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Operational Practices to Improve Ship Energy Efficiency

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ABSTRACT

The aim of this research was to contribute towards energy efficiency in the shipping industry through improved operational practices that reduce fuel consumption, hence exhaust emissions and the amount of carbon dioxide released into the atmosphere. This is in line with meeting global emission reduction targets and the mitigation of Climate Change.

A critical review is presented that was undertaken to understand Climate Change as a driver towards energy efficiency within the maritime industry. The regulations are reviewed along with existing operational practices and the enablers and barriers towards improvements. Several field studies that were undertaken to further examine current practices and barriers are described, including a questionnaire identifying the opinions and perceptions of seafarers. Based on conclusions from the review and field studies, a Framework for improving the energy efficiency of ship operations is presented.

The proposed Framework identifies that for practical solutions in the industry, human factors must be addressed in parallel with technical advances. The following features of the Framework to enable improvements are identified to be: a) Ship Operational Performance Monitoring for performance feedback distribution and supporting operational strategic decisions and b) updates to existing Operating Procedures. However, it is proposed that these features cannot be achieved on a wide scale without first the development of the following elements: a) Maritime Education and Training on energy efficiency; b) Analysis of ship Operational Profiles; c) A Ship Operational Performance Prediction (SOPP) Model. These three elements were developed and are described in this thesis.

The developments described in this thesis were enabled by the collection of operational datasets (namely Ship Reports, also commonly known as Noon Reports) and information for 21 case study ships; including tanker, container and bulk carrier ships. The collection of this data was enabled by field study visits.

Regarding the development of Maritime Education and Training on energy efficiency, three course curriculums are proposed. The training material developed for the Energy Resource Management course is then described.

The results from the analysis of Operating Profiles for the 21 case study ships are presented. Typical operating practices are identified along with the opportunities for energy efficiency improvements.

The Ship Operational Performance Prediction Model was developed using the Ship Report dataset for a case study tanker ship. The model predicts the ship's main engine brake power and fuel consumption with adequate accuracy and allows for assessment of the impacts due to different operating conditions. Specifically, a function to account for time dependent performance changes is developed so that the hull and propeller surface degradation and fouling are taken into consideration.

Finally, the utilisation of the developed elements within the proposed Framework to improve energy efficiency is discussed, so that the importance of methods utilising Ship Report operational datasets becomes evident.

ABBREVIATIONS

	Abbreviation	Description
A	AF	Anti Fouling
	AHR	Average Hull Roughness
	ANN	Artificial Neural Network
B	BSRA	British Ship Research Association
	BRM	Bridge Resource Management
C	CBT	Competency Based Training
	CCWG	Clean Cargo Working Group
	CFD	Computational Fluid dynamics
	CM	Continuous Monitoring
	COP	Conference Of Parties
	CPM	Continuous Performance Monitoring
	CPP	Controllable Pitch Propeller
	CRM	Crew Resource Management
	CS	Case Study
	CSI	Clean Shipping Index
	CV	Criterion Variable
E	EMSA	European Maritime Safety Agency
	EEDI	Energy Efficiency Design Index
	EEOI	Energy Efficiency Operational Indicator
	ESI	Environmental Ship Index
	ERM	Energy Resource Management, or Engine Resource Management
F	FC	Fuel Consumption
	FFR	Fuel Flow Rate
G	GHG's	Greenhouse Gases
	GMM	Gaussian Mixture Model
	GP	Gaussian Process
	GPD	Generalised Power Diagram
I	IEE	International Energy Efficiency Certificate
	IMO	International Maritime Organisation
	IPCC	International Panel on Climate Change
	ITTC	International Towing Tank Conference
K	KPI	Key Performance Indicator
L	LBP	Length between perpendiculars
	LCA	Life Cycle Analysis
	LOA	Length overall
M	MACC	Marginal Abatement Cost Curves
	MARPOL	International Convention for the Prevention of Pollution from Ships
	MCR	Maximum Continuous Rating
	ME	Main Engine
	MEPC	Maritime Environmental Protection Committee
	MET	Maritime Education & Training
	MRM	Maritime Resource Management
	MRP	Mean Referred Pressure
	MRV	Monitoring Verification and Reporting
O	OoW	Officer on Watch
	ORC	Organic Rankine Cycle
P	PBCF	Propeller Boss Cap Fin
	PV	Predictor Variable
R	RF	Radiative Forcing
S	SEEMP	Ship Energy Efficiency Management Plan
	SOG	Speed Over Ground
	SOPM	Ship Operational Performance Monitoring
	SOPP	Ship Operational Performance Prediction
	SPC	Selft Polishing Copolymer

	SR's	Ship Reports (commonly known as Noon Reports)
	STCW	Standards of Training, Certification and Watchkeeping
	STW	Speed Through Water
T	TBT	Tributyltin
	TDNN	100
	TMSA	Tanker Management Self Assessment
U	UNCLOS	The United Nations Convention on the Law of the Sea
	UNCTAD	United Nations Conference on Trade and Development
	UNEP	United Nations Environment Programme
	UNFCCC	United Nations Framework Convention on Climate Change
V	VIF	Variation Inflation Factor
W	WHR	Waste Heat Recovery
	WMU	World Maritime University

NOMENCLATURE

	Symbol	Description	Units
Upper Case			
A	AC	Admiralty Coefficient	
	A_{BT}	Transverse sectional area of the bulb at the position where the still-water surface intersects the stern	m^2
	A_E	Propeller, Expanded area	m^2
	A_o	Propeller, Disc area	m^2
B	B	Breadth	m
	BN	Beaufort Number	
C	C	A coefficient of resistance	
	C_B	Block coefficient	
	C_F	Coefficient of frictional resistance	
	ΔC_F	The change in the coefficient of frictional resistance	
	C_M	Midship coefficient	
	C_P	Prismatic coefficient	
	C_{stern}	Coefficient representing the aft body form	
	C_T	Coefficient of total resistance	
	C_W	Waterline coefficient	
	CO_2	Carbon Dioxide	
	CS	Case Study	
D	D	Propeller diameter	m
F	FC	Fuel consumption	
	FC_{ratio}	Fuel consumption ratio	
	FFR	Fuel Flow Rate	T/24 hrs
	Fn	Froude Number	
J	J	Advance coefficient	
K	K_Q	Torque coefficient	
	K_T	Thrust coefficient	
L	L	Length	m
	LCB	Longitudinal centre of buoyancy	m, %
	LCF	Longitudinal centre of flotation	m, %
N	N	RPM	
	N	Sample Number	
P	p	Propeller pitch	m
	P_B	Power, Brake	HP, kW
	P_E	Power, Effective	HP, kW
	P_P	Power, Propeller	HP, kW
Q	Q	Torque	
	QPC	Quasi Propulsive Coefficient	
R	R	Resistance	kN
	Rn	Propeller, Reynolds number	
	R_T	Resistance, Total	kN
S	S	Wetted surface area	m^3
	Sa	Apparent slip	
	SFOC	Specific fuel oil consumption	g/kWhr
	Sr	Real slip	
T	T	Average draft at midship	m
	T	Thrust	kN
V	V	Ship speed	Knots, ms^{-1}
	V_A	Apparent speed	
W	WD	Wind Direction	
Z	Z	Propeller, Number of blades	

Lower Case

G	g	Acceleration due to gravity	ms^{-2}
H	h_B	Position of the centre of transverse area	m
N	n	RPM	

Suffixes

A	A	Aft
B	Bal.	Ballast condition
	BPP	Between perpendiculars
C	Calc.	Calculated variable via the Data Elaboration Process (Section 9.2)
	Cali.	Calibration
	Corr.	Correction factor/value
	Corr.recX	Correction factor/value corresponding to the variable X recorded in the SR dataset
F	F	Fore
L	Lad.	Laden condition
N	Norm.	Normalised to the Normalisation Baseline defined
	NBase	Normalisation Baseline
M	MCR	Maximum continuous rating
O	OA	Overall
P	Pred.	Predicted by the regression analysis equations (Section 9.3)
	Pred.rec	Predicted corresponding to recorded input data
	Pred.XBase	Predicted for the X specified baseline (i.e. input data)
R	Rec.	Recorded variable in the SR dataset
S	SOG	Speed over ground
	STBase	Sea Trial Baseline
	STW	Speed trough water
	SW	Sea water
T	TD	Time dependent
W	WL	Waterline

Greek

	τ	Thrust deduction factor	
	η_{PT}	Efficiency, Total propulsion system	
	η_R	Efficiency, Propeller relative rotative	
	η_O	Efficiency, Propeller open water	
	η_D	Efficiency, Propulsive	
	η_S	Efficiency, Shaft	
	η_B	Efficiency, Propeller behind hull	
	η	Efficiency	
	ρ	Density	$kg\ m^{-3}$
	ν	Kinematic viscosity	m^2s^{-1}
	Δ	Mass Displacement	tonnes
	∇	Volume Displacement	m^3
	ω	Wake fraction	

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1. INTRODUCTION

1.1 Background Scenario and Motivation for Research

Around 80 percent of global trade by volume and over 70 percent by value is carried by sea (UNCTAD 2012) and this makes the shipping industry a vital part of the world economy. The characteristics of shipping trade are defined by supply and demand, which in turn are influenced by world events, economics, population and oil price. Stopford disuses how the shipping industry is influenced by each of these factors, and thus experiences more prosperous and harder times occurring in a cyclic nature (Stopford 2007). It has been observed that during periods of low demand, linked closely with a combination of low economic growth, the oversupply of ships and high oil prices, the shipping industry tends to respond by reducing the new build rate, increasing the scrapping rate and implementing measures to reduce fuel consumption. Such measures include operational decisions such as reducing ship speed to 'slow steaming'. Once the market picks up again these actions become less significant or reverse, and focus turns back to meeting the high and competitive demand.

Since the last significant downturn in the market following the 2007 economic crisis, the shipping industry has again been faced with an oversupply of vessels[1], historically low freight rates, and high bunker prices (Yao et al. 2012) (UNCTAD 2012). The bunker price alone was estimated to account for 35% of the operating cost for a tanker in 2012 (UNCTAD 2012) and up to 75% for a containership in 2010 (Ronen 2010). Therefore there has been a great incentive to improve the energy efficiency of ship operations and hence reduce fuel consumption. However, during emergence from past downturns in the market, no significant design changes to conserve or improve upon ship energy efficiency can be marked, nor the continuation

[1] Indicated by the recovered oil price compared to pre-crisis levels yet no strong recovery in the shipping market (UNCTAD 2012)

of energy efficient operational practices such as slow steaming. On the whole, in the past, concern regarding energy efficiency appears to diminish. However, during emergence from this current downturn there are significant factors that will influence and encourage the continuation and increase of energy efficient ship design and operation.

Supporting the move towards energy efficiency, there is concern about the future availability of oil resources (Fang et al. 2013). It is also predicted by many sources that the global population will continue to increase significantly, along with the number of developing countries that will have increased purchasing power. This will increase the demand for maritime transportation of raw material, manufactured goods and commodities. To meet this demand an increased number of ships in the world fleet will consume a larger total amount of bunker fuel (Fang et al. 2013), (UNCTAD 2012), (Buhaug et al. 2009) and (Bazari & Longva 2011); where the amount of bunker fuel consumed by a ship is proportional to the amount of exhaust emissions emit into the atmosphere. The type and amount of anthropogenic[2] exhaust emissions emit into the atmosphere has become an increasing environmental concern as the emissions typically contain Greenhouse Gases (GHG's) such as carbon dioxide; where anthropogenic Carbon dioxide has been shown to contributed towards detrimental Climate Change (Treut et al. 2007) and (Alexander et al. 2013). Climate Change has received International attention with the United Nations coming together to discuss how the problem should be tackled throughout all industries worldwide. Particularly over the past decade there has been increased pressure for actions. As a result, environmental concerns within the shipping industry has expanded from predominantly oil pollution to also include air emission pollution (Svensson & Andersson 2011). Nevertheless, focus on energy efficient shipping beyond the basic principles for economic operation still remains a relatively new and largely unimplemented concept. One of the first efforts to address this issue has been the

[2] *Pollution or pollutants originating from human activities; such as shipping*

mandate of the first maritime regulations on energy efficiency that entered into force on the 1st January 2013. For these reasons, when the shipping market sees better times once more it is expected that energy efficiency will remain important.

The need to improve energy efficiency within the shipping industry has sparked discussions, developments and innovation in many design and operational areas. Stakeholders that have been involved include, but are not limited to: international regulatory bodies; national governments; classification societies; ports; ship operators and owners; charters; machinery and technologies suppliers; academic and research institutes. The somewhat good news is that there are several short and long term technological and operational measures that could provide significant reductions in the carbon emissions emit by the shipping industry (Buhaug et al. 2009). However, this is providing implementation occurs, and continues, along with the continual development and maturity of energy efficient technologies.

An important consideration with the installation and implementation of new designs, technologies and operations, is the requirement of human intervention at many different levels; from decision making to physical implementation. Similarly, changes and improvements in ship operating procedures require effective communication and co-operation between many stakeholders. This gives rise to several consideration areas related to human factors, to effectively achieve fully integrated energy efficient ship operations, whilst maintaining safety and completing job role objectives.

1.2 Research Focus

The research presented in this thesis examines the responsibilities of different stakeholders for achieving energy efficient shipping by exploring the communication and decision making networks. The practical barriers and enablers to implementing energy efficient operational improvements are identified. The considered gaps in existing practices and research and are addressed within a framework constructed to support the improvement of energy efficient ship operations. The aspects of the framework developed in this research are considered to be the foundations for practical solutions attainable on an industry wide basis. The key focuses of the framework include:

- Increasing awareness, knowledge skills and motivation towards energy efficiency by ensuring the availability of maritime education and training addressing both technical and human factor topics.
- Identifying a method that provides understanding and quantification of ship performance to the different stakeholders directly related to ship operation: where the method includes the analysis of existing operating profiles, and the development a ship operational performance model.

