Figure 2. This means that energy efficiency of main diesel engines and propellers cannot be directly evaluated only by using measured parameters, since knowledge of input and output power level for each component is needed. All these three parameters were evaluated using first principle models, calibrated with manufacturers data. The most complex model was the one evaluating propeller thrust because of the higher number of derived parameters required to use corresponding diagrams, as described in Section 3.1. The decision to use manufacturers data describes early life system behavior, under healthy conditions, and does not consider energy degradation. It is an acceptable assumption though that during a period of 15 months in the first years of vessel life, component working points have a greater effect in resulting system energy performance than energy degradation, hence the impact of actual operational profile and conditions can be realistically examined.

3 Methodology

3.1 Dataset enrichment

In order to overcome the aforementioned dataset restriction, main diesel engine power was evaluated using the gearbox losses chart, power delivered to the propeller using shaft losses chart and propeller thrust using actual propeller open water diagrams and wake fraction data from towing tank tests. First, propeller shaft power P_{psh} in kW was evaluated using corresponding torque M_{psh} in kNm and speed n_{psh} in rad/s, as follows:

$$P_{psh} = M_{psh} n_{psh} \ . \tag{1}$$

Then, power delivered by the main diesel engines P_e, accounting for gearbox losses $P_{loss,gb}$, in kW is given from:

$$P_e = P_{psh} + P_{loss,gb} \ . \tag{2}$$

Power delivered to the propeller P_Q was evaluated afterwards, accounting for shaft losses $P_{loss,psh}$, in kW from:

$$P_Q = P_{psh} - P_{loss,psh} \ . \tag{3}$$

Propeller thrust T in kN and thrust power P_T in kW are established using the following relations:

$$T = K_T \rho n_{psh}^2 D^4 \ , \tag{4}$$

$$P_T = T v_a \ , \tag{5}$$

where ρ is salt water density equal to 1,025 kg/m^3, D is propeller diameter in m and v_a water speed in the ship's wake in m/s, obtained from vessel speed through water v_{log} in m/s and Taylor's wake factor w as:

$$v_a = v_{log} \left(1 - w\right) \ . \tag{6}$$

Thrust coefficient K_T was evaluated by reading corresponding propeller open water diagram with advance coefficient J and pitch to diameter P/D values. Advance coefficient J was evaluated from:

$$J = \frac{v_a}{n_{psh} D} \ , \tag{7}$$

Another important parameter evaluated is effective thrust power P_{TE} in kW, as seen in Figure 3:

$$P_{TE} = T v_{log} = \frac{T v_a}{(1-w)} = \frac{P_T}{(1-w)} \ , \tag{8}$$

and finally, required propeller thrust T_{req} in constant speed sailing was evaluated as a reference for obtained results, using ship towing resistance R_{tow} and thrust deduction factor t from towing tank tests, as:

$$T_{req} = R = \frac{R_{tow}}{1-t} \ . \tag{9}$$

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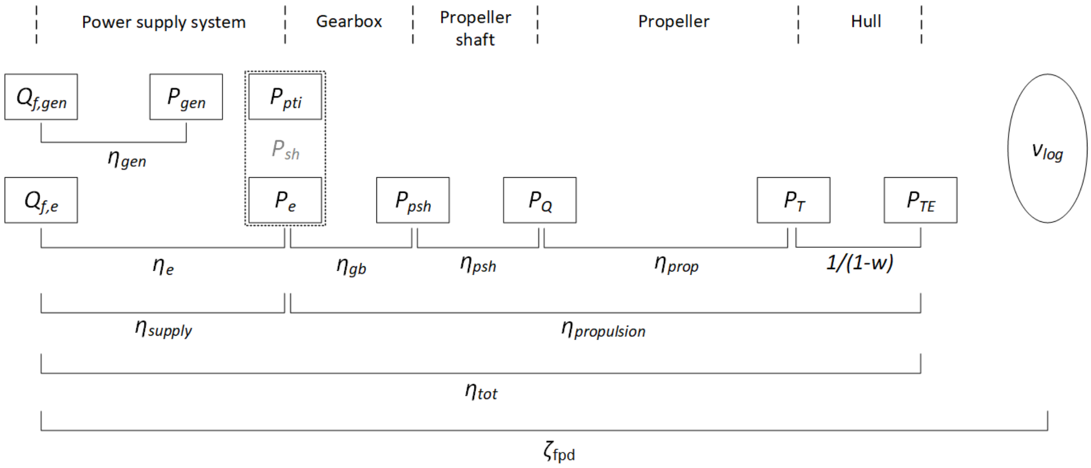

Figure 3: Energy performance indicators and parameters involved.

3.2 Power system energy efficiency

The majority of ships use fossil fuels in order to meet their power supply needs. The three main consumers on each ship in descending order are its main and auxiliary engines, and its boilers. Boilers' contribution is almost neglegible for all vessel types except for oil tankers (IMO, 2014). In conventional maritime power systems, chemical energy saved in fuels is released as heat through combustion. Main engines, most often diesel engines, convert this heat into work and provide it to the propellers either directly or through reduction gearboxes. Then, propellers turn this work into propulsion thrust in order to counter vessel resistance and accelerate the vessel. Auxiliary diesel engines on the other hand convert heat to work, work to electrical power and provide it to the electrical grid of the ship. These power conversions and transmissions introduce a number of component, subsystem and whole system energy efficiencies which in this study are evaluated from measured and derived parameters as described in Section 3.1.

3.2.1 Component-level

Main diesel engine efficiency η_e is defined as:

$$\eta_e = \frac{P_e}{Q_{f,e}} = \frac{P_e}{\dot{m}_{f,e}\, h^L} \,, \tag{10}$$

where $Q_{f,e}$ is heat flow released from fuel combustion in kW, $\dot{m}_{f,e}$ is fuel consumption in kg/s and h^L stands for fuel lower heating value assumed equal to 42,500 kW/kg. Diesel generator set efficiency η_{gen} is defined in a similar way:

$$\eta_{gen} = \frac{P_{gen}}{Q_{f,gen}} = \frac{P_{gen}}{\dot{m}_{f,gen}\, h^L} \,, \tag{11}$$

where P_{gen} is the electrical power provided in kW, $Q_{f,gen}$ corresponds to heat flow in kW and $\dot{m}_{f,gen}$ to fuel consumption in kg/s. Gearbox efficiency η_{gb} is defined as:

$$\eta_{gb} = \frac{P_{gb,o}}{P_{gb,i}} = \frac{P_{psh}}{P_{sh}} \,, \tag{12}$$

where $P_{gb,o}$ and $P_{gb,i}$ are power coming out and entering the gearbox respectively in kW. P_{psh} is power delivered to the propeller shaft in kW and P_{sh} is the power provided by the main diesel engines or the electrical motors to the shaft in kW, as follows:

$$P_{sh} = \begin{cases} P_e & \text{Other modes} \\ P_{pti} & \text{PTI mode} \end{cases} \,. \tag{13}$$

Propeller shaft efficiency η_{psh} is evaluated using power delivered to the propeller shaft P_{psh} and to the propeller P_Q in kW, as:

$$\eta_{psh} = \frac{P_Q}{P_{psh}} \,, \tag{14}$$

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and finally, propeller efficiency η_{prop} is provided by:

$$\eta_{prop} = \frac{P_T}{P_Q} = \frac{T v_a}{P_Q} . \tag{15}$$

3.2.2 System and subsystem-level

Power supply and propulsion subsystems energy efficiency was evaluated using total heat flow Q_f, shaft power P_{sh} for both power supply options defined in Equation 13, and effective thrust power P_{TE} in kW as:

$$\eta_{supply} = \frac{P_{sh}}{Q_f} = \frac{P_{sh}}{\left(\dot{m}_{f,e} + \dot{m}_{f,gen}\right) h^L} , \tag{16}$$

$$\eta_{propulsion} = \frac{P_{TE}}{P_{sh}} . \tag{17}$$

Ultimately, energy efficiency of the whole power system was provided by:

$$\eta_{tot} = \frac{P_{TE}}{Q_f} = \frac{P_{sh}}{Q_f}\frac{P_{TE}}{P_{sh}} = \eta_{supply}\eta_{propulsion} . \tag{18}$$

