SHIP PERFORMANCE – USING THE REAL WORLD AS A LABORATORY

Serena Lim, Serkan Turkmen, Ali B Rostami, Federico Prini, Vita R Kurniawati, Alessandro Carchen, Martin Gibson, Simon Benson, Richard Birmingham, **Robert S Dow, Alan J Murphy, Kayvan Pazouki,** Marine, Offshore and Subsea Technology Group, School of Engineering, Newcastle University.

SUMMARY

Ship performance monitoring is increasingly necessary due to continued pressures to reduce environmental impacts and operational costs throughout ship and fleet lifecycles. It also has the potential to enhance the structural design and improve the crew's safety. The current technology is enabling the development of highly robust monitoring platforms to continuously capture many diverse aspects of the ship and fleet activity in the ocean. The near future will see further enhancements of performance monitoring with the widespread advancement of sensor technology, data capture techniques, data filtering and cloud-based storage capacity. This must be coupled to further innovations in big data analysis to interpret and effectively exploit these real-world laboratory experiments. Conventional practice exploits design calculations, small-scale tests and numerical analyses to predict the full-scale ship performance. A body of diverse research activities at Newcastle University challenges this conventional approach by demonstrating the use of the real world as a laboratory. This paper discusses a multi-dimensional ship performance envelope which includes: on-board energy flow distribution; environmental impact and emissions; power and propulsion, structural response and the socio-economic aspects of ship operations.

NOMENCLATURE

CANBus	Controller Area Network
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Index
FGD	Focused Group Discussion
H_{SIG}	Hazard Significance Score
ITTC	International Towing Tank Conference
KPI	Key Performance Indicator
LF	Lift Net Fishing
Li	Likelihood
MARPOL	Marine Pollution
NMEA	National Marine Electronics Association
RANS	Reynolds-Averaged Navier-Stokes
RNLI	Royal National Lifeboat Institution
RV	Research Vessel
SEEMP	Ship Energy Efficiency Management Plan
SDGs	Sustainable Development Goals
SPMS	Ship Performance Monitoring System
SSFV	Small-Scale Fishing Vessel
UN	United Nations
UNEP	United Nation for Environmental Protection
VEP	Vessel Environmental Performance
WH_{SEV}	Hazard Severity Weighting

1. INTRODUCTION

Fluctuations in economic, regulatory, societal and safety standards require continual evaluation and modification of ship performance in many ways. Amongst the most prominent of the contemporary drivers on ship performance are those brought about through rapidly changing regulations. These aim at improving the environmental performance of ships, specifically addressing different emissions to air and water [1, 2] and the lifecycle impacts of the ship. Furthermore, there is a desire to increase the sophistication and performance of vessels to safely operate under increasingly harsh constitutions, for longer periods of time [3, 4], whilst the United Nations Sustainable Development Goals (UN SDGs) underpin the need for naval architects to consider vessel performance in low and middle income contexts [5].

This paper uses five case study projects to demonstate the value of using full-scale measurements to examine ship perfomance. The projects show the added value of full-scale performance tests compared to laboratory tests on a range of ship and small craft fleets. The links between these projects highlight how a multi-dimensional ship performance envelope can be developed. Areas of improvements to ensure a realistic and reliable prediction of full-scale vessel performance by taking into account the environmental conditions are also discussed. The use of data from these projects contribute to new knowledge that can feed into future ship design and operational practices.

In the late 19th century the father of modern naval architecture, William Froude, paved the way for how we normally measure ship performance today. The simplification made by Froude to visualise a ship as a simple plank marked the beginning of a study on frictional resistance of ship hulls using scaled experimental models [6]. Naval architects then carried on to develop ever more complex physical and mathematical models to better estimate the resistance of ships. The results from these models are extrapolated up to full scale and used to verify the measured performance of a real seagoing ship.

It is in this way most measures of ship performance have started, whereby a theory was first developed through observation of a specific performance phenomenon which then led to its representation with physical and mathematical models. These models are used to explore alternatives, understand dependencies and test variables that can be manipulated to cause alternative outcomes. Simulating the real case scenario is often complicated, hence most models are simplified to allow basic theory to explain boundary conditions and governing equations.

However, pertinent information is often lost during the development and use of representative models to measure ship performance. The uncertainties in such approaches are bypassed when a full-scale model is used, allowing nature to put the complexities back in for itself. With the availability of modern technology, experiments and research at full scale are now technically and economically viable.

2. CATEGORIES OF SHIP PERFORMANCE

Research on full-scale performance of ships addresses different aspects of concern and drives improvements across the marine industry. This paper examines the benefit of full-scale performance monitoring in five research areas:

- On-board energy management
- Environment and emissions
- Power and propulsion
- Structural response
- Socio-economic impact

These five topics are distinctly different areas of performance that, when taken together, provide the basis for treating the overall performance of ships as an integrated system. The following subsections address the research questions behind each of the topics in turn.

2.1 ON-BOARD ENERGY MANAGEMENT

The shipping industry is influenced by many factors, which make each ship and voyage a unique case. Hence, the most efficient way to determine a ship's performance is to assess it as an integrated and holistic system in which all components are interrelated rather than to look at the performance of each component separately [7]. Regulations and standards have been introduced to enable the assessment of the performance of vessels at full scale using real-time ship and system data in relation to their environmental impact and hull performance. ISO 19030 was introduced in 2016 to standardise the measurements of ship performance [8]. Continuous improvement of this standard is in progress to refine the best practice and to ensure accuracy and reliability of the measurements [9].

A data monitoring platform is designed to communicate with different on-board sensors, which are often under-utilised. Many existing sensors feed data into different individual monitoring systems, which do not communicate with each other, resulting in data mismatch and difficulty in relating data from different platforms. To overcome this hurdle, the sensor standardisation methodology was introduced, whereby raw data can be collected under a common hub. This proposed method can mine knowledge at multiple granularities to appropriately interpret the information and provide visualisation of the processed data [10]. This methodology is adapted for a wider application of data monitoring such as the calculation of the energy flow throughout the entire vessel.

An on-board energy management system as shown in section 3.1 is the key to improving the energy efficiency of a vessel during operations, which in turn could contribute to lowering the emissions impact. A robust monitoring system that reflects the real time condition of the vessel is vital to quantify and map the energy flow of a vessel during each operation.

2.2 ENVIRONMENT AND EMISSIONS

There are several regulations which investigate the effect of ship performance on the ecosystem and environment, for example, the Energy Efficiency Design Index (EEDI), which was introduced in 2011 and came into force in 2013, aims at encouraging the adoption of more energy efficient technologies on new ships. In addition, some regulations, e.g. SEEMP (Ship Energy Efficiency Management Plan) and EEOI (Energy Efficiency Operational Indicator), provide a mechanism for all in-service ships to reduce the fuel consumption in a cost-effective manner.

There is, however, a gap between when these regulations are adopted and when they legally enter into force, after which ships are bound to comply to. The protracted process through which regulations become legally binding has resulted in the shipping industry turning to 'independent voluntary initiatives' to improve the environmental profile of ships and meet the demands of customers and stakeholders.

Analysis of the initiatives, presented in section 3.2, highlights significant differences regarding their applicability to different ship types and locations, assessment rationales and environmental scopes. The existing initiatives lack the flexibility to be ship specific and many show bias towards certain environmental indicators, while others lack ambition and have a limited environmental scope. A holistic method of assessing the environmental impact and the emissions contributions which can be applied to multiple vessel types is presented.