1.3 Structure of the Thesis

The research presented in this thesis is organised into Chapters 1 to 11, each addressing the following content:

Chapter 1 provides a board overview and the scope of this research work.

Chapter 2 reports a critical review addressing the following: Climate Change as a driver towards energy efficiency within the maritime industry; maritime energy efficiency regulations, options for compliance, and additional industry initiatives to encourage the implementation of energy efficient shipping; the barriers and enablers for improving ship operational energy efficiency; ship performance prediction and monitoring methods.

Chapter 3 states the aim and objectives of the research.

Chapter 4 describes the method used to address and accomplish the research aim and objectives.

Chapter 5 presents the construction of an operational framework to improve ship energy efficiency, supported by completion of the following: field studies carried out by the author to gain knowledge, practical understanding and data resources; configuration of the network of internal and external stakeholders that have direct and indirect influence over ship operation; a field study questionnaire distributed to 317 seafarers to identify their opinions related to energy efficient ship operation.

Chapter 6 reports the development of Maritime Education and Training (MET) courses on energy efficiency. It includes the presentation of three course structures and the development of the training material for one of the courses.

Chapter 7 describes the procedures used for collecting and processing the operational dataset (used for the analyses in chapters 8, 9 and 10) and the dataset variables.

Chapter 8 presents an analysis of the case study ships' operating profiles. The case study ships are grouped by ship type (i.e. tanker, container, bulk carrier), and size classifications (e.g. Suezmax, Aframax). The following profiles are examined: passage type, speed, cargo load, trim, and dry docking and hull and propeller maintenance patterns.

Chapter 9 focuses on the development of the Ship Operational Performance Prediction model. The model development steps include: a data elaboration process using hydrodynamic and propulsion relationships to calculate ship resistance for each record in the operational dataset; a regression analysis; a data normalisation; a time dependent performance changes analysis, i.e. changes due to hull and propeller surface degradation and fouling.

Chapter 10 describes a series of case studies identifying how the research developments can be used in the Framework to address the research aim and objectives.

Chapter 11 presents the discussion of the research achievements, major contributions and novelties and suggestions for future work. The conclusions of the research are also stated.

2. CRITICAL REVIEW

CHAPTER INTRODUCTION

The aim of this chapter is to provide an overview to why energy efficiency is important within the shipping industry and why there is a need for the research presented in this thesis. Focus is placed on existing ship operational practices, identified best practices, and on research in the same field of study; thus the opportunities to improve ship operational practices are highlighted. This chapter has been constructed in four sections as follows:

<u>Section</u>

2.1: Climate Change as a Driver Towards Energy Efficiency

2.2: Energy Efficiency In The Maritime Industry

2.3: Operational Structures And Practices

2.4: Ship Operational Performance Prediction and Monitoring

Chapter Summary

2.1 Climate Change as a Driver Towards Energy Efficiency

Climate Change is the driver behind international and multi-industry commitments and regulations to reduce global anthropogenic[3] carbon emissions: including within the shipping industry. However, as a general perspective, there is little awareness regarding Climate Change and thus little motivation towards making low carbon lifestyle and industry practice changes; other than those enforced by regulations. Understanding the background to Climate Change science and the regulatory framework developed to mitigate Climate Change is therefore important.

2.1.1 Climate Change

There is a comprehensive collection of literature reporting Climate Change science. In particular, the Intergovernmental Panel on Climate Change (IPCC) has produced extensive reports detailing the state-of-the-art, as well as summary reports developed for wider public dissemination: (Alexander et al. 2013), (Bernstein, et al. 2007), (Solomon et al. 2007), (Scholes et al. 2007), (Treut et al. 2007).

Climate Change has already caused observable and measureable effects on a local, regional and global scale. The number and severity of effects are expected to increase further with increasing of Climate Change. The current and future effects include, but are not limited to:

- Seasonal changes; such as more frequent hot days and nights, and increased precipitation in some areas whilst the opposite in others.
- The increased frequency of severe weather events[4]; such as storms, tropical cyclones, flooding, fires, freezes, heat waves.
- Ocean acidification; due to absorption of the additional carbon dioxide in the atmosphere into the oceans.

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[3] *Man-made*
[4] *this is not to say that extreme events have not happened in the past, just not as often*

- Ocean temperature increase (to the depth of at least 3000m); as the oceans have absorbed around 80% of the additional heat due to Climate Change (Alexander et al. 2013)

It should be noted that Climate Change will impact differently in different geographical regions. Often the harshest impacts are experienced in undeveloped and developing countries that do not have the resources or infrastructure to adapt to the changes. As the causes of Climate Change can predominantly be attributed to industrialised, developed and developing countries, differentiated responsibility forms part of International concern (discussed in the next sub-section).

The impacts related to the effects of Climate Change can be positive or negative. A small example list of current and future positive impacts are given here, focusing on a few related to shipping:

- Improved crop harvest in an area and therefore improved food and trading resources.
- Improved water resources with changes in precipitation patterns.
- Improved habitats for ocean and land based plants, insects and animals, with the opportunity for species to migrate to new areas.
- Less heat or cold related deaths.
- The warmer oceans have been melting ice. This could open up new shipping routes in the future (Fang et al. 2013).
- Both the temperature and salinity of water (which is reducing as fresh water ice melts into the ocean) change water density. This will impact on a ships frictional resistance performance.

(Treut et al. 2007) and (Alexander et al. 2013)

A few examples of negative impacts include:

- Poor crop harvest condition in an area, therefore loss of food and trade resources.
- Changing habitats for ocean and land based plants, insects and animals, has and could lead to: extinction of a species that it is unable to adapt or migrate the changed habitat or compete with an invading species; loss of a species due to migration to a different area; the migration of disease spreading species in areas with no natural immunity.
- More extreme heat or cold related deaths: including increased UV exposure resulting in an increased number of skin cancer cases.
- Increased risk of deaths and environmental, industrial and domestic damage due to extreme weather: e.g. flooding, forest fires, extreme winds.
- The warmer oceans have been melting fresh water ice creating a sea level rise and flooding land permanently and periodically.

(Treut et al. 2007) and (Alexander et al. 2013)

Some future impacts are unknown, for example; changes in ocean density and weather patterns has the potential to change deep ocean currents as we know them today; which will impact on ship route planning and voyage execution. It is also a concern that Climate Change could result to a sequence of extreme events that, once started, could contribute to unstoppable further effects and impacts: once such extreme event is a methane release (Buffett & Archer 2004). It should be noted here that the concern related to Climate Change is not the existence of the Earth, moreover the detrimental impacts that it will have on human life.

A change in climate is experienced due to natural and external influences, where external influences include those due to human activities. Radiative Forcing is used to quantify the changes in climate by depicting the energy balance between the radiation energy received, absorbed and reemit by the Earth, its ocean, atmosphere and biosphere. (Solomon et al. 2007), (Treut et al. 2007), (Bernstein et al., 2007), (Loaiciga et al., 1996) and (Gaddy & Wieme 1940) discuss the different forcing drivers (influences) and their impact on a change in climate, along with climate feedback mechanisms. Importantly, it is composition of gas particles in the atmosphere that is the forcing driver that has contributed most significantly to net positive radiative forcing (Alexander et al. 2013), i.e. an increase in heat energy and hence climate temperature, namely Climate Change.

The group of gases and particles responsible for Climate Change are known as Green House Gases, GHG's. Amongst other properties of GHG's, their high absorption[5] of radiation essential 'traps' heat energy between the GHG layer and the Earth's surface: known as the Green House Gas Effect.

Chlorofluorocarbons and Hydrofluorocarbons are man-made GHG's (T.J. Blasing 2013) that have already been phased out of use by International regulations to reduce ozone-depleting substances (United Nations 1999). Water vapour has the largest volume in the atmosphere (T.J. Blasing 2013) and has the strongest detrimental GHG properties. However, it is not directly possible to control the amount of water vapour in the atmosphere as it is governed by the hydrological cycle (Loaiciga et al., 1996), which in turn depends on the climate at that time. Thus the concern is that water vapour will amplify the effect of Climate Change caused by other forcing drivers (Alexander et al. 2013). Methane has strong detrimental GHG properties[6], however its quantity in the atmosphere is small (T.J. Blasing 2013). Therefore, whilst it should not be ignored, at present methane is not considered the highest concern related to Climate Change. The highest concern is with Carbon Dioxide, (CO_2). CO_2 is a naturally occurring gas, it has the second largest volume in the atmosphere (T.J.

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[5] *High absorption of predominantly infrared radiation (thermal energy), which is typically re-emitted by the Earth's surface after solar radiation has been absorbed.*
[6] *The GHG properties of methane are almost 20 times more detrimental than CO_2; but quantity in the atmosphere much less than carbon dioxide ($x10^9$ compared to 10^6) (T.J. Blasing 2013).*

Blasing 2013), and it is regulated by the carbon cycle (Gaddy & Wieme 1940): (Solomon et al. 2007). However, since the industrial revolution, starting around the 1970's an additional amount of CO_2 has been released into the atmosphere due to man-made processes: anthropogenic CO_2 emissions. The additional amount of anthropogenic CO_2 in the atmosphere, above the naturally occurring amount, is significant (Alexander et al. 2013). (Thompson 2000), (Sherwood 1988) and (Lüthi et al. 2008) present findings from ice core drilling in Greenland and Antarctica, correlating the change in air composition (i.e. the increase in CO_2) with the increase climate temperature, dating back 800,000 years. The industrial revolution can be linked with the dramatic increase in CO_2 and temperature; much greater than the natural variations identified for the previous 800,000 years.

The primary man-made processes contributing to anthropogenic CO_2 emissions can be attributed to the combustion of raw materials to produce other forms of energy; required for the sustainability of industry and present life styles, predominantly in developing and developed countries. The amount of CO_2 released during combustion depends on the type of fuel used, the machinery installed and the associated efficiencies. More specifically, the amount of CO_2 released for the combustion of 1 kilogram of fuel depends on the carbon content of the fuel and fuel composition: the calculation of CO_2 emissions from fuel consumed can be found in (Theotokatos & Tzelepis 2015) and (Woud & Stapersma 2012). However, most often in the shipping industry, the composition of a fuel is not known on a day to day basis and therefore this calculation cannot be made. For this reason, generalised, non-dimensional, fuel consumption to CO_2 conversion factors (C_f) have been defined for the primary fuel types used within the shipping industry, shown in Table 1. The C_f value is multiplied to the amount of fuel consumed to calculate the carbon emissions emit.

Table 1: Carbon conversion factors given by the IMO (IMO 2014)

Type of fuel	Reference	Carbon content	C_F (t-CO_2/t-Fuel)
1 Diesel/Gas Oil	ISO 8217 Grades DMX through DMB	0.8744	3.206
2 Light Fuel Oil (LFO)	ISO 8217 Grades RMA through RMD	0.8594	3.151
3 Heavy Fuel Oil (HFO)	ISO 8217 Grades RME through RMK	0.8493	3.114
4 Liquefied Petroleum Gas (LPG)	Propane	0.8182	3.000
	Butane	0.8264	3.030
5 Liquefied Natural Gas (LNG)		0.7500	2.750
6 Methanol		0.3750	1.375
7 Ethanol		0.5217	1.913

In conclusion of the above point, the amount of anthropogenic CO_2 emissions emit within and outwith the shipping industry can be mitigated by reducing the amount of fuel consumed and by using fuels with a lower carbon content. However to achieve either of these solutions changes need to be made in human activities; requiring the motivation and knowledge to do so.

2.1.2 Public Attitudes Towards Climate Change

There is a large amount of public scepticism regarding the occurrence of Climate Change. (Cobb & Carolan 2011) identifies that attitudes towards Climate Change vary due to many variables that are weighted differently by individuals, including: demographics; perceived responsibility; voluntary or involuntary risks; trust in the organisations responsible for protection from the risks. (Gibson et al. 2015) identify that despite ‘every Intergovernmental Panel on Climate Change report, the predicted consequences of global warming become increasingly dire. Yet public engagement on the issue, particularly in the United States, lags far behind what is required for collective action.’ Therefore there are many challenges towards addressing this issue.

‘The challenges begin with the issue itself; as a story, climate change violates almost all of the traditional definitions of newsworthiness. Climate change is global, not local. It is chronic and slow-moving, not episodic or event-driven. As an issue, it is neither dramatic nor does it have an immediately obvious ‘human interface’.’

(Gibson et al. 2015)

Additional factors associated with Climate Change scepticism are the uncertainty surrounding the science and how it is portrayed by the media (Cobb & Carolan 2011), (Hmielowski et al. 2014), (Zehr 2000), (Gibson et al. 2015). This was particularly evident in the early years of Climate Change science when uncertainty was higher. However many people remain unaware of the developments and reduced uncertainty levels in climate change quantification and modelling: (Solomon et al. 2007), (Treut et al. 2007), (Bernstein et al., 2007) (Alexander et al. 2013). (Leiserowitz et al. 2010) presents the results of a survey carried out in 2008 and 2010 comparing the awareness and perceptions of 1001 American adults. Mixed positive and negative were demonstrated. For example, the largest proportion of participants (51% in 2008 and 47% in 2010) believed that 'humans could reduce global warming, but it's unclear at this point whether we will do what's needed'. An increasing proportion of participant believed that 'global warming isn't happening (5% in 2008 and 13% in 2010).