It must be noted that effective thrust power P_{TE} was selected as the end point of the energy chain defined in Equation 8, instead of effective towing power P_E seen in (Klein Woud and Stapersma, 2002). The main reason is that this analysis examines the dynamic energy performance of the system while sailing under real operational conditions, on the contrary to static considerations at the design phase, which are established through scale model tests. As a result a thrust based power parameter seems more suitable compared to using ship towing R_{tow} or actual resistance R. Moreover, despite IPMS dataset restrictions described in Section 2.3, thrust T parameter is possible to be directly obtained using a sensor, in contrast to vessel resistance R which must be derived accounting for instant actual and hydrodynamic added masses and accelerations, significantly improving accuracy. Especially in the case of using towing resistance R_{tow}, which is a theoretical parameter since the vessel is not towed, information concerning thrust deduction factor t is additionally needed.

3.3 Vessel energy effectiveness

Mission requirement of most vessels is the transportation of a certain payload over an indicated distance. This is achieved as discussed in the previous subsection by consuming fuel resources into their power systems. Overall energy efficiency η_{tot} of those systems provides a good indication on the fraction of resources that turn into useful output, but it does not offer though any information on the amount of resources required by the vessel in the first place. A factor providing resources 'paid' in order to reach a certain transportation level seems more appropriate. Effectiveness, in comparison to efficiency, appears to conceptually describe this difference to an adequate degree, hence is the term selected in this analysis. Literature on mechanical engineering applications, specifically in heat exchange applications, determines effectiveness as the ratio of actual heat transfer rate to the theoritical maximum (Kutscher, 1994; Narayan et al., 2010), but such a consideration in the case of energy conversion and transmission is already described by exergy or also called rational efficiency (Kotas, 1985). (Sui et al., 2019) uses a similar philosophy regarding effectiveness with the one adopted in this paper, but provides a different set of definitions. In this study, overall energy performance is described by vessel energy effectiveness as:

$$\zeta = \frac{m_{f,tot}}{W d} , \tag{19}$$

where $m_{f,tot}$ is the total amount of fuel consumed, d is the covered distance and W a typical transfer weight.

When deadweight and displacement do not show significant variation, as in the case of the same patrol vessel, we can consider covered distance as the main operational benefit. Hence, the weight term W can be ignored and, by further not accounting for current effects, distance covered through water d_{log} can be used. Vessel energy effectiveness is provided then by:

$$\zeta_{\text{fpd}} = \frac{m_{f,tot}}{d_{log}} = \frac{m_{f,e} + m_{f,gen}}{d_{log}} = \frac{\dot{m}_{f,e} + \dot{m}_{f,gen}}{v_{log}} . \tag{20}$$

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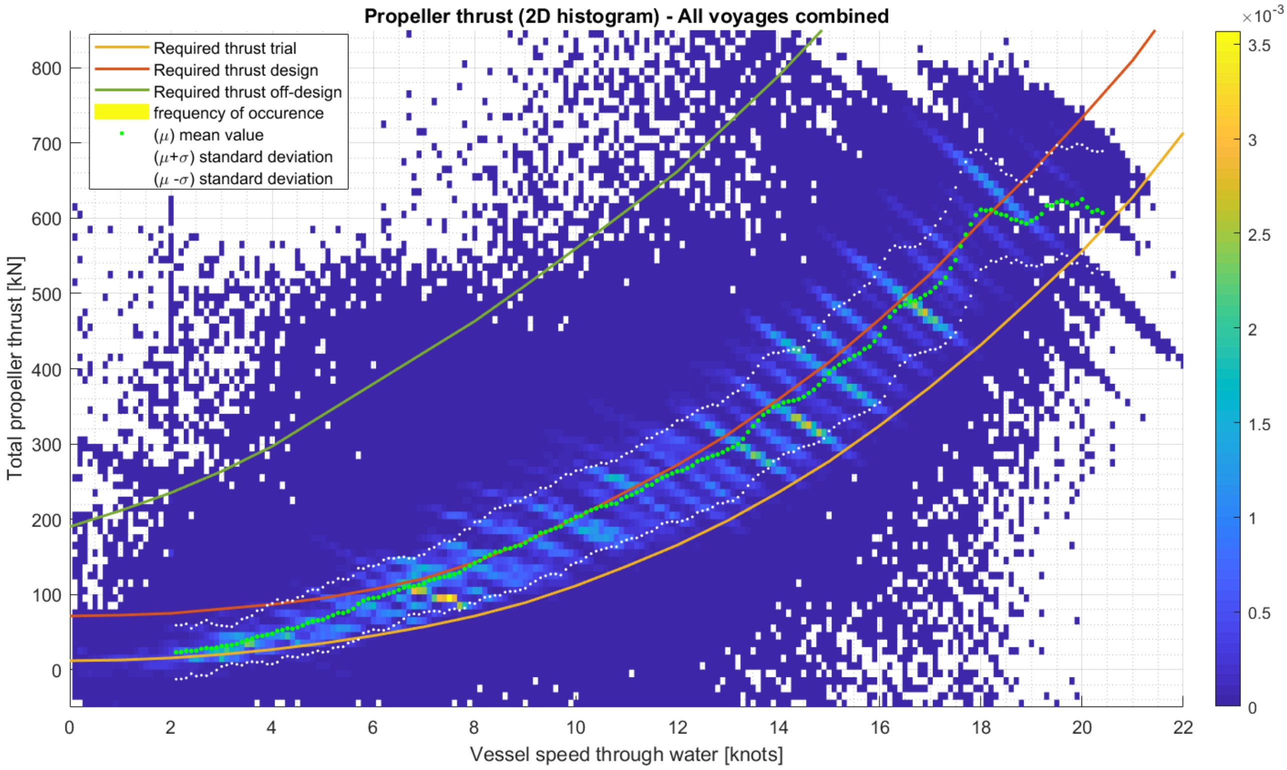

Figure 4: Mean value of provided propeller thrust for all three sailing modes of one main diesel engine operation, including frequency of occurance, mean value and standard deviation of all measurements.

3.3.1 Mean energy effectiveness and standard deviation

Vessels sail in operational conditions that variate a lot, posing different energy requirements. Application of all previously mentioned energy efficiency and effectiveness indicators results in a population of instant values as seen for instance in the case of propeller thrust in Figure 4. Despite the fact that these populations provide the limits of actual vessel operation, they do not offer any information on the achieved energy performance of the vessels. In order to overcome this issue, this paper proposes weighted mean energy effectiveness ζ_{fpd_μ} and corresponding standard deviation $\zeta_{\text{fpd}_\sigma}$ for constant vessel speed v as the main energy performance assessment tool, utilizing operational data, as follows:

$$\zeta_{\text{fpd}_\mu}(v) = \frac{\sum_{i=1}^{n} \zeta_{\text{fpd}_i} N_i}{\sum_{i=1}^{n} N_i} \,, \tag{21}$$

$$\zeta_{\text{fpd}_\sigma}(v) = \sqrt{\frac{\sum_{i=1}^{n} \left(\zeta_{\text{fpd}_i} - \zeta_{\text{fpd}_\mu}\right)^2 N_i}{\sum_{i=1}^{n} N_i \; - 1}} \,, \tag{22}$$

where ζ_{fpm_i} is one of the n different values of energy effectiveness found in the collection of datapoints within the defined vessel speed v range, and N_i the number of measurements for each different value i playing the role of weight. It must be noted that the same formulas were used for all parameters and energy performance indicators too. Finally, the importance of mean energy effectiveness can be seen from its relation to the actual amount of fuel consumed while sailing at a certain speed $M_f(v)$, which is provided by:

$$M_f(v) \;=\; \sum_{i=1}^{n} \dot{m}_{f,i}\, N_i \delta t \;=\; \dot{m}_{f,\mu} \sum_{i=1}^{n} N_i \;\delta t \;=\; \frac{\dot{m}_{f,\mu}}{v}\, v\, N_{tot}\;\delta t \;=\; \zeta_{\text{fpd}_\mu}\; v\, N_{tot}\;\delta t\;. \tag{23}$$

Equation 23 suggests that knowing mean energy effectiveness $\zeta_{\text{fpd}_\mu}(v)$, over the whole vessel speed range, combined with an assumed operational profile $N_{tot}(v)$ can actually provide the total amount of fuel required within a certain time horizon, necessary in life-cycle assessment analyses.