2.3 POWER AND PROPULSION

The powering efficiency of a marine vessel is typically affected by the growth of 'biofouling'. The term identifies those vegetal and animal species that adhere to any surface immersed into the water. All fouling species contribute to alter the hull and propeller surface roughness, leading to an increase of the viscous-related forces, e.g. viscous resistance of the ship hull and drag force on the propeller blade sections, directly related to the propeller torque. Recent studies [11-13] have estimated increases of shaft powering requirements, to maintain the same speed, of over 20% for slow ships covered with heavy slime. The relative capital loss and the environmental impact are significant. For instance, a fouled large tanker can lead to fuel penalties worth up to $5m per year, consequentially causing higher emissions.

To counteract fouling, coatings exist which attempt to delay or prevent the growth of fouling on ship hulls and propellers. These coatings have, however, a limited functional life. When their effectiveness fades out the vessel needs to be dry-docked and the coating re-applied before powering penalties become excessive. The ship operator becomes responsible for two major decisions: the choice of the anti-fouling coating and the choice of the dry-docking interval. The market currently offers several marine coating solutions (e.g. rosin-based, self-polishing copolymer, foul-release) that the consumer can choose from. The time between two consecutive dry-docks can also be optimised through strategic planning.

Laboratory testing methodologies to assess the effect of fouling on the vessel performance are complex and often fail to encompass all aspects of the vessel hydrodynamics. The first challenge is to replicate, or mimic, the physical and environmental conditions that a surface experiences when exposed to the marine environment for a prolonged time. The second challenge pertains linking the change in surface roughness caused by fouling to the loss of powering efficiency. Full-scale measurements can provide accurate estimates of the powering efficiency loss, but the effect of fouling must be separated from that of other environmental and operational 'disturbances', such as wind, waves, changes of displacement and water properties.

A method to assess the impact of biofouling on ship powering is outlined in section 3.3. The study, presented in more detail in [14], makes use of laboratory-based and full-scale measurements to assess and improve the efficiency of resistance and propulsion. A Ship Performance Monitoring System (SPMS) suitable to assess the effect of fouling on the performance of the vessel at real scale and under real operating conditions was developed [15]. Through monitoring the real-scale vessel performance, the study enables operators to carry out a retrospective assessment of the selected coating and make best decisions on the dry-docking intervals.

2.4 STRUCTURAL RESPONSE

Optimisation of ship structures is only possible with an understanding and the ability to predict the structural response of a vessel to the loads sustained. Because of the complex hydrodynamics and load effects that dominate the loading scenario at high speed and planing regime, the structural design of high-speed craft has traditionally relied on simplified approaches. For practical purposes, semi-empirical methods, such as those implemented as basic standards by many classification societies [16-18], are often used. Although successfully employed, these methods are not suitable for optimising the structure, which requires an enhanced knowledge of the structural response to the actual loads that the craft will experience throughout its life.

Numerical tools are increasingly more popular. The less sophisticated, such as potential flow solver, seem to be the state of the art, but with reservations on their ability to capture the planing hydrodynamics. Advanced methods, such as RANS and Euler equation solvers, are increasingly more popular and have successfully been used for single case studies (e.g. [19, 20]). Yet, in addition to their computational requirements, there is often not enough confidence to base the design solely on their results. Experimental measurements are an alternative to numerical simulations and a way of validating their predictions. Tests at model scale, in towing tanks or wave basins, are now standard practice. Although they provide ease of measurements and control over the waves that are generated, scaling is always problematic and the wave environment lacks the confused nature of a real seaway.

The accuracy of numerical simulations and the understanding of the limitations of small-scale experiments can be further enhanced by comparing results against real-scale sea trial data. The real seakeeping behaviour of a high-speed craft was investigated through dedicated sea trials with a vessel instrumented with sensors to measure motions and structural loads, as described in section 3.4.

2.5 SOCIO-ECONOMIC IMPACT

In order to ensure sustainable shipping, the three pillars of sustainability need to be strengthened: economic, environmental and social. Ship performance is not limited to the technical features. In fact, there are socio-economic aspects that affect the shipping industry. However, most of the discussion in this subject focuses on the economic impacts, such as profit, feasibility and financial risk, and little research has been carried out to evaluate the social impact of shipping activities [21]. Investigation of the socio-economic performance of vessels' operations requires a structured approach. This includes the engagement with stakeholders who are directly involved in the shipping operations to assist in data collection, analysis and verification.

Research was conducted to assess the socio-economic impact of the operation of vessels through their entire lifecycle [22]. The case study focused on small-scale fishing vessels (SSFV) operating in Indonesia. The methodology adopted and the findings on the socio-economic impact of vessel operations are discussed in section 3.5.

3. FULL SCALE PERFORMANCE

This section outlines the methodology adopted to address each of the research questions raised in section 2. The main research findings and results from using the real world as a laboratory are also presented.

3.1 ON-BOARD ENERGY MANAGEMENT

A real-time monitoring system on board a vessel can be used to access the energy flow of the vessel. Changes in the vessel and the on-board systems responses can occur rapidly, under the influence of weather and sea conditions, humidity and temperature. High data sampling frequencies are required to fully capture these changes. The system must contain enough memory to store a certain amount of data before this can be transferred to an on-shore database when an internet connection is available. Due to the high cost of transmitting data via satellite at sea, this data communication must be as concise as possible and robust in the event of transmission failure. The system must also be able to communicate to different types of sensor output to capture the data and map the energy flow throughout the entire ship. Due to the cost restraints of refitting, a common platform to allow all existing sensors to communicate is important. The system must be able to collect data continuously with a certain level of smartness, incorporated within the system, to display immediate (real-time) useful data to the crew.

A monitoring system for energy management was developed and tested on the research vessel (RV) The Princess Royal. The system collects data from all available sensors on board the vessel. Raw data collected is categorised into environmental properties, vessel properties and machinery properties. Table 1 shows the parameters recorded and the data source on the vessel. Vessel environmental properties such as the wind direction and wind speed are measured using an anemometer. Salinity and water temperature are measured using an inductive sensor and a temperature sensor respectively. Water depth throughout the voyage is determined using an echo sounder. Properties that are measured include the speed of the vessel, logged for both speed through water using a Doppler speed log and speed over ground using data gathered from GPS. Examples of machinery properties that are measured include the fuel consumption of the engine and other engine properties. Fuel usage is determined using positive displacement flow metres. Engine properties are gathered using inbuilt sensors of the engines, whilst torque and thrust are measured using a strain gauge system.

This attempt to standardise data monitoring on board vessels was successful and the data collected was carefully specified and validated. For cases where the data was collected through CANBus via a readily built-in system, further validation is needed to ensure the origin of the data. For example, the data collected from smart engines could be providing data that is measured using an inbuilt sensor or via a corresponding value that is determined using manufacturer's tests. A clear understanding of the source of data recorded is important for diagnostics and to avoid data from the same source to be duplicated.

Full scale performance of a vessel quantifies the overall energy flow during an operation. The generic methodology was developed to promote the understanding of energy efficiency on vessels of various sizes and mission profiles [23]. This methodology is adaptable as it reuses data generated from existing sensors and provides a list of selection of sensors that are customised according to the available resources. A systematic approach consisting of five distinct stages is recommended to accomplish a holistic approach for energy efficiency management. This includes the understanding of energy flow breakdown architecture, vessel survey to understand operation and conduct, review of the existing sensors and new sensor installation, sensor communication and data processing, and data analysis [24]. Figure 1 shows an example of a framework of a customised questionnaire that is used during a research vessel survey. This set of questionnaires covers all aspects of functions of the vessel activity during each operation, and also enables mapping of the duration of each energy consumer.