2.1.3 The International Response to Climate Change

1989 saw the first International regulations regarding concern for the climate with the enforcement of the Montreal Protocol on Substances that Deplete the Ozone Layer (United Nations 1999); based on the framework presented at the 1988 Vienna Convention for the Protection of the Ozone Layer (United Nations 1985). In 1992 the governments of the United Nations came together in Rio, and, with the support of the United Nations Environment Program (UNEP), they created the United Nations Framework Convention on Climate Change (UNFCCC) Treaty: also known as the Earth Summit. The objective of the treaty is:

'stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient.' (United Nations 1992)

The governments signed to the treaty meet annually at the Conference of Parties (COP) to make decisions on Climate Change actions to meet the UNFCCC's objective. Expert and scientific advice is sort by the COP, specifically looking to their advisory bodies; including the IPCC, and the Subsidiary Body for Scientific and Technological Advice. At COP3 held in Kyoto, Japan, 11th December 1997, the Kyoto Protocol was agreed upon, committing 186 participating industrialised countries to meet specified targets for Climate Change mitigation via the reduction of the GHG's; specifically anthropogenic carbon emissions (United Nations 1998). The Kyoto Protocol recognised the inherent differences of the shipping and aviation industries in comparison to land based industries; i.e. where operation is between nations and thus the apportionment of emissions to one nation is not easily defined. The International Maritime Organisation (IMO) was therefore recognised as the correct body to implement actions within the shipping industry (United Nations 1998). However, should sufficient actions not be implemented by the IMO, then the COP to the UNFCCC will seek other means to bring about implementation within the shipping industry. The Copenhagen Accord (COP 15) recognised that global emissions should be reduced to a level that will limit a global temperature increase to 2 degrees Celsius (United Nations 2010): based on the 2007 reports of the IPCC.

In addition to the international response to Climate Change, many national carbon emission reduction targets have been identified. For example:

'The 2008 Climate Change Act established the world's first legally binding climate change target. We aim to reduce the UK's greenhouse gas emissions by at least 80% (from the 1990 baseline) by 2050' (UK 2008)

'For 2020, the EU has made a unilateral commitment to reduce overall greenhouse gas emissions from its 28 Member States by 20% compared to 1990 levels.'(European Commission 2013)

2.1.4 The Shipping Industry's Response to Carbon Emission Reductions

Environmental concern within shipping was first recognised in 1956 under The United Nations Convention on the Law of the Sea (UNCLOS) Part XII, Protection and Perseveration of the Marine Environment (United Nations 1960). The International Convention for the Prevention of Pollution from Ships (MARPOL) was then adopted in 1973 with subsequent updates. With increasing environmental concern and International pressure to make improvements in the shipping industry, the IMO established a subsidiary body known as the Marine Environmental Protection Committee (MEPC) to assist with the development, adoption and amendment of conventions and regulations, along with measures to ensure their enforcement.

Annex VI Prevention of Air Pollution from Ships was amended to MARPOL, and entered into force in 2005: addressing the emissions of sulphur oxide, nitrogen oxide, ozone depleting substances and particulate matter, primarily in response to the Montreal Protocol. However, at this point MARPOL did not address carbon emissions as a GHG.

With the agreements made in under the UNFCCC treaty and the commitments under the Kyoto Protocol, the IMO, through the MEPC, initiated research and actions towards the reduction of GHG emissions from ships. The first comprehensive study on GHG emissions, specifically CO_2 emissions, from shipping was published in 2009 called *The Second IMO GHG Study* (Buhaug et al. 2009). In 2014 a Third IMO GHG Study was published (Smith et al. 2014).

Key figures from the second study demonstrate that shipping is the most efficient means of transporting cargo when considering efficiency as the tonnes of CO_2 emit per tonne of cargo transported per nautical mile. However, it was estimated that in 2007 shipping was responsible for 3.3% of total global CO_2 emission, with 2.7% from International shipping alone (Buhaug et al. 2009): Figure 1. The third study published that in 2012 total shipping emissions were approximately 949 million tonnes of CO_2, accounting for 2.7% of global CO_2 emission, and 796 million tonnes and 2.2% for international shipping alone (Smith et al. 2014).

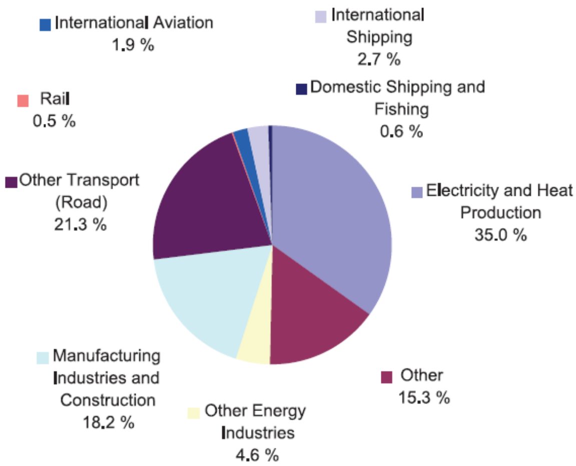

Figure 1: Emissions of CO_2 from shipping compared with global total emissions (Buhaug et al. 2009)

Again, achieving reductions in the amount of CO_2 emit by shipping becomes increasingly more important when considering the predicted growth of the shipping industry (linked closely with the growing population (UNCTAD 2012)). The Second IMO GHG Study 2009 concludes that:

'Mid-range emissions scenarios show that by 2050, in the absence of policies, carbon dioxide emissions from international shipping may grow by a factor of 2 to 3 (compared to the emissions in 2007) as a result of the growth in shipping' (Buhaug et al. 2009)

Furthermore,

'If a climate is to be stabilized at no more than 2°C warming over pre-industrial levels by 2100 and emissions from shipping continue as projected in the scenarios that are given in this report, then they would constitute between 12% and 18% of the

global total CO2 emissions in 2050 that would be required to achieve stabilization (by 2100) with a 50% probability of success' (Buhaug et al. 2009)

The discussed clearly demonstrates the need for energy efficiency to be implemented within the shipping industry, to reduce the consumption of fuel with a high carbon content, and hence CO_2 emissions. Furthermore, in summary of this section, CO_2 emission reduction levels are required to be in line with international and national commitments and targets, sufficient to contribute towards the mitigation of Climate Change, and in line with the shipping industries responsibilities. This is to prevent future detrimental effects and impacts of Climate Change as much as possible: where quantified effects and impacts are already being observed on a local, regional and global scale. These quantifications and future predictions are supported by state-of-the-art Climate Change science. However, despite all of the above requirements and actions, there is a vast amount of public scepticism and lack of awareness regarding Climate Change, international regulations and the need to implement changes. Often, where positive perceptions are observed, a lack of motivation towards the implementation of changes in life styles and practices remains. Thus the provision of awareness and motivation, by providing knowledge to all those who are required to make changes, is required.

2.2 Energy Efficiency in the Maritime Industry

2.2.1 Energy Efficiency Measures

In the Second IMO GHG Study a number of measures for increasing ship energy efficiency were identified (Buhaug et al. 2009). These measures fall into two categories: technological (design) measures concerned with the design of ships and their systems, and operational measures concerned with ship operation. Table 2 identifies groups of measures for each category and the carbon emission reductions that could be realised: potentially equating to a 25 -75% reduction in CO_2 emission, compared to the level referenced at the time.

Table 2: Assessment of potential reduction of CO_2 emissions from shipping by using known technology and practices (Buhaug et al. 2009)

DESIGN (New ships)	**Saving (%) of CO_2/tonne-mile**	**Combined**	**Combined**
Concept, speed and capability	2–50†		
Hull and superstructure	2–20		
Power and propulsion systems	5–15	10–50%†	
Low-carbon fuels	5–15*		
Renewable energy	1–10		
Exhaust gas CO_2 reduction	0		25–75%†
OPERATION (All ships)			
Fleet management, logistics and incentives	5–50†		
Voyage optimization	1–10	10–50%†	
Energy management	1–10		

* CO_2 equivalent based on the use of LNG.
† Reductions at this level would require reductions of speed.

Design improvements are considered to offer some of the largest step changes in future CO_2 emission reductions. It is therefore necessary that the continual design and development of low carbon ship designs and technologies starts now, to ensure availability for implementation as soon as possible. However, the drawbacks of design measures include: many can only be applied to new build ships; retrofits tend to have an investment cost and require docking time (loss of revenue); there is often uncertainty associated with the performance attributes of new technologies, systems and retrofit devices (including reliability in terms of safety, realisation of stated savings, and savings when installed in conjunction with other technologies and devices).

In comparison to design measures, most operational measures can be implemented readily by changes in operational procedures. They can be implemented for existing and new ships and can often provide reduction benefits at little or no investment cost: only some operational measures require the installation of hardware, software and or retrofits. One of the largest barriers to implementing operational measures is the lack of commitment towards making changes by each stakeholder who can influence the ship's operation.

Marginal Abatement Cost Curves (MACC) have been popular for demonstrating the reduction potential of different design and operational measures in terms of the cost per tonne of CO_2 that the measure could help advert, in millions of tonnes per year. An example is presented in Figure 2 (DNV 2010), but other MACC's can also be found in (IMO 2009b) and (Faber et al. 2011). The operational measures tend to be seen on the left due to the low or no investment and operational costs, whilst the design measures tend to be seen on the right.

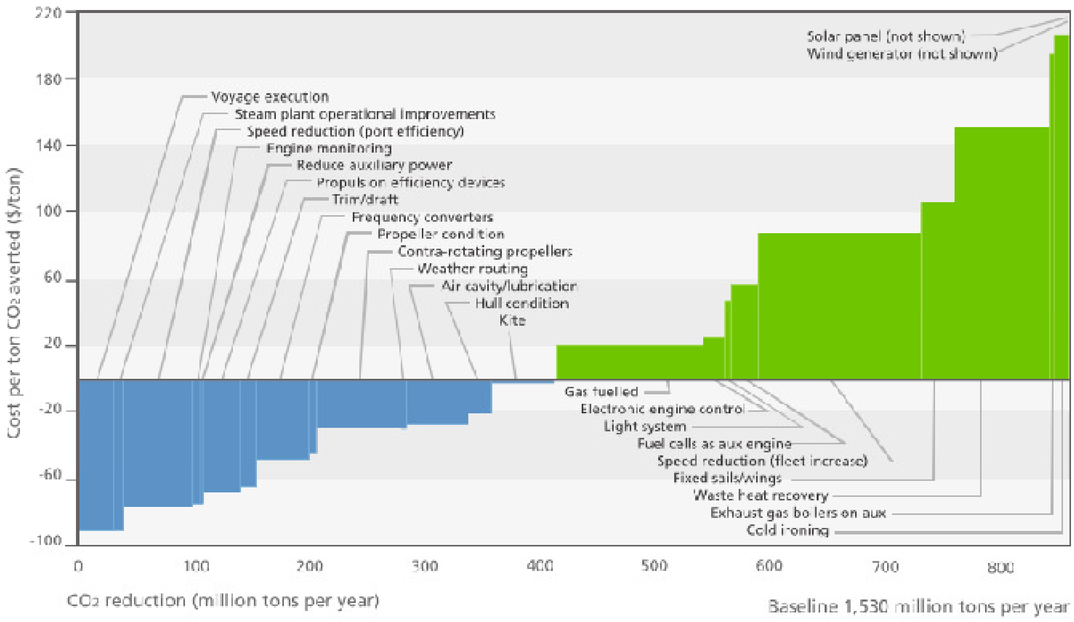

Figure 2: Average marginal CO_2 reduction cost per option – world shipping fleet in 2030 (DNV 2010)

To incentivise the implementation of both design and operational measures the IMO regulated the first maritime Energy Efficiency Regulations that entered into force on 1st January 2013. The regulations include, the Energy Efficiency Design Index (EEDI) focusing on design measures, and the Ship Energy Efficiency Management Plan (SEEMP) promoting energy efficient ship operation.

2.2.2 Maritime Energy Efficiency Regulations

The energy efficiency regulations were amended to The International Convention for the Prevention of Pollution from Ships, MARPOL, Annex VI, with the addition of a new Chapter 4. Compliance with the regulations is recognised by the certification and issue of an International Energy Efficiency (IEE) Certificate, provided by an authorised organisation or authority. The regulation amendments are summarised in Table 3 and full details can be found in (IMO 2012a).

Table 3: Summary of the Chapter 4 amended to MARPOL Annex VI

Chapter 4 is added to the end of Annex VI, including:	
Regulation 19	Application (which ships must comply with the energy efficiency regulations)
Regulation 20	Attained Energy Efficiency Design Index (Attained (EEDI)
Regulation 21	Required EEDI
Regulation 22	Ship Energy Efficiency Management Plan (SEEMP)
Regulation 23	Promotion of technical co-operation and transfer of technologies relating the other improvement of energy efficiency of ships
APPENDIX VIII	Form of International Energy Efficiency (IEE) Certificate
Regulation 25	Supplement to the International Energy Efficiency Certificate (IEE Certificate)

The regulations are applicable to all ships above 400 gross tonnage: although at present there are some ship types and propulsion types exempt from compliance, and there is the potential for a waiver to be agreed (IMO 2012a).

- **The Energy Efficiency Design Index (EEDI)**

The EEDI is a tool that can be used to calculate the amount of CO_2 emissions that a ship is expected to emit based on its’ design and installed machinery and technologies. The latest guidelines for the calculation of the EEDI can be found in (IMO 2014) with previous references and amendments in (IMO 2013c) and (IMO 2012b). The EEDI calculation is carried out before the ship goes to build (or before the start of a major conversions) and compliance is determined during a preliminary and final verification process (IMO 2010b). To comply with the regulation, the calculated EEDI must be less than the required EEDI: where the required EEDI is derived from reference curves developed for different ship types, based on deadweight: (IMO 2013b). The reference curves will become more stringent over time in line with the phased implementation plan for the EEDI, which should allow time for the development of the new technologies and design measures to reach maturity.