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Table 4: Reference operational conditions.

condition	sea state	wind speed	fouling
trial	0	max 5 knots	no
design	4	max 21 knots (Beaufort scale 5)	6 months out of dock
off-design	6	max 47 knots (Beaufort scale 9)	6 months out of dock

4 Results and discussion

4.1 Required propeller thrust and thrust power

Prediction of required propeller thrust in order to maintain a given vessel speed is one of the main issues ship designers and operators come across. It is influenced by environmental factors like wind and waves, by operational ones like loading condition, propulsion and sail mode, rudder activity, fouling, but also by acceleration and deceleration phases. Figure 4 shows frequency of occurence, mean value and standard deviation of all thrust measurements, against three operational condition curves used at the design phase of the vessel. Those curves, corresponding to trial, design and off-design conditions, were produced by running model tank tests and their description is given in Table 4. We can observe that trial curves, as expected, form a lower limit for all measurements presented. However, this is not the case with the off-design curves, since the vessel hardly ever sails in such bad weather conditions. On the contrary, design condition curves are in good agreement with mean value ones between 7 and 18 knots and are higher in the outer speed regions. Below 7 knots the fact that manoeuvring and low speed patroling takes place near the shore where weather conditions are better provides a convincing explanation. In the case above 18 knots, results appear to suggest that the crew decides to sail at such speed when weather conditions are closer to trial ones. What actually happens is indeed linked to external influencing factors but is linked to those diagonal areas of increased frequency of occurence seen in Figure 4 too.

As demonstrated in Figure 5, these areas refer to constant virtual shaft speed setting, provided by:

$$n_{virt} = \frac{p - p_0}{p_{nom} - p_0} n_{prop} \ , \tag{24}$$

where p is propeller pitch, p_0 is zero thrust pitch, p_{nom} is nominal pitch and n_{prop} is propeller speed. According

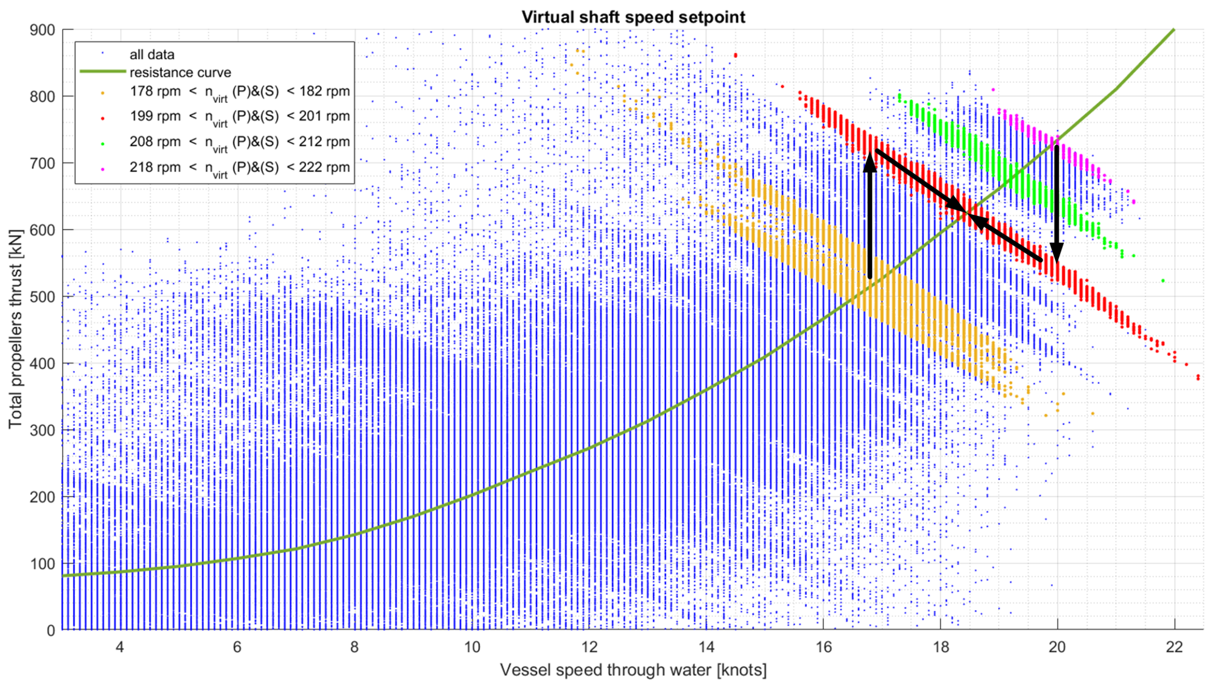

Figure 5: Propeller thrust and vessel speed trough water with highlighted areas of bounded virtual shaft speed. Hypothetical acceleration and deceleration phases are also demonstrated.

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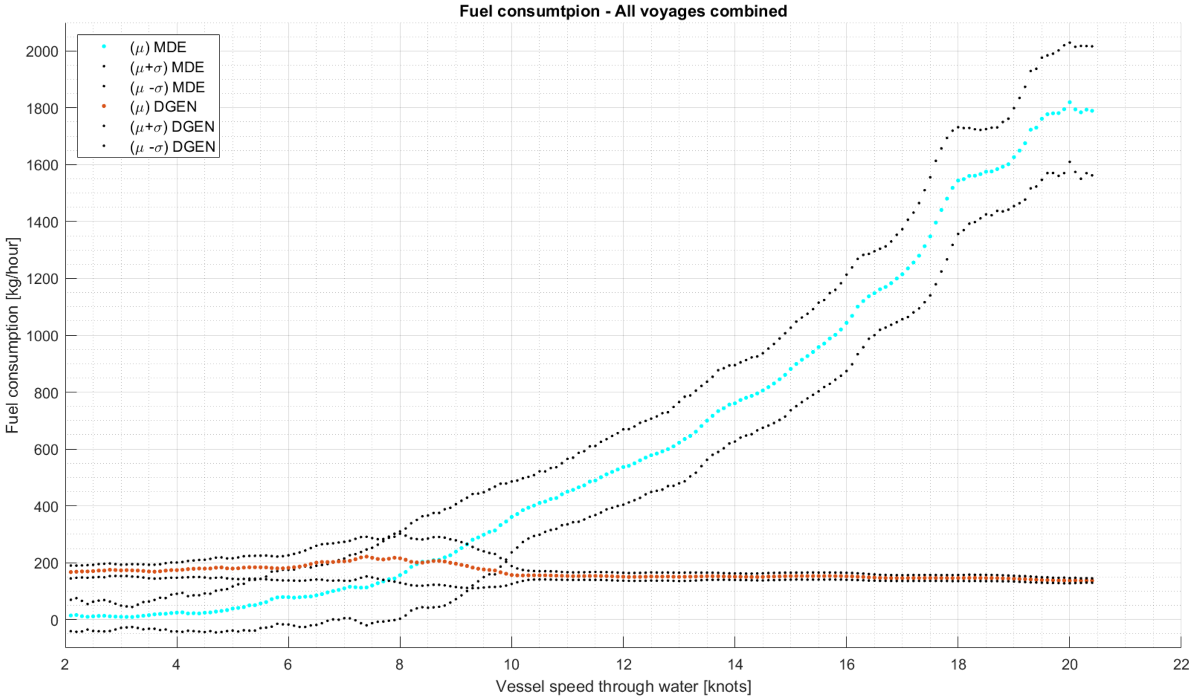