Table 1 Instrumentation and data source on board the RV The Princess Royal (from [10])

Target	Parameter	Data source
Vessel	Speed over ground (Kn)	NMEA0183
	Heading (°)	
	Latitude	
	Longitude	
	Course over ground	
	GPS validity	
	Speed through water (Kn)	
	Electromagnetic speed through water (Kn)	
	Rudder angle (°)	
	Water temperature (°C)	
	Salinity	Weather Station
	Wind speed (m/s)	
	Wind direction 3D (°)	
	Air temperature (°C)	
	Air pressure (Pa)	
Engine(s)	Fuel supply (Ltr)	enginei flow meters
	Fuel supply instantaneous flow rate (Ltr/sec)	
	Fuel return (Ltr)	
	Fuel return instantaneous flow rate (Ltr/sec)	
	Coolant level (%)	Engine CANBus
	Coolant pressure (bar)	
	Coolant temperature (°C)	
	Crankcase pressure (bar)	

	Engine speed (RPM)	
	Engine torque (%)	
	Fuel delivery pressure (bar)	
	Fuel economy (Ltr/hr)	
	Oil level (%)	
	Oil pressure (bar)	
Shaft	Torque (Nm)	Design unit's proprietary protocol
	Thrust (N)	
	Speed (RPM)	

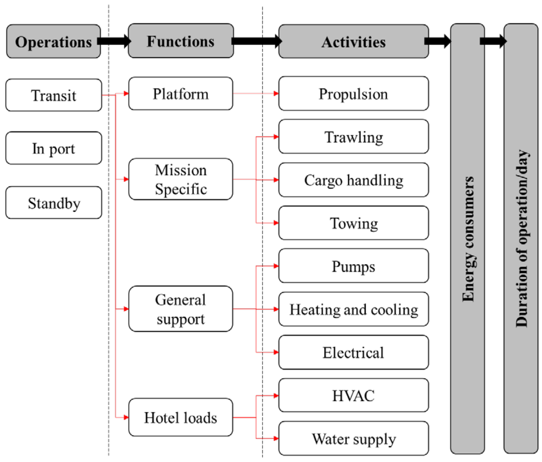

Figure 1 Customised questionnaire for survey (from [24])

Following the generic procedure of energy mapping methodology, independent Sankey diagrams that show the proportion of energy used on board the vessel during each operation and speed can be generated. Figure 2 shows the distribution of energy through the RV The Princess Royal in transit mode of 13 knots. Knowledge of detailed energy flow architecture and the relative proportions of energy consumed during the different operations and within each system or component will give a better understanding for decision making on improving energy efficiency and subsequently reducing the overall fuel consumption. This methodology is being tested out on tugs, specialised vessels such as offshore supply vessels and a passenger ferry. The information obtained through this methodology allows to gain useful knowledge that can contribute to future designs and operations of vessels. This approach has also been successfully applied to analyse the full-scale energy performance of tugs [25].

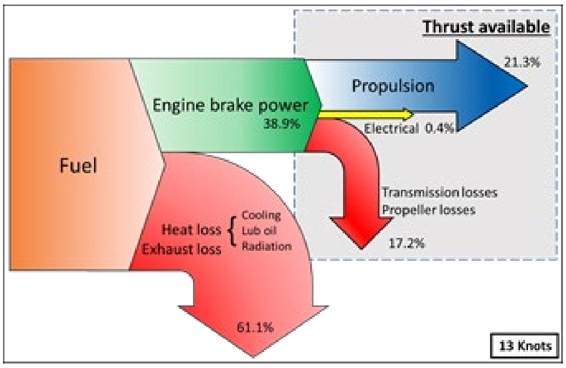

Figure 2 Energy flow Sankey diagram (from [23])

3.2 ENVIRONMENT AND EMISSIONS

Analysis of existing initiatives discloses remarkable differences regarding the variation in applicability due to the scope, ambition, and motivation of the methodologies used to assess the environmental performance of vessels. To fill these gaps, a method is proposed by which impacts of multiple vessel types can be assessed. Full-scale monitoring was employed to develop a holistic indexing method which assesses ship performance based on actual vessel's emissions and discharges. The method comprises two main parts, as shown in Figure 3. Part A (steps 1 to 6) consists of a procedure to calculate a weighting factor (%) for each ship-related pollutant based on its impact on the environment. Part B (steps 7 to 11) involves the collection of vessel and voyage specific data to quantify the actual emissions and discharges of pollutants into the environment.

The vessel-specific data is required to calculate the Vessel Environmental Performance (VEP) indicator for each hazard, which is multiplied by the likelihood of occurrence to give a score of hazard significance. This allows environmental hazards (i.e. pollutants) to be assessed based on the effect of the pollutant on the environment and the amount discharged or emitted from a specific vessel. Hazard significance scores are combined to give a total Ship Environmental Index score for the vessel. The method was tested on RV The Princess Royal during 4 separate voyages (V1 – V4). Table 2 reports the calculated Vessel Environmental Performance (VEP) in terms of normalised values on a scale from 0 to 5.

Table 2 Normalised VEP indicator scores for each hazard for the RV The Princess Royal

Hazard	**VEP indicator scores**				
	V1	**V2**	**V3**	**V4**	**Total**
CO_2	5.000	3.300	1.875	1.938	2.555
Methane	0.006	0.004	0.002	0.002	0.003
N_2O	5.000	3.300	1.875	1.938	2.555
SO_X	0.943	0.623	0.354	0.366	0.482
NO_X	3.146	2.076	1.180	1.219	1.608
PM	0.666	0.440	0.250	0.258	0.340
Refrigerant	0.006	0.006	0.006	0.006	0.006
VOC's	3.782	2.496	1.418	1.466	1.933
Antifoul coating	2.000	2.000	2.000	2.000	2.000
Sewage & grey water	0.018	0.012	0.032	0.036	0.027
Garbage	0.000	1.071	0.383	0.412	0.502

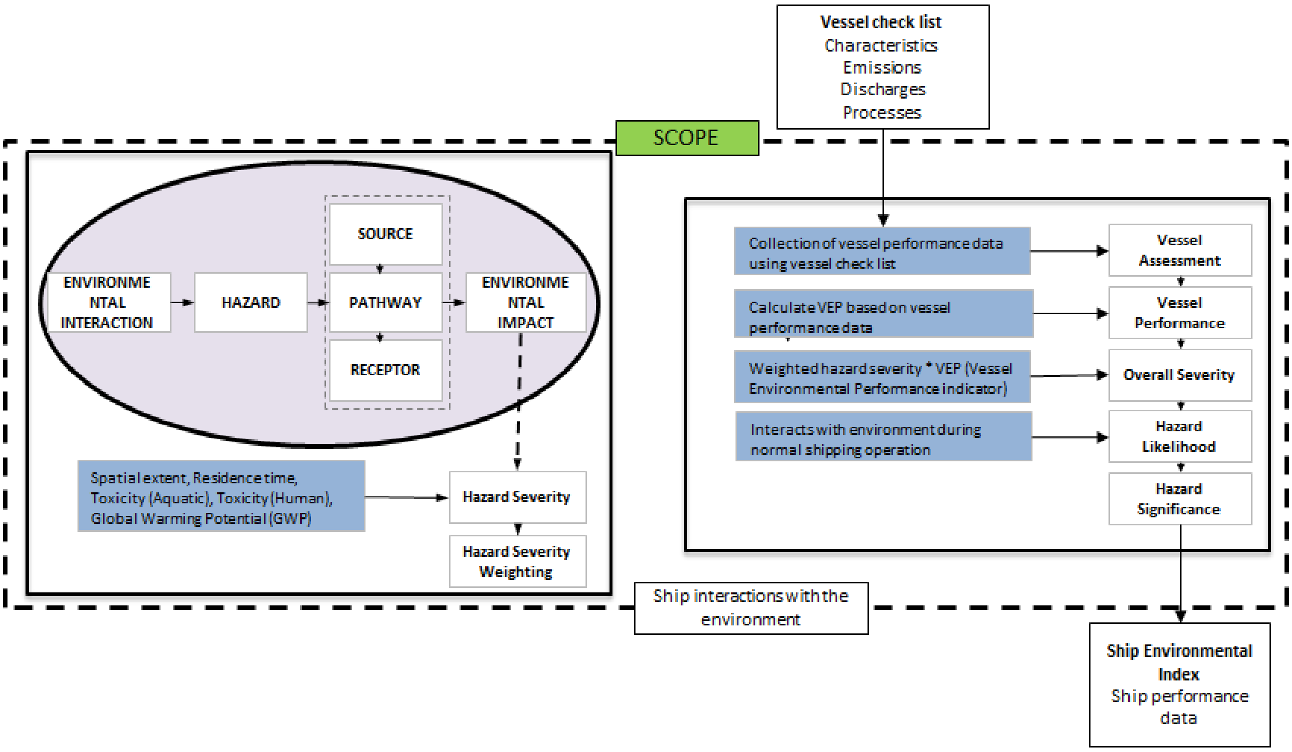

Figure 3 Holistic environmental assessment framework (from [26])