A limitation of the EEDI is that the calculation only takes into consideration one design point. However, the energy efficiency savings gained from design measures will vary significantly over the lifecycle of the ship due to operation away from the design point and conditions. The concern here is that the selected and implemented energy efficiency measures will reflect decisions to attain a good EEDI and thus may not provide the best energy efficiency solution for attaining savings in practice (i.e. during ship operation). Examples of optimising the implementation of design measures based on operational profiles are given in (de Kat et al. 2010) and (Greitsch et al. 2009).

(ABS 2013) and (Fathom 2013) review many of the design measures recommended for implementation in (Buhaug et al. 2009) and shown (predominantly to the right) in Figure 2. Considering practical design measure savings achieved and reported in the industry, (de Kat et al. 2010) reports that A.P. Møller Maersk, observed: that the most substantial savings per unit transported were achieved with an increase in average vessel size; 1 to 3 g/kWh were saved after the instalment of a closed loop auto tuning system for the main engine, controlling the injection timing; a 9% increase in fuel efficiency across the operating profile was achieved using Waste

Heat Recovery (WHR). (Armstrong 2013) reports that the Teekay experienced a 4% gain in propeller efficiency from the instalment of a Propeller Boss Cap Fin (PBCF), determined through model tests and validated by two Aframax tanker full scale test methods. (Knott & Buckingham 2011) reports case study investigations carried out for BMT for the implementation of design measures including; hull form modifications (namely the bulbous bow and aft end), micro-bubbles, sky sails, wing sails, flettner rotor, wind turbine, photo-voltaic solar panels, exhaust gas WHR, Organic Rankine Cycle (ORC).

- **The Ship Energy Efficiency Management Plan, SEEMP**

In contrast to the EEDI the aim of the SEEMP regulation is to increase the energy efficiency of ships whilst they are in operation; thus it is applicable to all ship, both new and existing. The SEEMP is a management plan that should be developed for each individual ship and integrated with existing company policy and management plans. It is meant to be a live document that is continually revised and developed though the cyclic process of planning, implementing, monitoring and evaluating. Guidelines for the construction of a SEEMP are found in (IMO 2012c).

The following quotes are taken from the SEEMP guidelines (IMO 2012c). Bulleted underneath are the key gaps within the industry that have not yet been addressed for wide spread operational energy efficiency improvements; although a few companies have been making proactive efforts. If not already discussed, justification of the highlighted gaps will be provided in the rest of this chapter:

'For effective and steady implementation of the adopted measures, raising awareness of and providing necessary training for personnel both on shore and on board are an important element.'

- **The next chapter section will discuss the development of a Maritime Education and Training (MET) course on energy efficiency for seafarers. It will be identified that there are several key points**

where further improvements could be made. Furthermore there are many methods for raising awareness out with a MET course, yet these are not widely considered in company strategies, policies and procedures.

'The energy efficiency of a ship should be monitored quantitatively. This should be done by an established method, preferably by an international standard.'

'… whatever measurement tools are used, continuous and consistent data collection is the foundation of monitoring.'

'To allow for meaningful and consistent monitoring, the monitoring system, including the procedures for collecting data and the assignment of responsible personnel, should be developed.'

- **At present there is no industry standardisation for data collection. Furthermore, the standardisation and consistency of data collection is not widely addressed on a company or even ship basis.**

'…In order to avoid unnecessary administrative burdens on ships' staff, monitoring should be carried out as far as possible by shore staff, utilizing data obtained from existing required records such as the official and engineering log-books and oil record books, etc. Additional data could be obtained as appropriate.'

- **In addition to data collection, there is no industry standard for quantifying, analysis and performing ship performance monitoring[7]. Furthermore, systems and the infrastructure to record, transfer (from ship to shore), collate data sets and analysis operational data are not widely established.**

'The purpose of goal setting is to serve as a signal which involved people should be conscious of, to create a good incentive for proper implementation, and then to

[7] *The next section will identify that the EEOI is currently the recommended method for performance monitoring but is not considered sufficient, an EU regulation for Monitoring Verification and Reporting (MRV) in the process of being enforced, and ISO standard is under development but the content is not yet known.*

increase commitment to the improvement of energy efficiency. … Whatever the goal is, the goal should be measurable and easy to understand.'

- **Goal setting is hindered by the lack of awareness about ship performance and operating profiles and by methods to quantify goal measurement, i.e. ship performance monitoring.**

Similar to the EEDI, an advantage of the SEEMP is that it is non-prescriptive so that the most applicable and viable measures specific to the company and ship can be selected: recognising that the operational requirements for each ship vary. A list of operational measures to be considered for implementation are given in the second half of the SEEMP guidelines (IMO 2012c); including several of the measures shown on the left in Figure 2 and discussed (Buhaug et al. 2009). It is noted that whilst the operational measure are listed and briefly described in the SEEMP, no explanation regarding how to practically achieve their implementation is given.

Again (de Kat et al. 2010) reports savings that A.P. Møller Maersk's container fleet observed from the implementation of operational measures. These include a 1% of total fuel consumption using an optimum trim program, and 70 – 80 kW savings by performing maintenance and optimisation of the ventilation system. Additional implemented measures include; engine tuning for the operating profile, turbocharger re-matching (with the installation of nozzles and fuel atomizers for lower load operation), and turbo charger cut-out systems. (Armstrong 2013) also reports a validated 1% saving from trim optimisation, trialled with Teekay Aframax tankers and for the ships on which the concept worked. Furthermore, (Armstrong 2013) reports; a 12% reduction in fuel efficiency (miles per metric tonne of fuel) between 2005 and 2010 from combined optimisation efforts that required minimal investment; a 2.5 MT/day saving in one year (and greater after that year) by optimising cargo heating plans; up to 3% saving in fuel consumption (neglecting time savings) by implementing route optimisation; a potential 5% saving from optimising the Controllable Pitch Propeller (CPP) program; a 2.5 MT/day fuel saving following a 10 year dry dock including a full blast for sister ships using a higher grade Self Polishing Copolymer (SPC) coating.

A key emphasis made in (de Kat et al. 2010) is that consideration of the operational profile is a priority for achieving successful operational improvements. However, the analysis of operating profiles is not common practice industry wide. (de Kat et al. 2010) discusses the need to update existing procedures in light of changes in operational practices: for example, an engine inspection policy, supported by experiences gained and visual inspections, was developed due to the maintenance requirements at low load operation. Both (de Kat et al. 2010) and (Armstrong 2013) emphasise the impacts and importance of organisational structures, common goals, and providing useful feedback to different stakeholders in the operational structure: 'Feedback is the single most effective measure that can sustain and increase the momentum of an initiative' (Armstrong 2013). (de Kat et al. 2010) reports the benefit of setting targets for 6 of their ship's crew to improve the operation of the installed Waste Heat Recovery (WHR) systems: current practices were considered to only achieve 55% to 95% of the benchmark but after three months by using and receiving feedback from the developed performance model, all six vessels improved their WHR efficiency to over 90% of the benchmark. Some vessels surpassed the target by finding 'innovative ways to produce more WHR than our models originally predicted'.

- **The expected impact of the EEDI and SEEMP regulations**

(Bazari & Longva 2011) reports an assessment of the CO_2 savings that could be achieved with the mandate of the EEDI and SEEMP alone. The assessment was made in light of different growth, regulation uptake, fuel price and wavier scenarios. It was shown that the SEEMP is likely to provide greater savings in the short to medium term and then remain at a constant rate once the maximum energy efficient operation has been established for the ship(s). At this point the EEDI will provide increased savings as new technologies are developed and become available on the market once tried and tested for reliability. A conclusion of the study was that the EEDI and SEEMP will provide significant CO_2 savings compared to the Business As Usual scenarios, although not enough to meet CO_2 reduction targets with world trade growth as predicted. It can therefore be expected that more, and more stringent, regulations and measures will be implemented in the future to meet international CO_2 emission reduction targets.

2.2.3 Maritime Regulatory and Industry Energy Efficiency Initiatives

- **The Energy Efficiency Operational Indicator, EEOI**

Within the SEEMP the Energy Efficiency Operational Indicator (EEOI) is recommended as the method for quantifying energy efficiency performance. However, its calculation remains voluntary along with the publication of results. The EEOI, similar to the EEDI, demonstrates the amount CO_2 emitted per tonne of cargo transported per nautical mile, however it is based on the input of operational data over time. The calculation of an average rolling EEOI is detailed in the guidelines (IMO 2009a) but the time period over which the rolling average should be calculated is not specified. This leaves room for interpretation. It has been observed that the EEOI is often used for higher level performance assessment, with a monthly or yearly average presented for a fleet of ships.

The EEOI is dependent on the supply and demand for ships in the sense that operational speed has a strong influence on the calculated value. Whilst the EEOI accurately reflects that operational measures such as slow steaming are beneficial for reducing emissions, when demand increases, operating speeds will most likely increase, therefore so too will the EEOI. As the EEOI is presented as an efficiency indicator an increase over time may not appear commercially attractive to customers at first glance, regardless of the cause of the increase. This is one of the disadvantages hindering its application. A further concern is that the EEOI calculation (and baselines if they are developed) could favour certain ship types, sizes and operational profiles, whilst unfairly disadvantaging others in direct comparison.

▪ Maritime Education and Training (MET)

It is stated within the SEEMP regulation that education and training is required. In light of the regulations and shipping energy efficiency developments, many classification societies and organisations have developed courses to provide awareness and knowledge primarily to fleet management, technical ship management and business management stakeholders. These courses tend to focus on the learning requirements applicable to the job role objectives of the stakeholders listed. Therefore, to address this issue further and for seafarers, the MEPC commissioned the World Maritime University (WMU) to develop a model course[8] on energy efficiency.

The initial work plan for the model course on energy efficiency was set out at the 60th meeting of the MEPC (IMO 2010a). It was specified that the course should be a one-week course, 30 hours, and 'will provide general background on the climate change issue and IMO's related work'. Each course topic for inclusion was highlighted; in line with the recommended best practices within the SEEMP. A draft of the model course was published (IMO 2011a) before a final draft was presented to the validation group at the 65th meeting of the MEPC (IMO 2013a). The validation group's comments included: the 5 day course was too long; the EEDI and EEOI should be thoroughly discussed and calculated; full mission engine-room simulator

[8] *The IMO model courses typically take on a standard format (IMO n.d.) and are predominantly focused on addressing the MET requirements specified in the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) (IMO 2010c).*

exercises should be complemented with other practical exercises. Amendments were made to the model course as considered appropriate.

In an independent paper (Baldauf et al. 2013) reviews of the overall structure and content of the draft model course; with the (IMO 2011a) course version referenced. It was commented that the course provides a 'starting point and should be further developed with experience gained by shipping companies and to support the distribution of good and innovative practices to implement sustainable energy efficient operation of ship and shipping companies.' (Baldauf et al. 2013) continues to highlight that the focus of the course is on enabling the distribution of knowledge about energy efficient best practices.

In agreement with (Baldauf et al. 2013) it is considered that there is additional knowledge that can be included based on the continual development and identification of best practices in the industry; i.e. as they are tried, tested and reported. Best practice examples based on collated experiences should be used to develop and populate further examples, exercises and case study scenarios to help support the delivery of the course content and key messages. It was also considered that further emphasis could be applied to: the impacts of operational structures and job role responsibilities on achieving energy efficiency improvements and the human factor skills required for achieving effective, integrated operational energy efficiency.

To trial the IMO model course, a train-the-trainer course was held from 18 to 22 February 2013, (WMU n.d.). The IMO model course is now available for purchase and participants who have completed all five sections of the course can receive recognition for their additional qualifications: 'participants who have attended all of these seminars will be awarded a special GL Academy certificate. It will certify that he/she has attended a comprehensive classroom based training, which covers all topics recommended in the model course.' (DNV.GL n.d.). The five sections of the course include: application & implementation of a SEEMP; hull & propulsion maintenance; voyage optimisation; optimised ship handling; energy efficient fleet management.

▪ Monitoring Reporting and Verification

A significant focus related to ship energy efficiency has been the development of a Monitoring Reporting and Verification (MRV) standard to quantify the carbon emissions emit by each ship in the world fleet. The largest barriers to the development of a MRV have been the diversity, inconsistency and uncertainties in the methods used to measure, collect and report operational data.

Whilst no MRV proposal has currently been accepted by the IMO, the European Union (EU) has put forward a proposal that was adopted at the EU environmental council on the 17th December 2014. If the EU parliament votes on the agreed text in the spring of 2015, the EU regulation will enter into force on the 1st July 2015. Deadlines for preparation, submission and implementation of company MRV plans will follow at intermediate dates, with the first reporting commencing in 2018. The regulation will apply to ships over 5000 GT that are operating to, from and between EU ports. The content of the EU proposal can be found (EU 2009). If a differing MRV proposal is adopted internationally by the IMO in the future, the EU MRV regulations should then be amended correspond.

The MRV proposal, states that carbon emissions should be calculated based on monitored fuel consumption or emission directly. The methods for fuel measurement include: bunker delivery notes, ship fuel tank monitoring and flow meters. The use of any one or a combination of these methods (if approved) allows flexibility for companies to utilise their best existing records without the mandate to install additional sensors: such as fuel flow meters. In addition to fuel consumption (or direct emissions), several additional parameters must also be recorded on a voyage basis, including but not limited to: departure and arrival ports and dates; cargo transported; distance travelled, transport work. Total summary reports should be produced by the company and as of 2019 annual emission reports should be submitted to the EU Commission and authorities of the flag states for verification.