Figure 6: Mean value and standard deviation of total fuel consumption for main diesel engines and generators.

to (Geertsma et al., 2017a), virtual shaft speed is the command provided by the crew to the main power supply and propulsion system. This means that in order to either accelerate or decelerate to a different sailing speed, an increased or decreased virtual shaft speed is set. Due to vessel inertia, thrust moves to another diagonal under almost constant speed and then speed and thrust balance at the crossing point indicated by the resistance curve at the same Figure. Ultimately, all those influencing factors cause thrust and thrust power measurements to have a standard deviation of 40 kN or 100 kW at 5 knots which increases with a linear trend to 100 kN or 900 kW at 18 knots. Those values stand for 60% and 13% of means respectively.

4.2 Power breakdown and energy performance

4.2.1 Fuel consumption and power breakdown

Figure 7 provides a power breakdown of the system for every vessel speed. As expected, both heat flow levels are much higher than the other power levels because of the thermodynamic conversion efficiency, and all curves show a slower increase rate above 18 knots because of the reduced thrust requirement discussed in the previous section. Another interesting point seems to be near 10 knots, since this is the maximum speed achieved running on electrical motors as illustrated in Figure 10. In an effort to understand system performance above and below this point, we can examine Figure 6 that demonstrates fuel consumption for main diesel engines and diesel generators. Our first observation is that at very low speed, generators fuel consumption is much higher than the one of main diesel engines as expected. Moreover, the fact that their fuel consumption stabilizes near 150 kg/hour, irrelevant of vessel speed, above 10 knots when the vessel always runs on main diesel engines, suggests this as the most indicative value of fuel consumption needed to cover auxiliary hotel loads when electrical motors are not active. The same observation seems to be the main reason behind total heat flow showing different behavior to main diesel engine output power below 10 knots, suggesting worse power supply efficiency when the motors are active. Finally, it is interesting to notice the uncertainty level standard deviation values reveal in the range between 4 and 10 knots, with maximum values near 150 kg/hour and 100 kg/hour for main diesel and auxiliary diesel engines respectively, mainly caused by electrical motors operation.

4.2.2 Energy efficiency

Presented power levels determine a number of energy efficiency factors. Figure 8 shows mean value of component level ones for varying vessel speed. As demonstrated, gearbox efficiency stays constant at 92% up to 6 knots, mainly because of the less efficient gearbox functioning in electrical motor mode, and then gradually climbs to a maximum of 98%. Propeller efficiency remains in the range of 59% to 70% above 6 knots after showing poor efficiency at a lower speed, because of pitch reduction seen in Figure 9. Regarding main diesel engine and

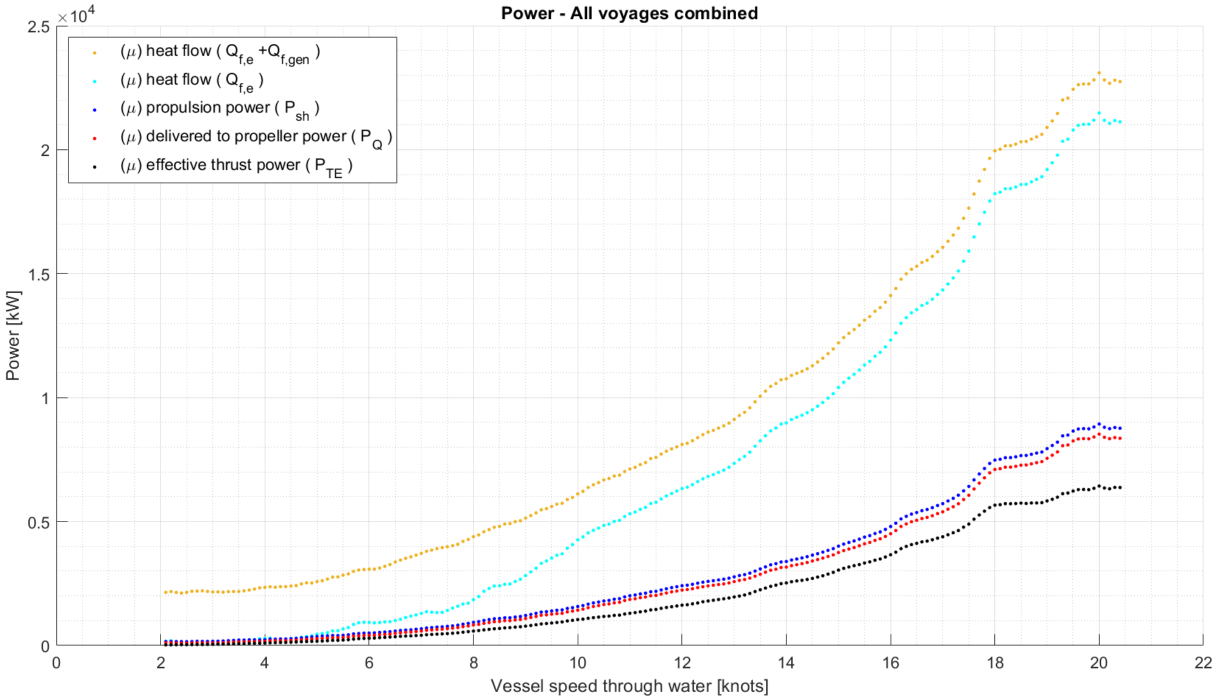

Figure 7: Mean value of different power levels.

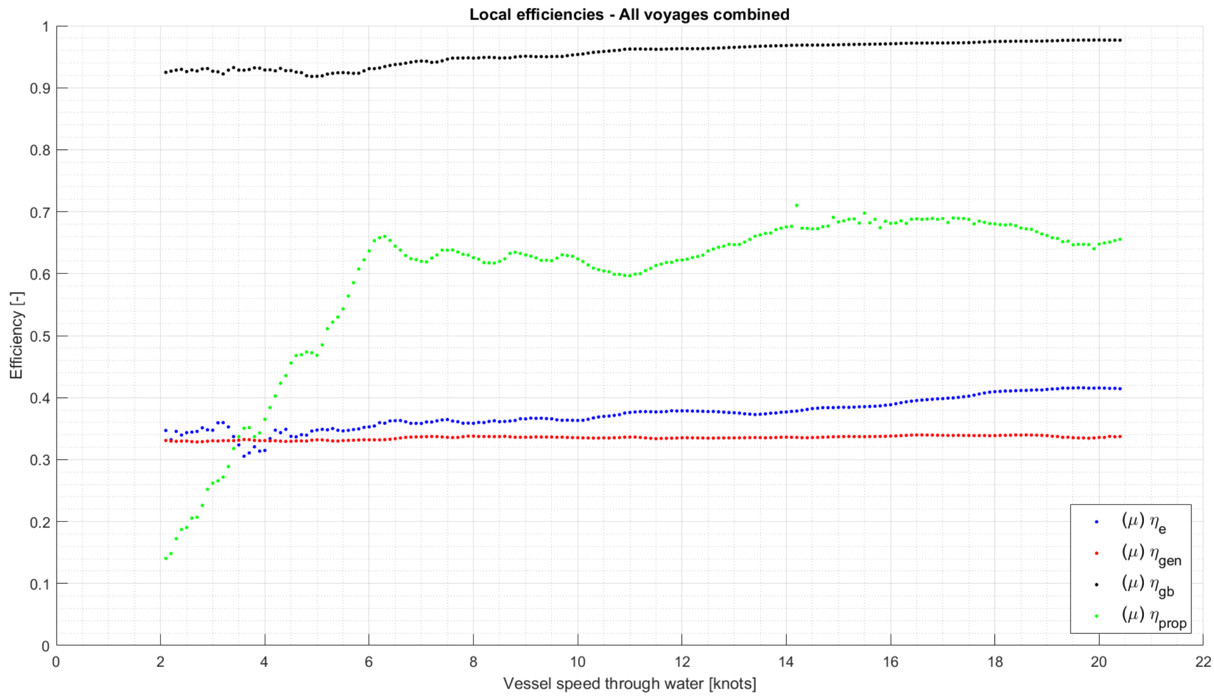

Figure 8: Mean value of component energy efficiency.