The likelihood (Li) of each hazard was determined in terms of a likelihood score. Based on whether the pollutant interacts with the environment during routine operation, a likelihood score of either 1 (no interaction) or 2 (interaction) was assigned to each hazard. All the hazards considered had a likelihood of 2 except for refrigerant. Weighting of these hazards, which are used to calculate an overall severity score for the ship, is given in Table 3.

To calculate the ship environmental performance, the significant score of each hazard (H_{SIG}) is calculated from the following equation:

$$H_{SIG} = WH_{SEV} * VEP * Li \qquad (1)$$

Hazard significance scores are added together to give a total score for the vessel. The total ship score (%) is calculated by dividing the total score by the maximum possible score. The maximum possible score is calculated assuming that the VEP score for each pollutant is set at the maximum permissible level (i.e. VEP = 5 for each hazard). The scores for each voyage are outlined in Table 4.

Table 3 Hazard severity weighting WH_{SEV} for the RV The Princess Royal

Interaction	**Hazard**	**Hazard Weighting**
Air	CO_2	9.04%
	Methane	7.23%
	N_2O	10.24%
	SO_X	7.23%
	NO_X	7.83%
	PM	5.42%
	Refrigerant (R600a)	5.42%
	VOC's	6.02%
Water	Oily water (bilge)	7.23%
	Antifoul coating	6.02%
	Ballast water	6.02%
	Sewage & grey water	6.02%
Noise	Underwater noise	3.61%
	On-board/port noise	3.61%
Land	Garbage	5.42%
Physical	Collisions with marine mammals	3.61%
Total		**100%**

In this method, a score of 0% represents zero emissions and/or discharges of pollutants to the environment and is therefore the maximum score that can be achieved. 100% represents a ‘dirty’ ship, which pollutes according to the maximum permissible limits for each hazard.

Table 4 Environmental performance scores for the RV The Princess Royal

Voyage	**Score (%)**
1	41
2	30
3	18

Figure 4 Test panels in clean and fouled conditions

4	19

3.3 POWER AND PROPULSION

Building on an experimental campaign based on experiments at small scale, full-scale tests were carried out to investigate the effect of fouling on the resistance of ships. The experiments at small scale used flat rectangular panels of 0.6 x 0.2m. A marine coating was applied to the panels and fouling was induced with two methods. Some panels were deployed into the water through a strut built on RV The Princess Royal (Figure 4). Other panels were installed in a slime 'farm' where fouling was artificially grown on the coated surfaces. The hydrodynamic performance of the fouling control coating, both in clean or fouled condition, was evaluated in a cavitation tunnel through measurements of the boundary layer and in a Flowcell through measurements of the pressure drop due to fouling. Figure 5 shows the effect of fouling on the skin friction coefficient of the coated plates. Comparison of the boundary layer of the panels retrieved from the strut and from the slime farm confirmed that the fouling species that grow in real conditions are different from those grown in an artificial environment. Fouling dynamically grown at full scale cannot therefore be accurately reproduced in artificial tanks [13, 14].

A full-scale SPMS was then used to assess the impact of biofouling on ship powering. Here the major challenge is isolating the effect of biofouling from disturbances caused by other environmental and operational factors. A SPMS based on a deterministic approach was specifically developed for the study and installed on RV The Princess Royal. The effect on powering of waves, wind, changes in displacement and in water properties were reversely calculated from appropriate on-board sensors and 'subtracted' from the measurements of shaft power. This process is commonly termed 'normalization' and is based on the superposition principle. In this work, the normalization closely followed the original Taniguchi-Tamura's method [27, 28]. The added resistances caused by the aforementioned disturbances were thus subtracted from the total measured resistance, taking into account the changes in propeller efficiency and loading condition. Added wave resistance was calculated with the support of numerical calculations and towing tank experiments, whilst direct wind resistance was evaluated from wind tunnel measurements. These are referred to as benchmarking calculations. Then, the difference between normalized speed-power curves taken with a clean hull (e.g. just after a dry-docking) and at some point later in time could be attributable to biofouling only. At last, carefully chosen Key Performance Indicators (KPIs) provided additional information regarding the hull and the propeller fouling state.

To undertake this analysis, the measurements in Table 1 were complemented by wave data from a bow-mounted wave radar and visual draught measurements. Wave spectra measurements were also hind-cast from a wave buoy nearby the vessel operation area.

The measurement system was configured as in Figure 6. An uncertainty analysis was carried out on the performance monitoring, leading to an estimation of errors in power measurements within 5% at the design speed range [15]. A simplified data flow of the SPMS developed for the task is shown in Figure 7.

To speed up the data acquisition process dedicated sea trials were conducted. Figure 8 shows power measurements over time for the same fouling state of hull and propellers. The graph demonstrates the consistency of the developed SPMS. Performance monitoring is still ongoing and additional data is currently being acquired.

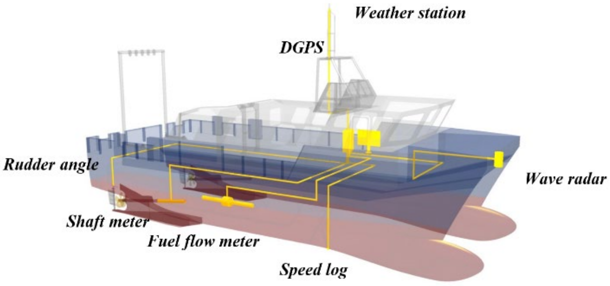

Figure 6 RV The Princess Royal SPMS

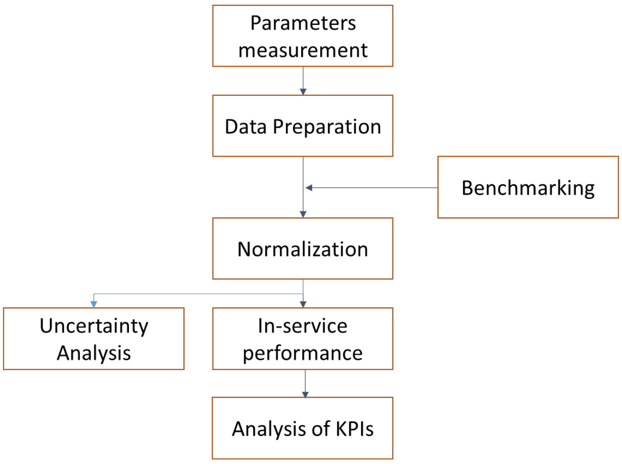

Figure 7 SPMS data flow

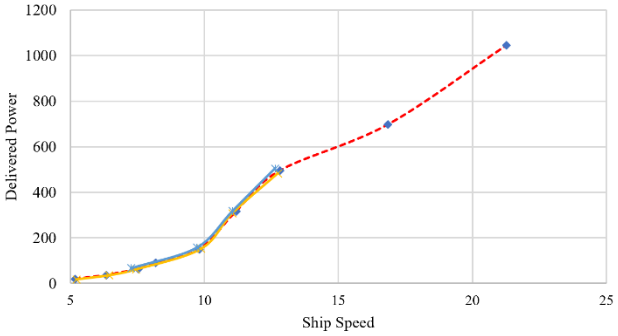

Figure 8 Speed-Power curve of the R/V with similar fouling conditions

3.4 STRUCTURAL RESPONSE

Typical applications of systems for monitoring the structural response are either short term, such as dedicated sea trials, or long term, involving continued monitoring for extended periods of time, from a single voyage up to the entire operational life of the vessel.