▪ Market Based Measures

Market Based Measures (MBM's) relate to the use of a financial incentive placed on the emission of GHG's to encourage improvements. International discussion on legislation for MBMs was somewhat paused over the past years as it was considered that the MRV initiative was first required to provide a verified carbon emission quantification, on which an MBM could be applied. For the details, discussions and further references for the proposed MBM measures, refer to *(IMO n.d.)*.

▪ Industry Tools And Initiatives

Independent of regulatory bodies, many groups and organisations have implemented a range of environmental performance initiatives to incentivise energy efficiency. Some of these initiatives do not include carbon emissions specifically, or identified indices or indicators: instead they focus on recognising environmental performance in other ways. (Svensson & Andersson 2011) carried out an inventory and evaluation of the 47 different initiative systems identified by the European Maritime Safety Agency (EMSA 2005). The 10 initiative discussed at further length in (Svensson & Andersson 2011) include: The Blue Angel; Clean Cargo Working Group (CCWG): Performance Metrics Tool; Clean Shipping Index (CSI); Energy Efficiency Operational Indicator (EEOI); Environmental Ship Index (ESI); Green Award; Green Marine Environmental Program; Rightship CO_2 Rating and Environmental Rating; RINA Green Plus; Triple-E.

▪ Existing Management Plans and International Standards, ISO

British (BS), European (EN) and International (ISO) standards, commonly known as ISO standards, are a set of management plans that a company can choose to adopt. Specifically, ISO 14001:2004 is the standard for Environmental Management Systems, and ISO 50001:2011 is the standard for Energy Management Systems. Both these standards share similarities with the SEEMP in that it they are structured on a Plan, Do (Implement), Check (Monitor) and Act (Continual improvement) methodology. However the ISO standards tend to focus on the management framework and do not include specific environmental performance criteria. There is therefore an added benefit to integrating the SEEMP to further enhance existing policies. Integration may also be carried out in parallel with existing ship safety management plans (such as the International Safety Management (ISM) Plan) or with any existing sustainability, environmental and energy efficiency plans.

In addition to mentioned standards, several ISO standards are under development for maritime environment protection, including the following:

- ISO 19030-2 Ships and marine technology - Measurement of changes in hull and propeller performance Part 2: Enabling performance based contracts and intercompany reporting
- ISO 19030-3 Ships and marine technology - Measurement of changes in hull and propeller performance Part 3: Enabling intra-company reporting
- ISO 19030-1 Ships and marine technology - Measurement of changes in hull and propeller performance Part 1: General principles
- ISO 20082 Ships and marine technology - Marine environment protection - Monitoring system for ship energy efficiency
- ISO 13073-3 Ships and marine technology - Risk assessment on anti-fouling systems on ships Part 3: Human health risk assessment of biocidally active

substances in anti-fouling paints on ships during the application and removal process

ISO 19030 is of particular relevance to this research as it is concerned with the measuring ship performance related to hull and propeller surface degradation and fouling. However, to date there is little information available detailing the content of the standard. However, it was reported by (MaritneInsight 2014) that the standard is expected to account for monitoring techniques using different levels of data, from noon reports to continuous monitoring data sets.

2.3 Operational Structures and Practices

The previous section introduced the regulatory and industry initiative to incentivise energy efficient shipping. The design and operational measures to help achieve energy efficiency were also identified; where many operational measures were highlighted as cost effective. So why have these operational measure not already been implemented in the industry? This section examines the influences of organisational structures, stakeholder networks and human factor issues that create barriers to implementation. Practices that could help address certain barriers are highlighted for consideration in a framework for improving ship operational energy efficiency; such as the framework developed and presented in Chapter 5

2.3.1 Operational Structures

Commercial shipping relies on the business driven demand to transport commodities, i.e. the cargo. This broadly dictates the type of ship that is utilised, the generalised route taken, and the demands for the safe and efficient passage of crew and cargo.

Shipping transport demand is influenced by world political, economic and security situations, as well as the availability or scarcity of raw materials and desired commodities. Each of these factors change over time; particularly with changes in the state of country development and population growth. A detailed explanation of how these factors have influenced maritime transport is given in: (Stopford 2007) for past trends; the annual United Nations Conference On Trade And Development reports (UNCTAD 2011), (UNCTAD 2012), (UNCTAD 2013) and (UNCTAD 2014) for the recent past trends; (Fang et al. 2013) and (Argyros et al. 2014) for future trends.

Ship operation is also dictated by the type of service (i.e. tramp or liner) and charter (e.g. bare boat, voyage or time charter, or within a pool) that the ship operates on.

The differences between the services and charters are described in (Stopford 2007) and highlighted differences include;

- Operating profiles: e.g. liner services tend to operate at a higher speeds and on a regular, scheduled route.
- The flexibility in different services: e.g. some ships transporting minor bulks must provide a versatile service to accommodate for a range of possible bulk cargos.

Relating the above to the opportunities for energy efficiency; operational flexibility may allow a ship to be easily adapted to energy efficient operations in terms of established ingenuity, versatility and efficient decision making practices. However, it may be easier to fine tune the efficiency of a ship with an operational profile that does not vary as much, and which does not have to be so versatile.

The type of service and charter is important in terms of the stakeholders responsible for the operational costs; particularly fuel and maintenance (e.g. hull cleaning) costs. For example, it is not necessarily the person who invests in an energy efficient operational measure that will gain from the fuel cost saving, thus why should they provide the time and or cost effort to implement the change. This is known as a split incentive. (Rehmatulla & Smith 2012) discusses split incentives for a ship under time charter, highlighting several split incentive scenarios.

Whilst addressing split incentives directly is not within the scope of research; it is highlighted that good communication, understanding and negotiations, between the stakeholders involved with the split incentive[9] can help to assist in the achievement of best energy efficient operational decisions. Awareness and a comprehensive knowledge of the best operational energy efficient practices should therefore also be attained by these stakeholders.

[9] *i.e. from the internal stakeholders: the commercial and technical management departments, and the ship owner*

2.3.2 Stakeholder Networks

External stakeholders are considered to be those that indirectly influence ship operations and hence are considered outwith the focus of the research presented. However, it is important to identify and recognise the external stakeholders as they influence the drivers towards energy efficiency and often define the operational boundaries in which the internal stakeholders have to operate (e.g. the laytime (time allowed for the voyage)). The internal stakeholders are considered to be those who have a direct influence over ship operations: namely onshore ship management and seafarers. These stakeholders fall within the scope of this research.

(Österman et al. 2009) identifies a high level breakdown of external stakeholders throughout the life cycle of the ship; each of which can be relate to influences over operational energy efficiency:

- Third Party Public and Media influence the energy efficiency of shipping by raising awareness and demand for energy efficiency amongst customers: inclusive of the final end consumer (the public) and those at each intermediate step along the supply chain, up to and including the cargo purchaser, owner and charter. (Marks & Spencer n.d.) is an example of an external stakeholder that places a high important on a low carbon supply chain: 'the only major retailer with carbon neutral global operations'.
- Legislators (e.g. the IMO, EU) have a significant impact in terms of adopting new regulations to encourage energy efficiency improvements; such as the EEDI and SEEMP.
- Classification societies support regulations with research, survey and certification.
- Insurance companies can influence the investment in technologies or operations by the clauses they include in their contracts and fees that they charge. These influences are broadly similar imposed by banks (the financers)

who decide whether or not to lend the finance to invest in a ship or retrofit project.

- The ship breaker does not influence the energy efficiency of the ship design or operation, however they should be considered within the full energy efficiency and carbon foot print life cycle of a ship.
- Ship builders often dictate the design of a ship related to the typical hull form design dependent on previous builds and experience, and yard machinery, facilities and capabilities. The most recent focus on energy efficiency (i.e. the EEDI) has stimulated improved practices in ship design optimisation.
- Brokers and sea transport buyers influence the operation of a ship on a voyage basis by communicating and influencing the selection (fixing) of a ship to transport the cargo from one defined port to another, within the required time period.

In addition to the above mentioned, there are many additional stakeholders that can influence ship operations dependent on the characteristics of the supply chain. (Stopford 2007) identifies the stages in a generic logistic chain, for example: producer > storage > land transport > storage > loading (ship) > discharging (ship) > storage >land transport > storage > importer. If there is a delay or problem at any one of these stages (perhaps due to uncontrollable events, poor communication and organisation, or poor completion of the supply chain task) this can lead to impacts on the ship's operation: thus creating operational boundaries for the internal stakeholders to work within.

2.3.3 Implementation Barriers and Enablers

A number of studies have been carried out to investigate the implementation barriers to energy efficient shipping. (Rehmatulla et al. 2013) draws similarities between energy efficiency and those previously identified for economic efficiency. Using a

MACC curve (such as that presented in Figure 2) (Rehmatulla et al. 2013) highlights a 30% unrealised cost and energy efficiency gap, which he then relates to the following market barriers:

Modelling artefacts – difference in saving potentials of economist vs. technologists
Rational behaviour – non market failures e.g. cost of capital, heterogeneity, etc.
Barriers – behavioural, organisational and economic market failures
(Rehmatulla et al. 2013)

(Rehmatulla & Smith 2012) report a survey carried out to investigate the above listed barriers. The survey was first distributed at the end of 2011 with a target group of global shipping companies owning more than five ships, consisting of; ship-owners; ship owner-operators; ship management companies; shipping division major charterers/cargo owners; in the wet bulk, dry bulk and container sectors.

It was identified that fuel consumption monitoring is believed to be the operational measure with the highest potential for reducing fuel consumption. Raising crew awareness and energy efficiency training was identified to have the 6th most potential out of 10 measures.

It was identified that a larger proportion of small companies (≈92% compared to ≈72 and 62%) have already taken up fuel consumption monitoring; (Rehmatulla & Smith 2012) discusses that this could be indicative of the investment cost being smaller and more manageable for smaller companies than larger ones. [Percentages are given as share of implementation per measure]. The container shipping sector[10] had taken up fuel consumption monitoring more than the dry and then wet bulk sectors. Ship management companies (≈85%) have taken it up more than ship owner-operators

[10] *Only 4 participants responded from the container shipping sector and thus the result could include bias.*

(≈82), ship owners (≈65%) and charters[11] (≈45%). It is interesting to note that some charters are also specifying fuel consumption monitoring procedures for implementation onboard. In some scenarios this could be in addition to the procedures specified by the other company types mentioned, thus increasing the workload of seafarers to complete and maintain all systems required.

Ship management companies were shown to have implemented raising crew awareness and energy efficiency training the most (≈65%), followed by ship owner-operators (≈61%) and then ship owners (≈41%): however it was not shown to be implemented by charters. It was implemented more in the container shipping sector[10] and then in the wet and dry bulk sectors. Medium sized companies were shown to have implemented raising crew awareness the most (≈65% compared to 45 and 50%).

The survey also investigated what were considered to be the most important barriers to implementing the measures. In order of most importance, these were: lack of reliable information and cost and savings; difficult to implement under some types of charter; lack of direct control over operations; uncertain/long payback; not allowed due to charter party clauses; other; savings cannot be fully recouped from the investment; additional costs e.g. transactional, contractual; lack of access to capital. Many of the mentioned (i.e. those relating to charters and operations) emphasis the need for the commitment of internal and external stakeholders to work towards energy efficiency improvements. The operational boundaries in which the internal stakeholders have to work within are hence also highlighted. The reliability of information on savings could be improved with a standardised method to monitor ship performance, providing the method is suitable for detecting the resolution of savings expected.

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[11] *Only 2 participants responded for charterer, and thus the result could include bias.*

(Poulsen 2011) also examines the barriers and enablers to operational energy efficiency, highlighting the complexity of the stakeholder network within the shipping industry and the interactions and communications required. Actions by regulatory authorities and clear incentivises are identified as enablers toward energy efficient operation. Agency problems are highlighted as barriers and the conflicting incentives between the commercial and technical management departments are discussed. The paper also emphasises the importance of transparent policies and incentive structures between stakeholders.

Similarly, (Johnson & Andersson 2011) identifies that the transparency of personnels' responsibilities and actions, and the distribution of information about energy efficiency performance, as enablers. It is stressed that this is even more important in the absence of an established monitoring procedure. (Johnson & Andersson 2011) reports interview findings where '… interviewees that worked or were working in organisations where they felt that they were discouraged to work on energy efficiency'. This highlights the need to consider existing operational procedures and policies to avoid this from happening. (Johnson & Andersson 2011) recommended that standard operating procedures should be used as guidance for setting up energy efficiency best practices. This could include taking guidance from ISO 50001, the SEEMP, or safety management systems such as the Tanker Management Self Assessment (TMSA), (OCIMF 2008).

Regarding the SEEMP, (Bazari & Longva, 2011) conclude that two drivers towards effective use of the SEEMP are: 'More vigorous awareness building and cultural change on board ships.' and 'more collaboration between industry stakeholders and a solution to issue of split-incentives.'

2.3.4 Human Factors

(Bielić 2009) discusses different company organisational structures based on the 1992 Human Resource Management IMO model course; identifying both hierarchical and matrix schemes and how they impact on working atmosphere teamwork. (Koutsoukou 2008) also reviews different organisational structures discussing how they have changed over time. The structures include: unitary functional, multidivisional, matrix network and hybrid organisational structures. It is highlighted in (Koutsoukou 2008) that the nature of shipping is inherently multinational and multidivisional: often with offices in many different countries, with different departments within one office and the ship in yet another location. These are some of the reasons why organisational structures and company cultures play such a significant role in influencing the effectiveness of ship operations.