generators efficiency, the latter stays almost constant at 33% to 34% and the former increases from 35% at 5 knots to 38% at 20 knots with a linear trend. The unstable behavior below 5 knots is probably caused from the difference among the zero, one and two main engine operation and the time spent on each mode. Further in presenting system local and global energy efficiencies, Figure 11 demonstrates results at a subsystem and whole system level. Propulsion efficiency which is mainly influenced by propeller and gearbox ones, increases rapidly from 10% at 2 knots to 50% at 6 knots and after that slower to 61% at 20 knots with a maximum value of 65% in the range of 15 to 18 knots. Power supply efficiency shows a maximum value of 38% at 20 knots, mainly because of internal combustion engines bounded efficiency, and decreases to 7% at 2 knots. Looking at the way this efficiency drop

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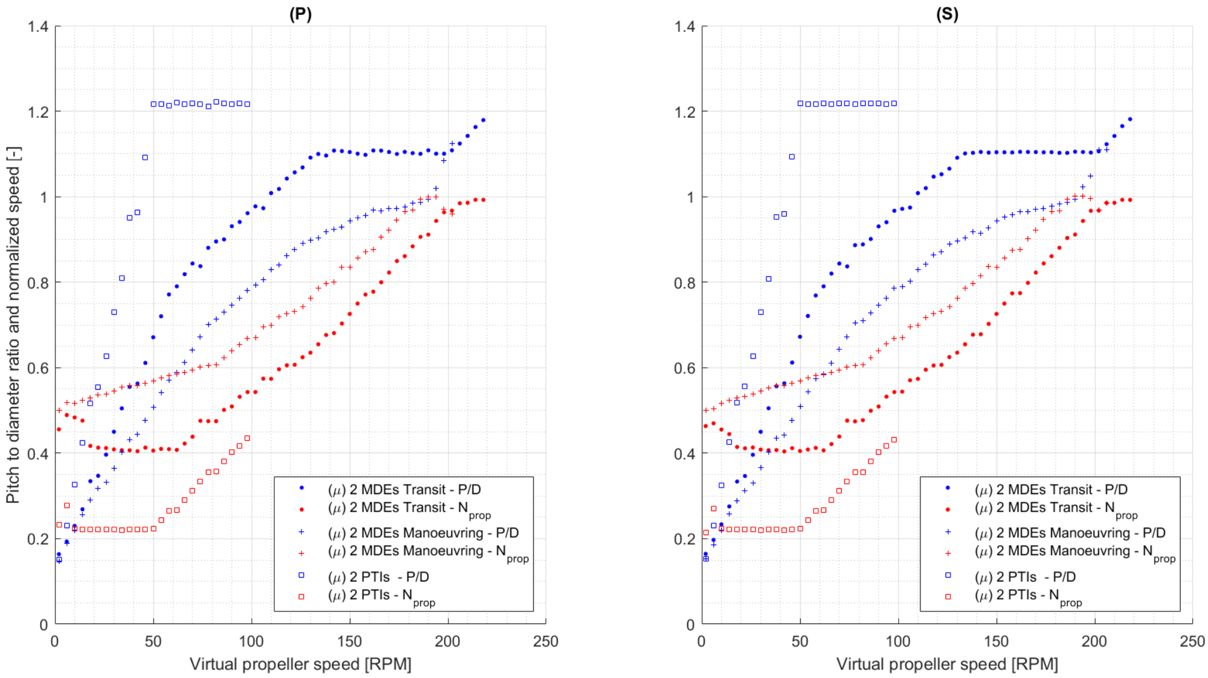

Figure 9: Mean value of propeller pitch to diameter and rotational speed for constant virtual shaft speed, in 2 MDEs manoevring, transit and 2 PTIs mode .

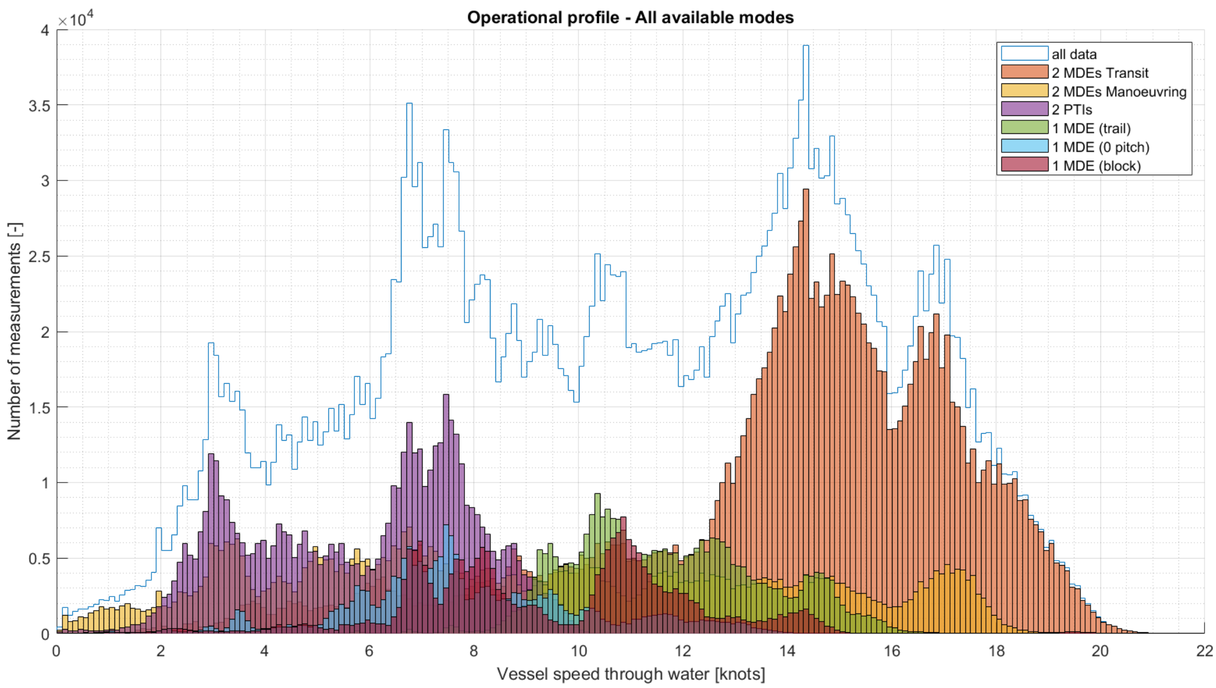

Figure 10: Vessel speed through water profile for all different vessel modes.

happens, an 28% value at 11 knots once more indicates the improved trend observed above that point and the worse one below where more modes are selected. Finally, overall system efficiency expressing the fraction of total heat release power that turns into thrust one, presents an almost linear increasing trend with a value of 9% at 7 knots, 20% at 15 and a constant 24% one above 18.