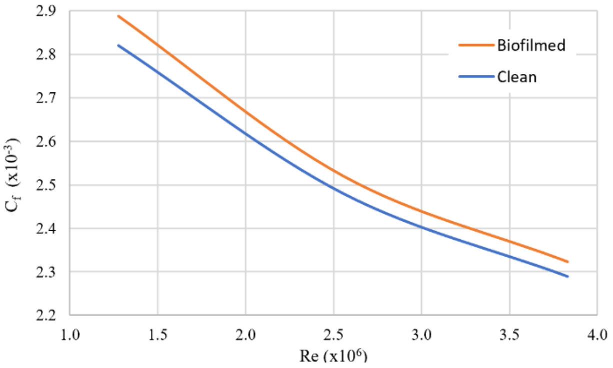

Figure 5 Dynamically fouled coating from the strut arrangement of the RV The Princess Royal

Although systems for short-term measurements are mature enough to find successful application, sea trials are not carried out on a regular basis. They are expensive, time consuming and, if carried out for design purposes, they require a prototype vessel to be built first. Long-term and through-life monitoring systems [29] also find some practical application. Some of the desired capabilities, such as damage detection and prognosis of the state of the structure following damage, are currently areas of active research and so far have been developed at a basic science level.

Extensive sea trials monitoring structural loads were undertaken on a 17m search and rescue craft, as part of collaborative research with the Royal National Lifeboat Institution (RNLI) and Lloyd's Register. The trials were part of a major plan that combines numerical methods and experiments to enhance the structural design and operation of the RNLI's lifeboats and of small high-speed vessels [5]. The study focused on the Severn class lifeboat, for which the RNLI had undertaken a programme to extend its operational life. Hydrodynamic simulations were performed to predict motions and global wave loads on the vessel. Towing tank tests with a solid and a segmented scaled model of the Severn were used to validate the motions and global wave loads predicted numerically. To complete the study, sea trials on an instrumented Severn were conducted to:

1. Validate numerical predictions and model tests against measurements taken at full scale and in a real environment.
2. Account for slamming-induced loads that are difficult to predict numerically and measure at small scale.

An overview of the trials is given in this section, whilst more details can be found in [5, 30]. The tests took place in the North Sea and consisted of 11 trials conducted at speeds ranging from 5 to 25 knots and in different sea states with a significant wave height from 0.3 to 4.6 metres. During each trial, data was collected continuously from: 1 triaxial accelerometer, 1 triaxial rate gyro, 2 thermocouples and 58 linear strain gauges (example in Figure 9). The sensor layout had been devised to measure accelerations and angular velocities at the centre of gravity of the vessel; hull girder bending moments to due wave loads and vertical bending moment induced by slamming (also 'whipping'); local panel deflection due to wave pressure and slamming on the hull bottom and at the bow; and local panel deflection due to green water on the fore deck. All the 66 channels were fed into one acquisition unit and sampled, according the nature of the measured quantity, at either 256 or 2048 Hz. A measure of the sea state was also necessary to correlate the vessel motions and its structural behaviour to the wave environment. For this, a wave buoy deployed central to the trial area was used, whilst additional wave data was obtained from other two wave buoys moored near the trial area.

The trajectory followed during the trial (example in Figure 10) involved runs at different headings to account for the effect of the seaway on the vessel responses and the duration of each run was set so as to collect adequate data samples for the analysis. In total, the task produced over 30 hours of data recording.

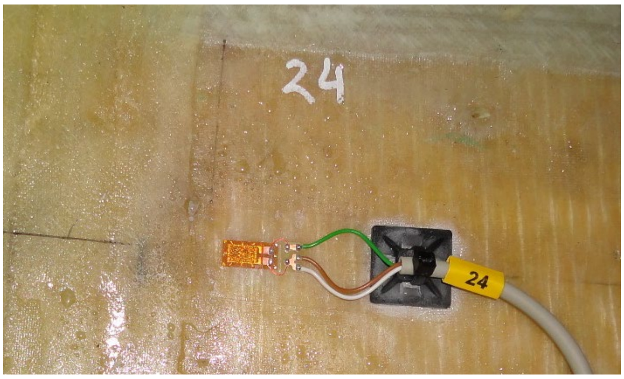

Figure 9 Strain gauge bonded to the hull bottom

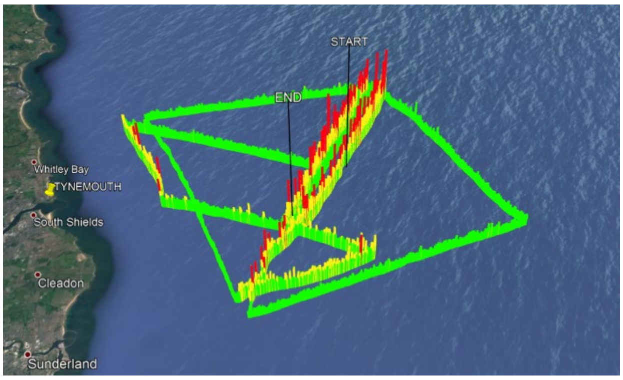

Figure 10 Example of trial trajectory with vertical accelerations superimposed (from [30])

The sea trials, in combination with the other experiments and simulations, allowed the direct calculation of the seakeeping loads sustained by the vessel under specific operating conditions. It was then possible to reconstruct loading envelopes and asses the structural response of the vessel through finite element analysis.

3.5 SOCIO-ECONOMIC IMPACT

An assessment of the socio-economic impact of vessel operations was carried out on small-scale fishing vessels (SSFV). The choice of the vessel type was based on several reasons. The features of a SSFV allow the study to be conducted using site specific data. The operation of a SSFV involves diverse stakeholders and influences both the fishing and non-fishing community. Socio-economic aspects of the operation of SSFV are also important as they affect the fishery policy and management.

The study was conducted in Palabuhanratu, one of the main capture fishery sites in Indonesia. Amongst the various fishing vessels operating in the region, lift net fishing (LF) was chosen as case study due its popularity. A typical LF consists of a vessel and ten fishing gears spread out at sea. A gear consists of a 9 x 9 m floating bamboo platform attached with fishing nets and lamps. The vessel therefore has the function to shuttle the fishers from the port and relocate the platforms when required.