Language barriers, cultural differences, and operation in different geographical locations can lead to feelings of separation and detachment; where improved operations are more likely to occur when teamwork is high, common objectives are recognised, and the sense of individual value, recognition and empowerment are felt by personnel. This is therefore an important element to consider for improving the energy efficiency of ship operations.

(Lolos 2008) examines the relationships between ship management and onboard management teams in terms of; communication, operational support, decision making authority, conflict, misunderstandings, cultural differences, and linguistic difference. It was concluded that the following are important for safe operations: good communication; efficient flow of information at all levels; frequent visits and developing trust to build up relationships; training to develop both hard and soft skills. Whilst aimed at improving safety, these conclusions also hold true for the achievement of energy efficient ship operations.

(Koutsoukou 2008) also examined the relationships between different mini-teams within a company, highlighting that vessel managers, technical managers and the superintendents are key personnel where ‘by combining all their skills and expertise in the best way they will substantially contribute to the increase of the revenues of the company.’: again also transferable to energy efficient operations. Furthermore it was concluded that working relationships should be strengthened, particularly with face-to-face visits, information sharing and creating ‘the feelings of belonging to the company as a whole’.

Human factor management concepts that can be considered for the improvement of energy efficient ship operations included the following:

- **Human resource management**

Human resource management is closely linked with business strategy, where each personnel member should have defined job roles and responsibilities. A personnel member should be matched to a job role that complements their skills.

- **Accountability**

Closely related to human resource management, accountability is identifying who is responsible for what tasks and/or performance. These responsibilities should be made very clear to avoid misunderstandings. Poor accountability management can lead to errors and induced stress if placed to highly or on the wrong personnel member. On the opposite end of the scale boredom and hence detachment and lack of motivation could occur if accountability is placed too loosely. A particular consideration within the shipping industry is related to automation. This can reduce the occurrence of human errors but can also remove some accountability from the responsible personnel member.

- **Behavioural management**

Behavioural management is related to reducing undesirable behaviour. For energy efficiency, this can be considered as the creation of an energy efficient culture.

Whilst developing this culture, the education of skills to promote the same culture to others is valuable; including good leadership and teamwork skills.

- **Personnel engagement**

Personnel engagement is extremely important for the generation of individual efforts as well as teamwork: both essential for the achievement of energy efficient ship operation. Personnel engagement is related to how motivated a personnel member is towards their job role tasks and it can be encouraged via each of the previously described factors. Engagement can also be generated via recognition of common goals, receiving feedback, and receiving recognition of good performance: each of which can be supported by the utilisation of a ship operational performance monitoring system. Engagement can be difficult within the shipping industry, particularly where the crew members only operate on a specific ship for a short time period and with different crewing teams: making it harder to form an attachment and pride to the working environment and build teamwork relationships. As engagement is important for motivation, and where motivation is essential for the implementation of best energy efficient practices, it is highlighted as an important point to consider in an framework to improve energy efficient shipping.

For references related to the factors mentioned above see: (Schuler & Dowling 1993), (Petrovici 2014), (Gist 1987), (Koutsoukou 2008),(Lolos 2008) (Abuzeinab & Arif 2014), (Maak 2007) and (Gao & Zhang 2006).

A study by (Köpke & Catarino 2012) identified that crew awareness of fuel oil consumption optimisation can be a significant enabler towards its achievement. A procedure developed by Germanischer Lloyd together with its subsidiary FutureShip was used to identify the cost efficiency of a ship. Savings were identified before and after the crew underwent a 2 day onboard expert group workshop where they discussed structured ship systems and practical operational measures for implementation. For two case study ships the fuel oil consumption savings achieved by a reduction in fuel consumption and an increase in the cargo transported were 3%

and 7%, corresponded to a decrease in the EEOI by 15% and 22%. A follow up study 9 months after the workshop identified that trim optimisation, the utilisation of improved cargo weight information flow and awareness of ship speed were still actively being used to achieve savings. The conclusion of the study is that there are savings to be realised by increasing seafarer awareness about energy efficiency and its implementation.

2.4 Operational Performance Prediction and Monitoring

Section 2.2 made it apparent that there is a need to monitor and quantify ship performance with relation to existing and future maritime regulations; namely the SEEMP and MRV. Section 2.3 identified that fuel consumption monitoring is considered to be one of the operational measures that has the highest potential for enabling carbon emission reductions. Methods for ship performance quantification, feedback and recognition were identified to be significant for improving human factors related to energy efficient ship operation. This section reviews existing ship performance prediction and monitoring methods to identify where improvements can be made to provide a method that can be applied widely within the shipping industry to enable fleet wide carbon emission reductions.

2.4.1 Defining Ship Performance

A SOPM system typically needs to be supported by a Ship Operational Performance Prediction (SOPP) model, neither of which are new concepts or research topics. The most common SOPM methods use a SOPP model to predict ship performance in given conditions, and then compare this with the recorded performance derived from data recorded in an operational dataset. The following parameters are typically used to indicate ship performance: fuel consumption, propulsion efficiency, power and resistance. The amount of carbon emission emit is another performance parameter of interest to this research. Combinations of different parameters can be used to express performance relationships, such as: EEOI, speed loss, power increase, transport efficiency. The parameters or relationships selected to report ship performance are often referred to as the Key Performance Indicators (KPI's), where each KPI's must be selected carefully to suit the performance feedback information relevant to each personnel member and their job role.

2.4.2 Operational Datasets

To perform SOPM an operational dataset is required. The datasets available from shipping companies typically fall under two categories: Ship Reports (SR's)(often referred to as Noon Reports) or Continuous Monitoring (CM) reports. At present there is no standardisation for the recording of data variables in either of these datasets. Therefore their content depends on individual company procedures and the sensor and measurement devices installed onboard. This can vary from ship to ship even within the same company. Furthermore, the observation, measurement and the final data values recorded differ with the subjectivity and procedure variations introduced by different individuals making the recordings. The lack of standardisation is perhaps somewhat surprising considering the early recognition of the benefits that it could provided for SOPM (Bonebakker 1954). (Bonebakker 1954) commented that 'it should become a tradition to collect records systematically at regular times; they should be complete, and taken simultaneously': this is not so different from the recommendation statements within the SEEMP regarding consistent data collection, previously identified in this chapter.

The following bullet points describe some of the generic attributes of SR and CM datasets. A more detailed description is presented later in this thesis (Chapter 7). It should also be noted that complementary external datasets, in addition to SR's and CM reports, may also be utilised by a company if commissioned; such as weather data.

- **Ship Report datasets**

When sailing at sea Ship Reports (SR's) are typically collected every day at noon, hence, they often known as Noon Reports. The term "Ship Reports" is used in this thesis, as it was identified to the author (by different personnel working in shipping companies) that the reports are also recorded on arrival and departure of port, or for a change in operations, dependent on the company's reporting procedures. SR's are filled out by the deck Officer On Watch (OoW) and are typically a summary of the average values recorded in the deck and engine room logs. The deck and engine room logs are recorded by the OoW on the bridge and in engine room retrospectively, and they are completed four times a day with the change in watch. (Carlton 2012) provides a list of the typical variables included in the deck and engine log: it can be noted that not all the recorded variables are transferred to the SR. The logs are often still recorded by hand and kept as paper records but nowadays most SR's are stored electronically. However, it should be noted that the electronic format is often not one where individual records can easily be collated for subsequent analysis (i.e. each record remains as an individual email or attachment within an email). SR's are not widely used for the analysis of ship technical performance as their collection purpose has primarily been for commercial reasons: a review of ship logs is more commonly requested if a performance problem is identified. The SR's therefore reflect commercial reporting requirements and uncertainties, rather than technical performance. Nevertheless, the primary benefits of SR's is that they are made by all ships and thus offer the most widely available source of operational data that has been (i.e. provides a time history) and continues to be collected.

A SR record typically always contain the following data variables: Date/time, location, heading, report type, passage type, Beaufort Number, wind direction, distance, speed over ground, fuel consumption of the main engine, auxiliary engine and boilers (including for different fuel types), and comments. SR records sometimes contain: average draft at midship, forward draft, aft draft, RPM, speed through water, shaft (or brake) power, sea temperature, air temperature. Additional variables, which are sometimes included, by can be calculated from the already listed variables; for example trim and slip. The SR data variables are usually based on observations, standard installed measurement sensors and devices, or calculated from other measured variables. They are generally considered a low quality data set due to: low collection frequency; a mix of averaged and instantaneous values; the used methods measurements and observations.

- **Continuous Monitoring datasets**

Continuous Monitoring (CM) reports are typically collected at a higher frequency than SR's and by automated data capture using installed sensors and measurement devices. They are generally considered to be a higher quality dataset that provides information about ship performance with increased accuracy; although the quality varies depending on the variables included and how they are measured. For instance, a data set may include part CM data whilst the other part is still obtained from SR's. The installation cost of sensors and measurement devices is the main deterrent from collecting CM datasets. The frequency of data collection could vary from several times a day, to every hour, minute, or few seconds. Again it is typically the cost that dictates the frequency of data collection and transfer from ship to onshore for performance analysis. The data variables contained in CM data sets may replace or be in addition to many of the data variables listed for SR's, and may include: speed through water; wind, wave, swell and current force and direction and or wave height; rudder angle; ship roll, pitch and yaw motions.

There are several companies actively leading the way in the shipping industry with the implementation of in-house developed or commercially available systems for improved data capture, analysis, and SOPM. However, at present these companies only represent a small proportion of the world fleet that have a combination of: cash flow and or capital; technology infrastructure; knowledge and skills resource; motivation towards the implementation. Therefore most companies owning and operating the world fleet do not collect CM datasets or data containing more than just the 'typically found in SR's' list of variable previously given. Furthermore, it is not likely that the companies owning and operating the world fleet will decide to invest in the additional sensors and systems to improve data and performance monitoring accuracy due to a lack of guaranteed savings and additional barriers such as split incentives (discussed in Sub-section 2.3.3). It is therefore considered that without regulatory incentive the latest advances in SOPM will not become widely used within the industry in the near future. Yet efforts to support the achievement of carbon emission reductions are needed now.

2.4.3 Resistance Performance Prediction

Having identified the datasets available for SOPM, the methods for SOPP are considered in the following sub-sections. Early ship performance prediction methods stemmed from the desire to inform the ship design process, where the prediction of resistance in calm water took the initial focus for estimating the power requirements of a designed ship. During the design process a service margin is added to the calm water resistance prediction accounting for the additional resistance due to operating in average environmental conditions, and with hull and propeller surface degradation and fouling (ITTC 2008). Many of the resistance prediction methods established are still widely used; where the separation of total resistance can be considered in components and the coefficient of each component can be evaluated separately. This idea was first presented by William Froude who also carried out specific research on the frictional resistance coefficient (C_F) by changing the roughness and length of flat planks. (Duckworth et al. 1955). The use of model tests and extrapolation methods became a popular method for predicting ship resistance. Improving the accuracy of model tests, extrapolation to full scale and understanding the uncertainties is still an area of continual evaluation and development (Holtrop 2001), (Bose & Molloy 2009), (ITTC 2011b) & (Kamal et al. 2013). A summary of key calm water resistance research developments are summarised in (SNAME 1998), (Carlton 2012) & (Molland et al. 2011).

With model test experiments increasing, several empirical series were developed based on their results to provide a performance prediction for similar ship forms and propulsion types. The most common and well established standard series for single screw merchant ships include: Series 60; British Ship Research Association (BSRA) Series; Statens Skeppsprovingansalt (SSPA) Series; Maritime Administration US

(MADRAD) Series: (Molland et al. 2011). The advantages of using one series over another is predominantly based on the ship form and expected operating profile (e.g. service speed range) of the similar ship for which the performance prediction is desired.

Similar to the data series, a well known and widely used empirical method for ship resistance and powering prediction is the Holtrop and Mennen method. [This method was used for the development of the SOPP model presented in Chapter 9 and therefore specific aspects of the method are identified here and later in this chapter.] The (Holtrop & Mennen 1982) method was produced using a statistical regression analysis of model-scale and full-scale data. Subsequent to the Holtrop and Mennen's 1982 publication, the method was developed further by Holtrop to provide a better estimate for high speed craft with Froude Numbers above 0.5, and for the influence of propeller cavitation and partial propeller submergence (Holtrop 1984). Both methods can be applied to a wide range of ship types providing that the ship's form can be depicted well by its principal dimensions and form coefficients. Despite changes in ship design over the years (more so for higher speed ships), modern hull forms are still considered to be well represented by their hull form parameters (particularly fuller ships, such as tankers) and thus both prediction methods are still widely used today.

A wide range of numerical methods can be used to predict ship resistance. Numerical methods offer the opportunity to compute resistance without requiring a large dataset from model or full scale tests. With the advent of, and with increasing computational power, the use of numerical methods for Computational Fluid Dynamics (CFD) has grown significantly: including the application of Reynolds Average Navier-Stokes equations (RANS). These methods offer the opportunity to examine individual ship and propulsion performance at a desired level of detail in different flow regimes. However their most significant disadvantage is that they can become complex, computationally intensive and require expert knowledge. Thus whilst they offer great opportunities for use in ship design, optimisation, and specific operational performance scenario evaluations, their application to practical SOPP and SOPM, as considered in this research, is limited at present. A full review of developed methods for resistance prediction can be found in the International Towing Tank Conference (ITTC) Resistance Committee Reports, (ITTC, 2011a: and previous reports).