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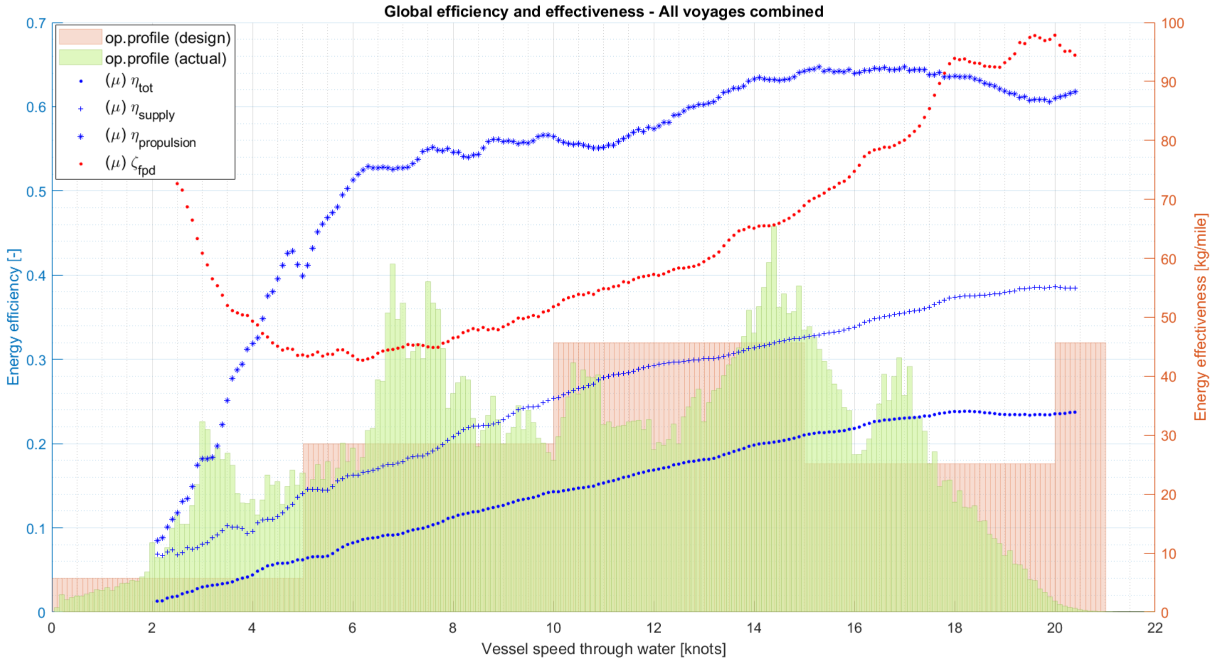

Figure 11: Mean value of power supply, propulsion and overall energy efficiency and of energy effectiveness. The difference of design and actual vessel speed profile is also demonstrated.

4.2.3 Energy effectiveness

This paragraph examines results regarding energy effectiveness which, as discussed in section 3.3, provides the resource cost of sailing at certain speed and operational conditions. Figure 11 demonstrates the mean value of energy effectiveness over the whole operational spectrum, showing a convex function behaviour with a minimum value of 44 kg/mile near 6 knots. This stands for a bit less than half the requirement of 90 kg/mile observed at 18 and 2 knots. Despite the fact that according to Equation 21, mean value can be used to evaluate total consumed amount of fuel, standard deviation values between 15 to 10 kg/mile at 5 and 20 knots respectively seen in Figure 13, standing for 30% and 15% of mean value, clearly show that different operational conditions and different mode selection can greatly affect the energy performance of the vessel. Ultimately, it must be noted that energy effectiveness can easily be turned into an environmental impact factor using a carbon factor as described in (Psaraftis, 2012). For instance at a value of 3.11 tons of carbon dioxide per ton of fuel consumed, we observe that sailing with 6 knots instead of 18 actually saves 137 tons CO_2/mile.

4.3 Hybrid propulsion

Hybrid propulsion for the examined patrol vessel was selected in order to improve energy efficiency at low speed, where slowly running diesel engines show high specific fuel consumption. It must be noted that apart from the energy driver, avoiding running diesel engines at low speed is beneficial from a maintenance perspective too. The results presented in this paper prove that this choice did not meet the energy saving goal set. As expected from the design analysis, propulsion efficiency improved because running on motors did not pose any overloading restriction and higher pitch values were set, as seen in Figure 9. Power supply efficiency on the other hand dropped. Examining overall energy efficiency, we observe that the same effective thrust power P_{TE} level suggests, from Equation 17, that requested power on the shaft P_{sh} is lower in 2 PTIs mode. Since the nominator of Equation 16 decreases, a proportional decrease of the denominator, where we find total fuel consumption $\dot{m}_f$, is needed in order for overall energy efficiency to improve. After splitting generator fuel consumption in one part dedicated to provided electrical power for hotel auxiliary loads $\dot{m}_{f,hotel}$ and one running the motors $\dot{m}_{f,pti}$, total fuel consumption is given from:

$$\begin{aligned} \dot{m}_f &= \dot{m}_{f,e} + \dot{m}_{f,gen} \\ &= \dot{m}_{f,e} + \dot{m}_{f,hotel} + \dot{m}_{f,motor} \,. \end{aligned}$$

When the vessel runs on main engines, $\dot{m}_{f,motor}$ is equal to zero and $\dot{m}_{f,hotel}$ corresponds to a value near 160 kg/hour, as seen in Figure 6. When it runs on motors, $\dot{m}_{f,e}$ is equal to zero and all power on the shaft comes from

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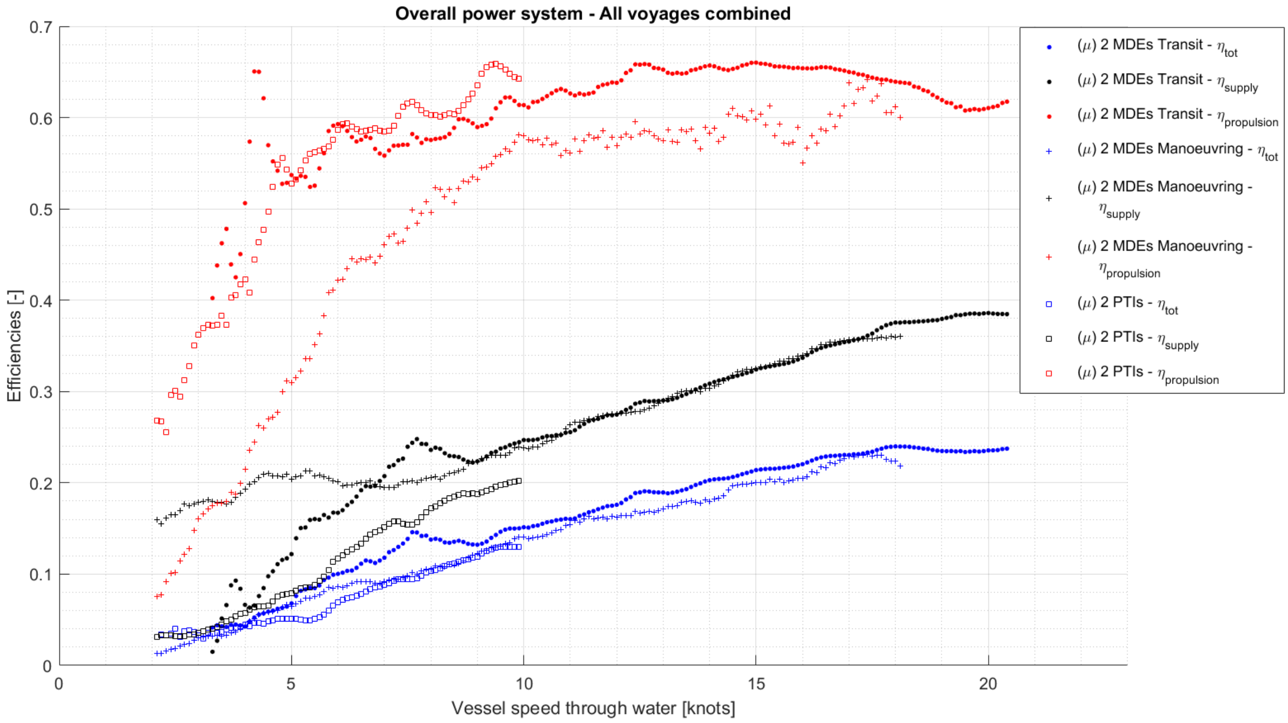

Figure 12: Mean value of power supply and propulsion subsystems, and system overall energy efficiency for the main sailing modes.