Table 5 Weighting factor and gap analysis

Stakeholders	Impact categories	Code	Subcategories	Weight	Gap
Workers	Human rights	A1	Child labour	0.056	3.50
		A2	Forced Labour	0.056	1.42
		A3	Equal opportunities	0.056	1.00
	Working conditions	B1	Freedom of association	0.056	0.42
		B2	Fair salary	0.056	3.75
		B3	Working hours	0.056	0.25
	Health and safety	C1	Health and safety	0.083	2.25
		C2	Social benefit/social security	0.083	1.25
Local community	Cultural heritage	D1	Delocalisation and migration	0.028	0.00
		D2	Community engagement	0.028	0.25
		D3	Cultural heritage	0.028	0.00
		D4	Respect of indigenous rights	0.028	0.25
		D5	Access to immaterial resources	0.028	0.75
		D6	Access to material resources	0.028	0.75
	Socio-economic repercussions	E1	Safe and healthy living conditions	0.028	2.50
		E2	Secure living conditions	0.028	0.75
		E3	Local employment	0.028	0.00
Society		E4	Prevention and mitigation of conflict	0.028	0.89
		E5	Contribution to economic development	0.028	0.00
Value chain actors		E6	Suppliers relationship	0.028	0.50
Society	Governance	F1	Public commitment to sustainability issues	0.042	1.00
		F2	Development of technology	0.042	0.44
		F3	Free from corruption	0.042	0.67
Value chain actors		F4	Fair competition	0.042	1.50

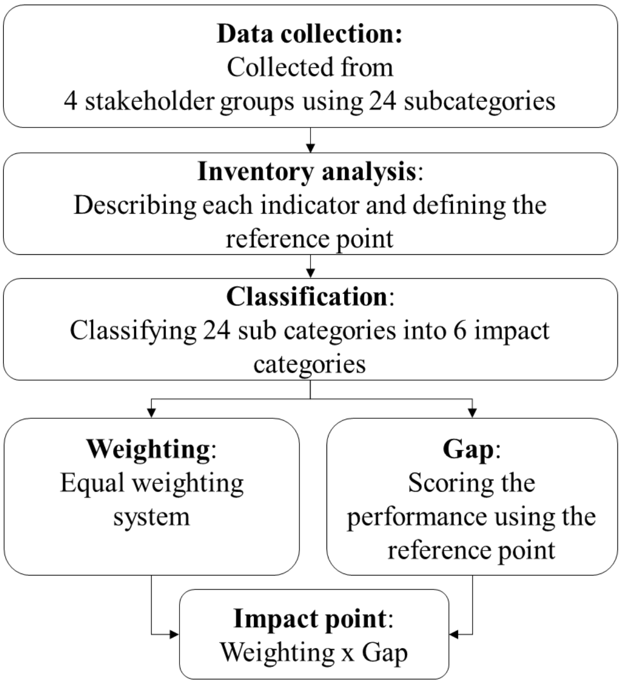

Figure 11 Framework for socio-economic impact assessment

Data was collected through two fieldworks conducted in 2015 and 2016. The following paragraphs describe the data analysis and the results of the study.

The socio-economic impacts were assessed in the lifecycle perspective using the guidelines developed by the United Nations for Environmental Protection (UNEP) [31]. In this study, the impacts of SSFV operations were characterized through 24 subcategories, each of which relates to different groups of stakeholders, including workers, value chain actors, local community and society. Therefore, information regarding the impact indicators for each subcategory was collected through interviews with 60 respondents and through focus group discussions (FGD) with 32 participants representing diverse stakeholders' groups. For assessment purposes, indicators were subsequently classified into six impact categories, specifically: human right, working condition, health and safety, cultural heritage, socio-economic repercussion and governance. Since the data was mostly qualitative, a quantification method from Manik et.al [32] was adopted to produce impact scores. Figure 11 shows the assessment framework applied in the study.

For practical reasons, the weighting factors were defined using an equal weighting system by assuming that all indicators were equally important. Furthermore, gaps resulted from the performance scores, which are measured using the reference point such as regulation or national standards. The weighting factors and gaps for each subcategory are presented in Table 5.

The impact point value refers to the gap between the current status and the regulations, or standards, in force for each subcategory, hence a high value indicates that further improvement is required. The total impact is presented in Figure 12. It can be seen that the major socio-economic issues in LF operations concentrate in human rights, working condition and health and safety; and that the most affected stakeholder are the workers. A typical worker group in LF consists of one skipper, one deck crew member and 10 – 20 fishers. When the survey was conducted, about 20 LF vessels were actively operated and the number of LF workers was 188.

The high impact points in human rights are mainly caused by the presence of few fishers under 18 years old. Even though they are only a small number (3-5 persons) and work voluntarily, it is against the employment law, hence the high impact points. With regard to the working condition, salary is the critical factor since the annual income received by a fisher is lower than the regional minimum wage (£979 compared to £1406). Nevertheless, the skipper has a chance to receive a higher income, up to £1566. Furthermore, safety equipment is not provided neither on the vessel nor on the platform. The fact that most of the platforms are located close to each other and in proximity to the shore might drive the preference to leave the safety equipment behind.

Lift net fishing is conducted by local people, as most stakeholders are local residents. It was introduced by Bugis people in 1960s and since then it became one of the major fishing practices in the region. As part of local economic support, no significant issue is found related to cultural heritage and socio-economic repercussion except the fact that most fishers are currently living in poverty, which is directly associated with poor living condition.

This study produces the baseline to improve the socio-economic performance of lifting net fishing with focus on the high point impact categories. Since an equal weighting system is applied, there are further opportunities to improve the assessment method by considering different weighting systems.

The study shows that vessel operations with the support and acceptance of the local community perform better in terms of socio-economic sustainability. However, employment regulation aspects can be overlooked because the current practice of vessel operations is based on local wisdom and social traditions.

4. KEY FINDINGS AND FUTURE DIRECTIONS

4.1 ON-BOARD ENERGY MANAGEMENT

The generic methodology of real-time data monitoring on board vessels is to promote the understanding of energy efficiency on vessels of various sizes and mission profiles. Acquiring reliable and validated data is the first step towards optimisation of systems, fault detection and forecasting vessel performance. Knowledge of the detailed energy flow architecture and the relative proportions of energy consumed during the different operations and within each system or component will give a better understanding for decision making on improving energy efficiency and subsequently reducing the overall fuel consumption and reduce the impact of emissions [33]. The next phase is to conduct a careful analysis on the information obtained through this methodology to gain useful knowledge that can contribute to future designs and operations of vessels.

4.2 ENVIRONMENT AND EMISSIONS

A holistic method was proposed to assess the environmental influence of ships by developing a mechanism to prioritise pollutant discharges and justifying indicator weightings used in assessing the environmental indexing system. The developed indexing system has its basis on real world measurement from a ship has proven to be practically applicable to an operational vessel.

The next step is to apply the methodology to other vessels to obtain a larger data set, hence allowing comparisons between ships according to their environmental performance. For this purpose, 40 ships were instrumented with emission sensors and the data collection is currently ongoing. The methodology developed to evaluate the environmental performance of a ship is currently being applied on inland ships and has the potential to be extended to larger ocean-going vessels.

4.3 POWER AND PROPULSION

The experiments on the coated panels demonstrated that the fouling dynamically grown at full scale is difficultly reproduced in artificial environments. The SPMS developed on board the RV The Princess Royal and the dedicated sea trials provided consistent powering and performance results with similar fouling condition. This proved the effectiveness and accuracy of the presented methodology in handling the complexity of the vessel hydrodynamics and hence its capabilities in measuring the fouling effect on the vessel powering.

The study revealed that the gap between laboratory predictions and full-scale assessment is still in need to be bridged. The data that is currently being acquired from the vessel will allow the investigation on the possibilities of full scale SPMS to be deepened further to this end.