In extension of calm water resistance and powering prediction, components of additional resistance contribute greatly to a ship's operational performance. The quantification of the components of additional resistance is not just of design and research interest, but also of commercial shipping, where the prediction of following is important: fuel consumption and hence fuel costs; speed loss in a sea way which can result in the late delivery of cargo; safety related aspects due to structural loading, machinery operating envelopes, crew and cargo safety and comfort. The causes of added resistance above calm water resistance that are considered have the greatest impact include:

- Waves conditions (significant wave height, mean period, direction, spectrum)
- Wind conditions(speed and direction)
- Hull and Propeller surface roughness (fouling and surface degradation)

Additional resistance is also created by, but not limited to, changes in rudder angle, shallow water operation, and changes in air and sea temperature and density. The impact of these influences is expected to be small in comparison to wave, wind and surface roughness components; thus they will not be reviewed further here but references can be found in (Carlton 2012), (Molland et al. 2011) & (ITTC, 2011a: and previous reports).

▪ **Added resistance due to wind and waves**

(van Berlekom 1981) examines the impact of wind on ship performance and concludes that the impact of indirect wind effects (i.e. the forces and moments acting on the ship under the water, along with rudder resistances and the impact of drift), is small compared to the direct wind effects (i.e. the forces and moments above the water acting on the ship). The latter has been reported by wind tunnel testing: such as the work of (Isherwood 1973; van Berlekom 1981), and (Appendix A: van Berlekom 1981) for larger tankers and containers at the time. Furthermore, it was concluded that the direct wind effects on ship resistance are in the same magnitude as the effects of waves; where the additional resistance due to fouling is also of equal importance.

The added resistance due to operation in waves is predominantly due to ship motions (creating radiated waves and incident wave reflection) and wave diffraction (with both the ship and radiated waves). (Pérez Arribas 2007) identifies that radiated waves due to ship motions are considered to be the largest contribution to added resistance whilst diffraction is considered to have the least effect: partially in short waves. The vertical ship motions (heave and pitch) are identified as the most significant in comparison to other motions: where roll and yaw complicate the added resistance prediction. Head seas are typically used for the first prediction estimates of added resistance as they present the highest resistance scenario (Pérez Arribas 2007). Furthermore, (Pérez Arribas 2007) reviews different methods that have been developed over the years to predict added resistance in regular waves, including the momentum and energy, integral pressure and radiated energy methods. Methods for performance prediction in regular wave can then be used with linear superposition to predict added resistance in irregular seaway. (Carlton 2012), (Molland et al. 2011) & (Zakaria & M.S.Baree 2008) provide further reviews of different analytical methods developed to compute the components of added resistance due to wind and regular and irregular waves. (ITTC, 2011a: and previous reports), (Bhattacharyya 1978) & (Lloyd 1989) review different methods, proofs and their application. (ITTC 2002a) discusses the established method for extrapolating model experiment results in regular waves to predict power increase in irregular waves.

It is noted here that SR datasets typically define the wave and wind conditions using the Beaufort Scale rather than measurement of the significant wave height, mean period and direction of the surface waves and swell. Thus the methods mentioned for the prediction of added wind and wave resistance would only provide approximations based on the interpretation assumptions of the Beaufort Scale to significant wave height, mean period, direction and spectrum. Whilst Sub-section 2.4.5 will discuss how some of the analytical methods mentioned are often used SOPM systems based on CM datasets, it is considered that they will not necessarily provide an improved solution for SOPM with SR's due to the assumptions that will have to be made, the subsequent uncertainties and the offset added complexity of calculation.

Considering a direct method used to quantify ship operational performance, (Kwon 1981) predicts the impact due to wind and wave added resistance (i.e. speed loss) based on the Beaufort Number. This method was later improved in (Townsin & Kwon 1982). The empirical formulae for speed loss in head sea wind and waves presented by Kwon and Townsin are shown below:

For tankers in laden:

$$\frac{\Delta V}{V} 100 = 0.5\, BN + \frac{BN^{6.5}}{2.7 \times \nabla^{2/3}}$$

For tankers in Ballast:

$$\frac{\Delta V}{V} 100 = 0.7\, BN + \frac{BN^{6.5}}{22 \times \nabla^{2/3}}$$

For containers in design load condition:

$$\frac{\Delta V}{V} 100 = 0.7\, BN + \frac{BN^{6.5}}{2.7 \times \nabla^{2/3}}$$

The Beaufort scale is used rather than wave characteristics, simplifying the method of application to one that could be used with SR data. The performance prediction using the formulae compared well with calculated and model test results [These results are shown in Figure 60 in Chapter 10 as they are used for comparison with the developed SOPP model presented in Chapter 9]. Townsin and Kwon's results, along with the compared results, demonstrate that for both small and large tankers the increase in speed loss is relatively linear up until around Beaufort Number 4 or 5, up to around 5%, and then increases steeply in the range of 24%. The larger tanker demonstrated the ability to sail in a slightly higher Beaufort Number than the smaller tanker.

Aertssen carried out a series of full scale trials onboard large containerships to assess their service performance and sea keeping characteristics: (Aertssen 1957; Bhattacharyya 1978), (Aertssen 1963), (Aertssen 1966) and (Aertssen & Sluys 1972). In addition to the typical measurement instruments installed onboard ships (including a torsion meter and speed through water log), the container ships on trial had accelerometers, gyroscopes and wave recorders installed so that the ship motions and weather conditions could be determined more accurately. Only an anemometer was used for wind speed measurements and therefore corrections for wind resistance were corrected for based on wind tunnel model tests. Measurement observations were recorded every hour in moderate sea conditions and continuously in severe seas. Analysis of the collected data revealed similar trends in speed loss to those identified by (Townsin & Kwon 1982): where the speed loss in head seas increase steeply around Beaufort Number 4 to 5 at around 5%: (Aertssen 1963). [Graphs presented in Chapter 10]. It was also demonstrated that the 5% speed loss corresponded to a power increase around 25%. (Aertssen 1957; Bhattacharyya 1978) demonstrated that in following seas a performance gain is achieved up to around Beaufort Number 4 and 5, after which a speed loss starts to be experienced. Therefore Beaufort 4 and 5 can be considered as the conditions where ship motions start to form a significant contribution towards added resistance.

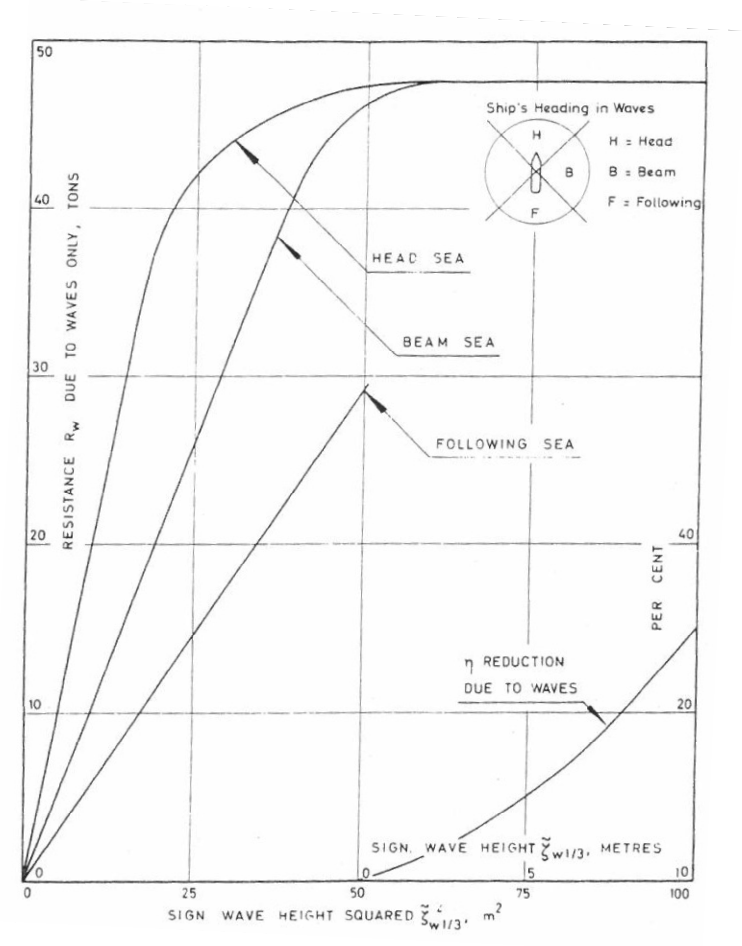

Figure 3: Resistance due to waves only (Aertssen & Sluys 1972)

Results from (Aertssen & Sluys 1972) are shown in Figure 3 where the resistance due to waves only (i.e. corrected for wind resistance), is plot against the significant wave height squared. The linear trends confirm the squared relationship between the additional wave resistance and significant wave height, up until the point where extreme motions occur leading to slamming and propeller emergence. A key feature of Figure 3 is the plot of estimated total propulsion efficiency loss due to operation in waves; seen to be up to around 30% in waves with a significant wave height of 10 meters.

▪ Added resistance due to surface degradation and fouling

The last of the three significant contributions to additional resistance above calm water conditions, is generated by the surface roughness of the hull. This additional resistance is caused by added hydrodynamic drag, which can be apportioned to a change (delta) in the frictional component of resistance. Hull roughness is characterised by the following: surface's mechanical properties; damage and degradation of the surface over time; hull fouling.

The mechanical properties of a hull are defined by the quality of the ship build and the application of the paint system, i.e. depending on the flatness of plates, smoothness of welds, and the smoothness of layered paint application (including drips, runs, sagging, overspray, and grit inclusion (Townsin 2003)). A hull is coated with several layers of paint where the last are typically an Anti-Fouling (AF) paint. There are many different types of AF paints that each exhibit different 'as applied' mechanical properties (i.e. smoothness). Increased roughness will then be added to the hulls surface over time with damage and degradation due to but not limited to: damage from the anchor, the quay side, corrosion, flaking or breakdown of the paint system. Fouling will also occur which is the attachment of organisms to the hull. Micro fouling is typically the first type that starts to build up as soon as a ship enters the water i.e. the build up of a slime layer. This is followed by the attachment of weeds and then macro fouling; i.e. vegetive and animal fouling, such as shell growth and barnacles, that attach themselves using self produced glues, also known as cements (Kane 2012). Macro fouling (commonly known as calcareous fouling) often requires a substantial power and energy to be removed (Kane 2012). However, with developments in antifouling paints, in 2003 Townsin reported that 'calcareous fouling is less common than it was in the 1930's and is supplanted today by weed fouling' (Townsin 2003). Further reading on the types of fouling can be found in (Kane 2012), (Rompay 2012), (Taylan 2010) and (Anderson et al. 2003).

During the late 1900's it was though that a solution to fouling to had been found. This was using a self-polishing copolymers (SPCs) containing a biocide called tributyl tin (TBT). Not only did this paint system effectively deter fouling, it also became smoother over time (Townsin 2003). However this solution was not to last. In 2001 the use of TBT was banned, with a complete phase-out enforced by 2008. This was due to the toxic damage that TBT causes to the marine environments and species in an area (Anderson et al. 2003) and (Townsin 2003). No one paint system has since been identified to be as effective as the TBT coatings although research and developments in the area have been extensive. Different best solutions are available on the commercial market suitable for different applications. The most widely used types include:

- Controlled depletion polymer (CPD) (contains biocides)
- Self-Polishing Copolymer (SPC) (contain biocides)
- Hybrid SPC (contain biocides)
- Foul Release (does not contain biocides)
- Hard coatings (does not contain biocides)

The following references provide further information on the different paint types: (Kane 2012), (Rompay 2012), (Taylan 2010), (Anderson et al. 2003) and (Fathom n.d.).

The selection of one paint system (paint type and application amount) over another will depend on several ship specific factors. One factor is the initial investment cost of the paint and application, and future maintenance costs. Another is the life performance of the paint in relation to the ship's operating profile: for example, some paints work better in the short term whilst others will provide better savings over a longer maintenance period. An example is provided in Figure 4.

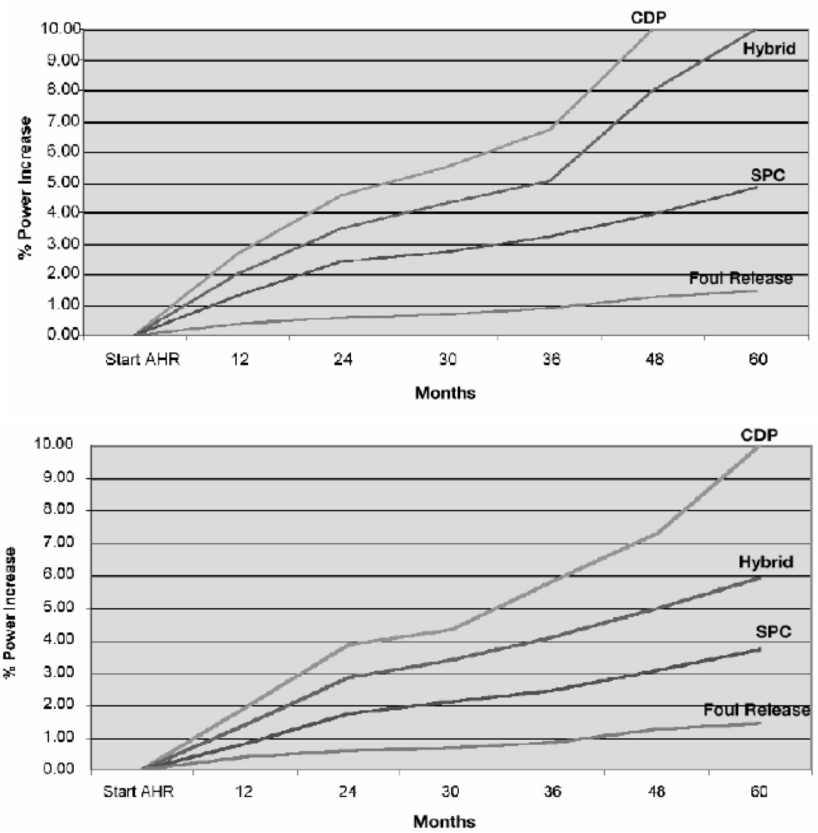

Figure 4: Power increase for a typical fast, fine ship (e.g. container liner) (ITTC 2005)

Further operating profile considerations that influence (or should influence) paint system selection include:

- **Ship speed**: Is the average ship operating speed high enough to deter fouling from attachment and/or high enough for fouling to be shed (i.e. a function of some paint systems)?
- **Operational area**: Fouling species vary in different operational areas. A ship regularly operating in a specific area with a known type of fouling species should have a corresponding paint system selected. Furthermore, the sea water temperature, nutrients, salinity and alkalinity not only affect the type of fouling species in an area, but also the rate of fouling increase. Other weather conditions such as sunlight exposure also affect the rate of fouling increase.