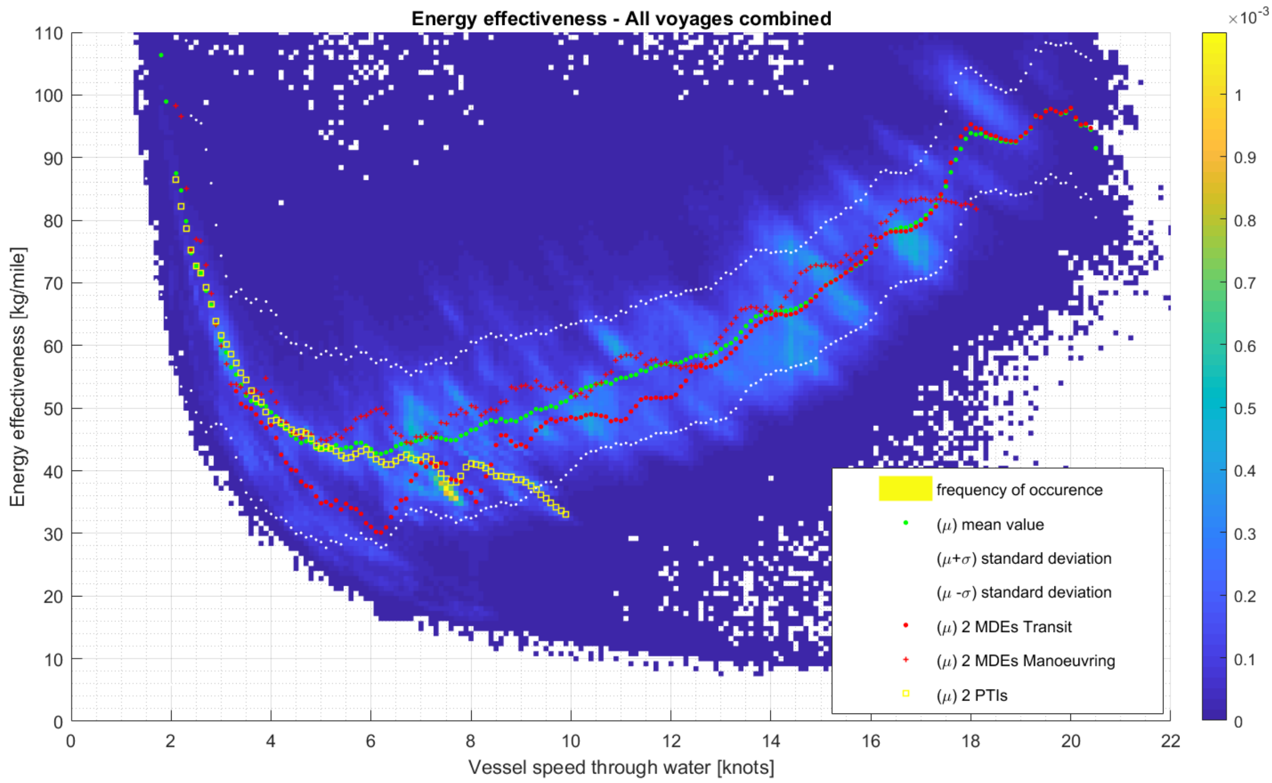

Figure 13: Mean value, standard deviation and frequency of occurence of energy effectiveness, including mean value of main propulsion and sailing modes.

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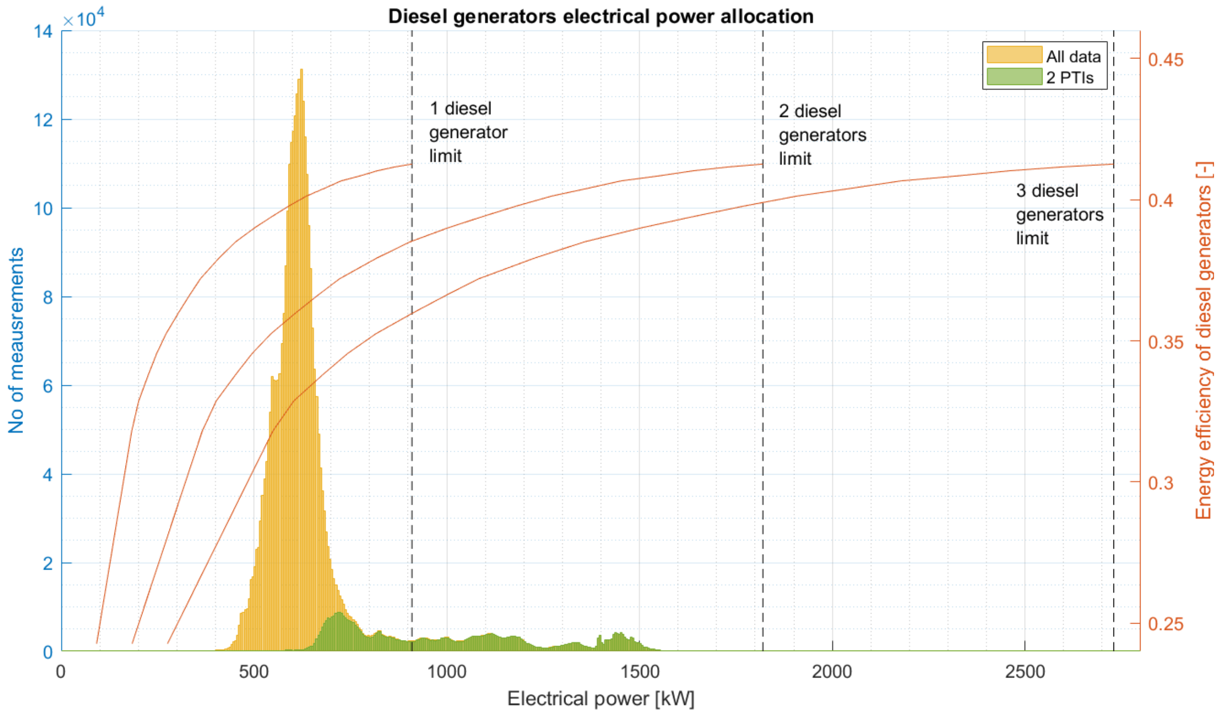

Figure 14: Diesel generators electrical power supply and energy efficiency.