4.4 STRUCTURAL RESPONSE

The sea trials conducted with the RNLI’s Severn class lifeboat, together with numerical and experimental results, enabled the prediction of the short and long term seakeeping loads sustained by the structure. Work is currently ongoing to identify possible structural ‘hot spots’ and areas of potential improvement in view of the life extension programme that the RNLI is undertaking on the Severn. The results could also be extended to

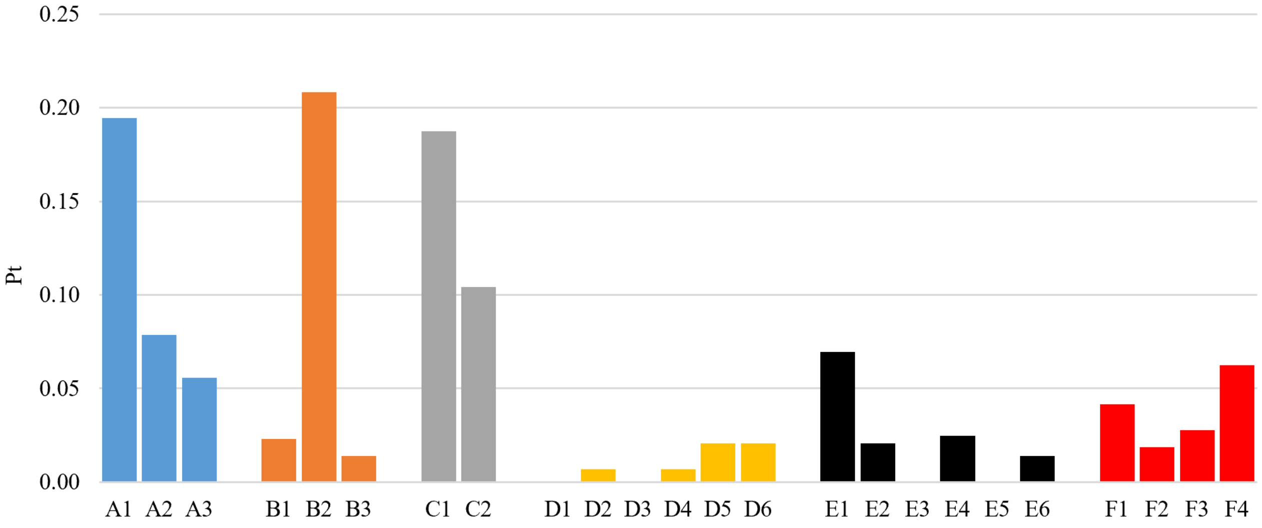

Figure 12 Socio-economic impact of LF operations

other RNLI's lifeboat classes and to high-speed craft in general.

The knowledge developed on the behaviour of the structure also sets the basis for the implementation of a long-term data acquisition system. Some of the main benefits associated with the prolonged monitoring of the structure were identified as: to verify design assumptions in terms of design versus actual loads experienced; inform on the usage of the vessel, improve the calculation of design, lifetime and extreme loads and improve fatigue life calculations; flag extreme load events and aid targeted inspections; provide feedback to the crew on the loads that are being sustained and on the utilization of the structure; and help understanding possible causes of incidents and failures. There are numerous possibilities according to the specific needs of designers, maintainers and operators, some of which are currently being explored for the Severn.

4.5 SOCIO-ECONOMIC IMPACT

By their very nature, studies involving socio-economic aspects relating to vessel performance would be limited without recourse to field (full scale) 'measurements' (e.g. surveys) incorporating humans' involvement with the vessels. The added value of primary data (first hand data from fieldworks) is significant because by using the world as a laboratory, research is conducted with direct interaction with the source of the data. The communication with the data source allows problem solving mechanisms to be developed that are socially acceptable. The methodology suggests that a complete socio-economic impact study is not justified by solely using secondary data (e.g. statistics and literature reviews). The assessment, successfully conducted on a specific Indonesian community, provided an in-depth understanding of the socio-economic performance of vessel operations that can be used as baseline for its further improvement.

5. CONCLUSIONS

The five case studies presented in this paper demonstrate the added value of using the real world as a laboratory to assess ship performance.

Monitoring systems are capable of informing operators on the actual on-board energy usage, which would otherwise be masked because of the complexity of the 'real world' environment. It is now possible to assess the real effect of fouling on the powering and resistance of vessels, hence enabling operators to carry out assessments of the selected coating and make best decisions on the dry-docking intervals. Full-scale measurements have provided greater confidence in the prediction of the seakeeping loads and structural response of vessels and demonstrated the added value of the longer-term monitoring of vessel structures. Genuine environmental indexing to rank vessels according to their real performance rather than a 'supposed' theoretical impact has been made possible by measurements of the actual environmental footprint.

The use of fieldwork data and the interaction with the real world enhances socio-economic assessments of the operation of ships and fleets, for which the human input is essential and cannot be entirely captured by generic and statistical data.

At face value, these conclusions were drawn from individual studies, but point to a more comprehensive monitored future where interactions in the 'complex' ship system can be revealed by bringing together this level of monitoring and this diversity of multidisciplinary actors. The paper demonstrates the benefits of considering ship performance as a multi-dimensional system that, to be fully understood, requires using the real world as a laboratory.

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7. REFERENCES

[1] IMO (2011). Resolution MEPC.203(62), Amendments to the annex of the protocol of 1997 to amend the international convention for the prevention of pollution from ships. *International Maritime Organization*.

[2] IMO (2013). MARPOL Annex VI and NTC 2008 with Guidelines for implementation. *International Maritime Organization*.

[3] Roberton, D.M.V. (2015). *Residual life assessment of composite structures: with application to all weather lifeboats* (Doctoral dissertation, University of Southampton, Southampton, UK).

[4] Prini, F., Birmingham, R.W., Benson, S., Dow, R.S., Sheppard, P.J., Phillips, H.J., Johnson, M.C., Mediavilla Varas, J. and Hirdaris, S. (2018). Enhanced structural design and operation of search and rescue craft. *13th IMDC International Marine Design Conference*, Helsinki, FI, 439-452.

[5] Wibawa, P.A., Birmingham, R.W. and Woodward, M.D. (2015). Design of sustainable fishing vessels – future challenges for the Indonesian fisheries. *12th IMDC International Marine Design Conference*, Tokyo, JP, 357-367.

[6] Froude, W. (1872). Experiments on the surface-friction experienced by a plane moving through water. *British Association for the Advancement of Science, 42*, 118-124.

[7] Faber, J.F. and MJJ't Hoen (2015). *Historical trends in ship design efficiency*. CE Delft, Delft, NL.

[8] ISO (2016). ISO19030 Measurement of changes in hull and propeller performance. *Ships and Marine Technology*.

[9] Bertram, V. (2017). Some heretic thoughts on ISO 19030. *2nd HullPIC Hull Performance & Insight Conference*, Ulrichshusen, DE, 4-11.

[10] Lim, S., Pazouki, K., Coraddu, A. and Murphy, A.J. (2017). Standardisation of data monitoring on-board vessels. *12th SDEWES Conference on Sustainable Development of Energy, Water and Environment Systems*, Dubrovnik, HR.

[11] Schultz, M.P. (2007). Effects of coating roughness and biofouling on ship resistance and powering. *Biofouling*, 23(5), 331-341.

[12] Demirel, Y.K., Uzun, D., Zhang, Y., Fang, H.C., Day, A.H. and Turan, O. (2017). Effect of barnacle fouling on ship resistance and powering. *Biofouling*, 33(10), 819-834.

[13] Yeginbayeva, I.A. (2017). *An investigation into hydrodynamic performance of marine coatings "in-service" conditions,* (Doctoral dissertation, Newcastle University, Newcastle upon Tyne, UK).

[14] Atlar, M., Yeginbayeva, I.A., Turkmen, S., Demirel, Y.K., Carchen, A., Marino, A. and Williams, D. (2018). A rational approach to predicting the effect of antifouling systems on 'in-service' ship performance, *3rd International Symposium on Naval Architecture and Maritime*, Istanbul, TR.

[15] Carchen, A., Turkmen, S., Pazouki, K., Murphy, A.J., Aktas, B. and Atlar, M. (2017). Uncertainty analysis of full-scale ship performance monitoring onboard The Princess Royal. *5th International Conference on Advanced Model Measurement Technology for the Maritime Industry AMT'17,* Glasgow, UK.