$\dot{m}_{f,motor}$. Then total fuel consumption depends on generators efficiency η_{gen}, and we would expect the efficiency to improve and $\dot{m}_{f,hotel}$ to be lower, since electrical power requirement is higher compared to serving just the auxiliary loads. The situation though is different as seen in Figure 14 and provides us with the first hint on the resulting lower power supply efficiency. Actually it shows that when the motors are not active, one generator is able to provide all required power at a 50% to 75% load corresponding to about 40% efficiency. When the motors are active required electrical power varies from 600 to 1550 kW. We do understand that despite the fact that one generator is capable of providing all required power till 910 kW, at least two generators run in order to cover any sudden increase in demand. This results in generator efficiency between 36 to 41% in two and 33 to 39% in three generators running. Hence, $\dot{m}_{f,hotel}$ is always, but for running on motors at full power, produced at a lower efficiency than in main engine modes, which makes $\dot{m}_{f,motor}$ reduction requirement even more ambitious. Figure 8 shows that main engine efficiency is close to 35-37%. Accounting for a generous electrical motor efficiency equal to 95-97% (Sofras and Prousalidis, 2014) and even when using two generators instead of three, power that makes it to the shaft hardly goes above 40% which would allow similar $\dot{m}_{f,hotel}$ and better $\dot{m}_{f,motor}$ over $\dot{m}_{f,e}$. As a final note we observe that even the best possible generator efficiency at 42% would reduce $\dot{m}_{f,hotel}$ by 2% and $\dot{m}_{f,motor}$ by 3-4% over $\dot{m}_{f,e}$. Having in mind that propulsion efficiency at 2 PTIs mode hardly outperformed 2 MDEs transit mode by 2-3%, causing P_{sh} to drop by 2-3% too, it seems that overall fuel saving gain of hybrid propulsion integration is neglegible. The main cause of this is that propulsion efficiency did not improve significantly and that diesel generators size and power allocation did not appear to be optimal, accounting for the actual operational conditions and profile.

4.4 Operational profile

The operational profile of the vessel was found different to the typical one of a patrol vessel, used at the design phase. The vessel cruised more frequently between 5 knots and 10 knots, and less frequently in the range of 10 to 14 knots as seen in Figure 11. It also spend much more time between 14 to 18 knots than expected and hardly ever cruised above 20 knots. These differences suggest an 15% and 25% overestimation of total covered distance and consumed fuel respectively. Furthermore, Figure 15 shows that apart from these cumulative values, their distribution over different speeds varies from the design assumptions too. Bearing in mind the significant difference vessel speed makes in overall energy performance, and the fact that fuel cost is comparable to initial investment cost (van Straten and de Boer, 2012), we conclude that life-cycle costing considerarions, in the assessment of any alternative solution, require accurate operational profile predictions in the first place.

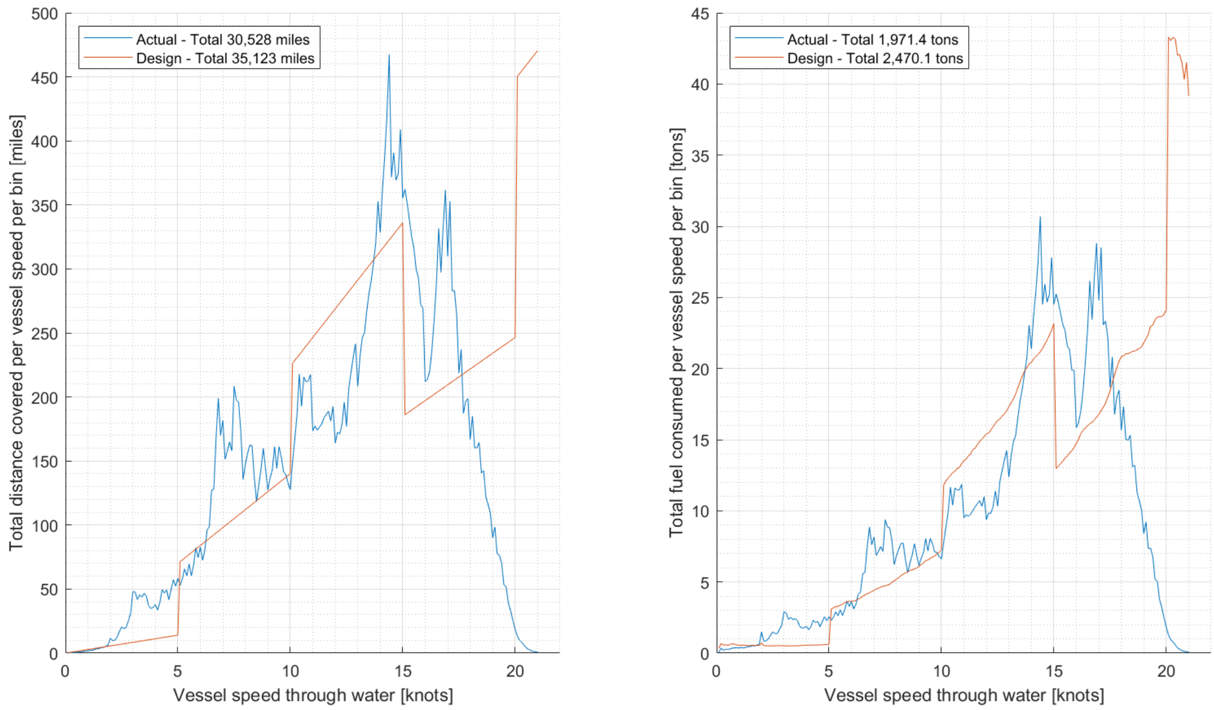

Figure 15: Design fuel consumption and covered distance scenario against actual operational performance.

5 Conclusions and future research

Maritime industry is forced to reduce its greenhouse gas emissions in the near future. Two key goals in order to achieve that are reducing the uncertainty linked with the adoption of new green technologies, and also making use of the full potential of existing technologies. This piece of work demonstrated a way in which operational data analysis and enrichment can contribute to both by examining the case study of a patrol naval vessel. The feedback to designers and operators can be summarised as:

- The use of mean value and standard deviation of measurements coupled with two dimensional histograms, obtained from a high frequency sampled dataset, was proven to be a suitable way to capture underlying trends and the uncertainty of many parameters.
- Mean energy effectiveness for constant vessel speed over the whole range of vessel speed, as introduced in this paper, was proven to provide all information regarding the amount of fuel consumed during the operation of the vessel, which coupled with the operational profile can assist in future life-cycle assessment analyses.
- Required propeller thrust showed significant variation over its design assumption. Mean value might be in good agreement for an important speed range, but not accounting for the time spent at increased or decreased required thrust does not directly lead to an energy performance uncertainty estimation.
- Actual vessel operational profile was found different to the one assumed at the design phase. This means that different options were examined based on overall fuel consumed and covered distance assumptions that did not reflect actual vessel operation. Since fuel cost accounts for a large part of an investment, life cycle assessment considerations seem risky without accurate speed profile predictions.
- In the assessment of new technologies, this paper emphasizes the need to consider overall efficiency from energy stored in fuels to effective thrust power respecting subsystem interaction. Hybrid propulsion for the examined patrol vessel was selected in order to reduce fuel consumption at low speed, substituting slowly running diesel engines. This analysis revealed that its implementation did not meet energy performance expectations because propulsion efficiency improvement was not enough to compensate for the inferior diesel generators and gearboxes efficiency.
- The most energy effective and environmentally friendly option is to sail at the lowest possible speed down to a minimum, though it is important to avoid a lower speed than this as energy effectiveness drops drastically.

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This paper demonstrates the potential of assessing the energy efficiency, effectiveness and environmental impact of a ship's operation using continuous monitoring. It also raises though, a number of aspects to be investigated in the future. The main one is that all those data become available after the vessel has been built and put into service. This does not affect the establishment of a feedback link to the operator, although the suitable type of tools, models and human interface must be examined, but it is an issue in enhansing the design process. Hence, finding the right information and the form in which it can be used together with first principle models can be considered the consequent next step of this study. Moreover, future work should focus on the uncertainty of evaluations by establishing sensor accuracy, modeling accuracy and investigation into system degradation.

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