[16] ABS (2014). Rules for building and classing high-speed craft. *American Bureau of Shipping.*

[17] DNV (2012). Rules for classification of high speed, light craft and naval surface craft. *Det Norske Veritas*.

[18] LR (2014). Rules and regulations for the classification of special service craft. *Lloyd's Register.*

[19] Le Sourne, H., Couty, N., Besnier, F., Kammerer, C., and Legavre, H. (2003). LS-DYNA Applications in shipbuilding. *4th European LS-DYNA Users Conference*, Ulm, DE, 1-16.

[20] Aktas, B., Prini, F. and Benson, S. (2017). Full-scale unsteady RANSE CFD seakeeping simulations of a high-speed craft. *20th Numerical Towing Tank Symposium NuTTS'17*, Wageningen, NL, 16-21.

[21] Chen, J.H., Zeng, X. and Deng, Y.B. (2016). Environmental pollution and shipping feasibility of the Nicaragua Canal. *Marine Pollution Bulletin*, 113(1-2), 87-93.

[22] Jorgensen, A., Le Bocq, A., Nazarkina, L. and Hauschild, M. (2008). Methodologies for social life cycle assessment. *International Journal of Life Cycle Assessment*, 13(2), 96-103.

[23] Lim, S., Pazouki, K., Murphy, A.J., Younessi, S. and Graham, N., (2016). Systematic rationale for assessing energy flow across the entire vessel operation. *International Conference on Energy Efficient Ships. The Royal Institution of Naval Architects,* London, UK, 25-31.

[24] Lim, S., Pazouki, K. and Murphy, A.J. (2017). Holistic energy mapping methodology for reduced fuel consumption and emissions. *36th International Conference on Ocean, Offshore and Arctic Engineering OMAE2017. American Society of Mechanical Engineers*, Trondheim, NO.

[25] Lim, S., Ben, Z. Pazouki, K. and Murphy, A.J. (2018). Capturing and analysis real time tug data. *37th International Conference on Ocean, Offshore and Arctic Engineering OMAE2018. American Society of Mechanical Engineers,* Madrid, ES.

[26] Gibson M., Murphy, A.J. and Pazouki, K. (2017). A novel approach to holistic environmental assessment of ships. *Shipping and Changing Climates Conference*, London, UK.

[27] ISO (2015). ISO 15016 Guidelines for the assessment of speed and power performance by analysis of speed trial data. *Ships and Marine Technology*.

[28] ITTC (2012). Speed and power trials, Part 2 Analysis of speed/power trial data. *ITTC Recommended Procedures*.

[29] Salvino, L.W. and Collette, M.D. (2009). Monitoring marine structures. *Encyclopedia of Structural Health Monitoring*.

[30] Prini, F., Benson, S., Birmingham, R.W., Dow, R.S., Ferguson, L.J., Sheppard, P.J., Phillips, H.J., Johnson, M.C., Mediavilla Varas, J., and Hirdaris, S. (2018). Full-scale seakeeping trials of an all-weather lifeboat. *SURV 9 Conference: Surveillance, Pilot & Rescue Craft. The Royal Institution of Naval Architects*, London, UK, 25–36.

[31] UNEP (2009). The Guidelines for social life cycle assessment of products. *UNEP/SETAC Life Cycle Initiative*.

[32] Manik, Y., Leahy, J. and Halog, A. (2013). Social life cycle assessment of palm oil biodiesel: a case study in Jambi Province of Indonesia. *International Journal of Life Cycle Assessment,* 18(7), 1386-1392.

[33] Murphy, A.J., Weston, S.J., and Young, R.J. (2012). Reducing fuel usage and CO2 emissions from tug boat fleets: sea trials and theoretical modelling. *International Journal of Maritime Engineering*, 154, A31-A41.

8. AUTHORS BIOGRAPHY

Dr Serena Lim is a Research Associate in the School of Engineering at Newcastle University. She has a background in structures and hydrodynamics of vessels and offshore engineering. She currently works on data analysis of marine engineering systems using analytical, theoretical and machine learning approaches. This combined knowledge is being used to develop a holistic real-time energy management system for vessels.

Dr Serkan Turkmen is a Research Associate at Newcastle University. He is a naval architect and marine engineer. His recent research has been on a novel rudder system, the Gate Rudder, which has already been installed on a container vessel. He designed the new pressure drop measurement system of the Flowcell and the dynamic slime growing farm of Newcastle University, which are used by both academia and industry.

Dr Ali B Rostami is a Research Associate at Newcastle University, currently working on a project related to inland shipping. His background is in Naval Architecture and Marine Engineering. He has been working on marine engineering related projects since 2005.

Federico Prini is a Research Associate at Newcastle University. He is working on a research project with the Royal National Lifeboat Institution (RNLI) and Lloyd's Register to enhance the structural design, operation and maintenance practice of small high-speed craft. Before joining the University, he gained internship experience with the motor yacht shipyard Ferretti Group. After a Bachelor in Pleasure Craft Engineering and a Master in Small Craft Design he is currently registered for a PhD in marine hydrodynamics and structures.

Vita R Kurniawati is a PhD student at Newcastle University. She was awarded a bachelor's degree from the Faculty of Fisheries and Marine Science, Bogor Agricultural University (BAU) and a Master in Marine Technology from School of Marine Technology, Sepuluh Nopember Institute of Technology (ITS). She is also a lecturer at BAU. Her PhD thesis, entitled 'Sustainable development of fishing operations: a case study focusing on small vessels in Palabuhanratu, Indonesia', will be completed in 2018.

Alessandro Carchen is a PhD student at Newcastle University where his main research focus is on the development of an online ship performance monitoring system dedicated to biofouling and anti-fouling coating analysis.

Martin Gibson is a PhD student at Newcastle University. His main research focus is on environmental impacts and assessment in a marine context and on the development of a holistic approach for the environmental assessment of vessels.

Dr Simon Benson is a Lecturer in Naval Architecture at Newcastle University and academic director of the Marine Propulsion Laboratory. He is responsible for teaching and research in marine hydrodynamics and structures. His previous experience is in industry working for BMT Fluid Mechanics and IHC Engineering Business before completing a PhD investigating the structural performance of aluminium high-speed ships. His PhD and post-doctoral work were sponsored by the Office of Naval Research.

Prof Richard Birmingham is a Professor of Small Craft Design at Newcastle University where he has been a member of the academic team for over twenty-five years, including seven as Head of School. He is currently president of The Royal Institution of Naval Architects. He has worked on collaborative research projects with the RNLI for over 20 years and he is currently a member of the RNLI's Technical Advisory Panel. His research interests include also design for sustainability in its widest sense and in particular in the context of artisanal fishing boats in the developing world.

Prof Robert S Dow is a Professor in Marine Structures and the Head of the Marine, Offshore and Subsea Technology Group within the School of Engineering, at Newcastle University. He is responsible for teaching and research in marine hydrodynamics and structures. He has extensive experience of full-scale sea trials with measurement of structural loads and response.

Dr Alan J Murphy, BEng, PhD, CEng, CMarEng, FIMarEST, FRINA, FHEA, is a Reader (Associate Professor) in Maritime Engineering at Newcastle University. He was formally a sea-going Marine Engineer. For more than a decade he has led a large portfolio of UK government, European Union and Industry funded research projects, many broadly on the theme of sustainable shipping through the reduction of airborne pollution and improved energy efficiency of marine machinery systems.

Dr Kayvan Pazouki is Lecturer in Marine Technology at Newcastle University. He was a seagoing marine engineer for nine years, before joining the University. His research area is in the development of monitoring tools through physical and/or inferential measurement systems. He was involved in the European project "Clean North Sea Shipping" regarding energy efficiency management and emission prediction of ships trading in the North Sea region and developed voyage emission prediction tools.