- **Voyage type profile**: Fouling increases at a much higher rate when a ship is slow moving or stationary. Therefore not only is the average ship speed a consideration, but also the amount of time spent in port, at anchor or drifting. The difference between sailing in ballast and laden will also impact the fouling accumulation on the section of the ship's sides that is submerged or emerged with a change in draft.

Whilst the analysis of a ship's operating profiles is clearly important for strategic decision making, they are not widely analysed within the ship industry. In addition to this, a significant limitation to the selection of the best paint system for a specific ship is at present, the lack of a standardised method to quantify, benchmark and monitor the paint system's performance over time. A SOPM system that can be used by all ships and that can detect changes in ship performance due to time dependent changes (such as hull surface degradation and fouling) is therefore important to identify.

Another factor to consider when selecting the type of paint system for a ship is the type and frequency of maintenance that it will require to avoid an excessive fuel bill. The most typical hull maintenance practice is to perform a hull clean during the five year docking cycle in line with the class surveys. This is the most widely used practices as it does not require an additional dry dock: which not only costs to perform, but also results in a loss of revenue due to the time lost in service. During dry dock, the common types of hull maintenance events include a clean using a high or low pressure wash, which may or may not include a scrub or brush of the surface. The exact process should be selected based on the mechanical properties of the paint. For example, specific brushes should be used for silicon based paints as they are very easily damaged. Furthermore, the wrong type or over scrubbing may remove layers of CPD or SPC paints, reducing the layers of biocide protection and shortening the effective life performance of the paint. If significant damage is caused to the paint surface then no savings may be observed, or even a penalty, when the ship returns to service. After the hull clean (still in the dry dock) spot repairs are typically made to specific areas and patches of the hull where the paint system is removed, repairs are made to the hull if required, and then the paint system is reapplied. After spot repairs, the entire hull is recoated with the antifouling paint for at least the top layer. Nevertheless, at the edge of the spot repairs the surface often demonstrates bumps that increase the frictional resistance of the ship when it returns to service compared to when the paint system was originally applied. In fact, the only time that the hull roughness may return to its initial conditions is if a full blast and reapplication of the paint system is carried out. The performance may even be improved if a better paint system is selected. However this is typically only carried out after 10 to 15 years of a ships life (Rompay 2012).

In addition to dry docking maintenance, in-water hull cleaning can be performed although this will very much depend on the paint type. If the wrong cleaning brushes are used or a poor quality of cleaning is carried then this can damage the paint surface and or remove layers, and hence increase the roughness in the short and long term (Munk 2006). Furthermore, in-water hull cleaning is banned in many areas and ports to avoid the transfer of the fouling and paint biocides from the ship to the surrounding environment. Therefore, if in-water hull cleaning is required, the operating schedule and routes of the ship need to be considered carefully when selecting the paint type to ensure that the ship will not have to take significant time out of its commercial schedule to find an appropriate maintenance facility. This is also a consideration related to dry docking facilities with resources and skills for maintaining different paint systems.

The decision to perform a dry dock and or in water hull cleaning typically requires communication between stakeholders in the commercial and technical departments and with the ship (i.e. the voyage manager, vessel manager, master of the ship), where each can contribute their expertise on the performance of the ship both commercially and technically. Other stakeholders may also be included in this decision, particularly those related to financial expenditures. Without the use of a SOPM system, the most common methods to decide when hull maintenance is required include: when a dry dock survey is required; if a noticeable fuel consumption increase is identified that can be assumed indicative of hull fouling; if inspection by underwater divers identifies that hull maintenance is required.

Quantification of the impact of hull roughness on ship frictional resistance, and hence total ship resistance, powering and fuel consumption, is of interest. The Average Hull Roughness (AHR) is an identified parameter that can be used to indicate the hull roughness (Townsin et al 1981; Townsin et al. 1985 and ITTC 2005). Hand held devices called a Hull Roughness Analysers can be used to quantify the AHR, however, such measurements are not commonly made for ships in the world fleet. An alternative option for quantifying the impact of surface roughness is to measure the thrust and torque of the propeller. (Townsin et al. 1985) describes a generalised calculation expressing the change in ship performance as a power penalty due to hull and propeller surface roughness. However, again the thrust and torque of a propeller are not commonly measured onboard ships and thus utilisation of this calculation for SOPM is limited. As the installation of torque meters increases the combined impact of hull and propeller roughness can be examined. More recent methods to quantify the impacts of hull roughness on ship performance are beginning to be explored in CFD, such as the work of (Demirel et al. 2014). The impacts of propeller roughness are also explored, such as the work of (Wan, Nishikawa and Uchida 2002) and (Uchida & Nishikawa 2005) which will be discussed in Section 2.4.4.

As a note here, the impacts of hull roughness also apply to the propeller, which also roughens and fouls over time. Propellers can be coated in an antifouling paint although in most cases their metal finish is just polished to a smooth surface (Townsin 2003). The impact of propeller surface roughness has not been a focus of this section as the added resistance generated from the propeller is small compared to the hull due to the comparable surface area: (Townsin 2003). Therefore propeller roughness has been discussed in the following Section 2.4.4 as it has a much more pronounced impact on the propulsion efficiency.

Considering the impact of hull fouling on ship performance, Aertssen reported the increase in power observed by the direct trials of several containers ships. Figure 5 demonstrates an example of how the power increased due to fouling for one of the ships. The rate of power increase increases most steeply at the start of the maintenance period and decreases in a step change after dry dock maintenance (although not back to the original performance due to spot maintenance as previous discussed). It should be noted that the performance gain experienced during dry dock cannot be isolated from any other maintenance that may have occurred during the dry dock period; unless sufficiently detailed information is provided. It is also shown in Figure 5 that in the second maintenance period the total increase in power did not reach the total reached before the dry dock in the same time period since last maintenance; where the total increase in power corresponds to around 10%.

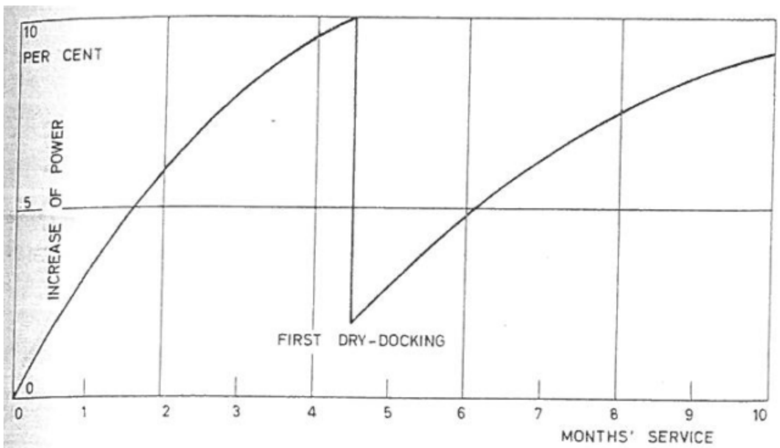

Figure 5: Increase of power due to fouling (Aertssen 1966)

(Taylan 2010) identified that slime or algae fouling can increase resistance by about 1 to 2 % whilst hard-shelled fouling (such as barnacles, tube worms and mussels) can increase ship resistance up to around 40%. Furthermore (Schultz 2007; Kane 2012) identified the power penalty experienced from different types of fouling for a frigate class vessel: Figure 6.

Description of Visual Hull Condition	Added Propeller Shaft Power (%)	Type of Fouling
Freshly Applied Hull Coating	0%	no microfouling
Deteriorated Coating or Slime	9%	microfouling
Heavy Slime	19%	microfouling
Small Calcareous Fouling or Macroalgae	19%	macrofouling
Medium Calcareous Fouling	33%	macrofouling
Heavy Calcareous Fouling	84%	macrofouling

Figure 6: Influence of hull and propeller condition (Schultz 2007; Kane 2012)

(Munk 2006) describes the use of a developed SOPM system, CASPER, to identify changes in ship added resistance. The following observations were made relating to the added resistance of the hull and propeller due to surface degradation and fouling for a number of individual case studies:

- A development increase at less than ½% per month
- A development increase between 0.7 and 1% per month
- A development increase at a very fast rate of 6% per month: example of poor treatment in dry dock
- Propeller polishing at 6 month intervals resulted in a 5 ton per day fuel saving
- Hull cleaning resulted in approximately 10 tons per day fuel saving
- Some ships can have a very high added resistance, approximately 50%

The following general conclusions were also made from the study:

- The added resistance for a ship is approximately 30%: equating to a 1 knot speed loss and 12 tons per day increase in fuel consumption at design speed for an Aframax tanker, and 1.8 knots and 70 tons per day for a container ship.
- Approximately one third of all ships are in good condition with added resistance under 20%; 50% of all ships are in a reasonable condition but could be improved.

- In the best case scenario, after a typical dry dock (i.e. spot blast maintenance), the added resistance will remain between 0 to 4% above the baseline resistance. The saving due to the maintenance could be between 5 to 20%.
- Ideally, the hull should be cleaned before hard fouling accumulates, as slime and algae can be removed relatively easily with soft brushes and thus damage and depletion of the paint system will be less likely.

As a note, caution should be taken when comparing percentage performance results from different studies. This is because the percentage depends on the baseline conditions used for comparison, for example, the baseline surface conditions could relate to the following conditions: hydrodynamically smooth; as applied (e.g. surface at the time of sea trial); at a specified trial for average operational conditions.

As a final point (IMO 2011b) estimated that, over an average sailing interval, hull and propeller roughness due to hull and propeller degradation and fouling accounted for 9 to 12 % of the world fleet's GHG emissions at the time.

2.4.4 Propulsion Performance Prediction

The prediction of resistance is only part of the ship performance problem. The resistance force exerted on the ship has to be overcome by the thrust produced by the propulsion system to achieve and maintain a forward speed. Thus propulsion performance is considered in this sub-section.

The widely established formulae for the calculation of the following performance parameters can be found in Appendix A – List of Equations; resistance, brake power, propulsion efficiencies, fuel consumption, carbon emission.

- **Benchmarking Performance**

Brake power is one of the important parameters used for quantifying ship performance as it is associated with the fuel consumed (related to fuel cost) and speed of a ship (related to voyage scheduling): thus is of both economic and commercial interest. When a ship is built, a power-speed curve is produced to demonstrate that the design or guaranteed speed of the ship in calm water and unfouled conditions can be achieved. This is carried out during a sea trial for which the procedures are described in (ITTC 2012). Whilst carried out for the purpose of contractual verification, the power speed curve is often used for benchmarking changes in a ship's performance. However, the following concerns are raised regarding the accuracy of technical performance that can be expected:

- It is common for one sea trial to be carried out for a set of sister ships. Thus performance differences between the sister ships are not captured in the sea trial data.
- Sea trials should be carried out in calm water conditions but this is not often feasible. Whilst the International Towing Tank Conference, ITTC, suggests methods for correcting to calm water conditions (ITTC 2012), there is still error that may be apparent in the recorded sea trial data (Insel 2008): 'The

wide variety of sea trial conditions and utilisation of sister ships has indicated a precision limit of about 7–9% can be achieved.'

- The sea trial procedure is based on specific design conditions. However, a ship operates in a range of off-design conditions where the off-design performance is not necessarily proportional to the variations in design performance.
- For some ships, particularly container ships, it is not possible to carry out the sea trial in laden. Therefore they are extrapolated for the ballast trial results.

- **Influences on Propulsion Performance**

In ideal conditions the speed of the ship would be proportional to the speed of the propeller [for discussion purposes a Fixed Pitch Propeller (FPP) is considered]. However, in reality the phenomenon of slip occurs. The apparent slip ratio (E.5 shown in Appendix A) can be derived from the measured ship speed and RPM. However, the real slip ratio requires depends on the flow speed of the water entering the propeller. This can be estimated from the ship speed based on the wake fraction (E.6: Appendix A). The real slip ratio is affected by changes in the ship resistance and hence load on the propeller (which means that it is highly correlated to the ship's speed), and the propeller efficiency. Thus slip can be said to be due to changes in following:

- Average draft at midship and trim
- Sea conditions: including surface waves and swell, wave induced motions and currents
- Wind conditions: including wind speed and direction and induced drift
- Transient operation: including changes in speed, heading
- Propeller pitch: for CPP's
- Hull surface degradation and fouling

- Propeller surface degradation and fouling

The prediction of factors related to an increase in resistance have been discussed in Sub-section 2.4.3. Therefore, this sub-section focuses on the prediction of the propulsion efficiency: primarily making reference to the open water characteristics of the propeller.

▪ **Propulsion performance prediction**

Similar to the hull form series, several propeller series have been produced over the years based on model test results to predict the performance of similar geometry propellers. The different series can be selected for use based on how well they match the propeller for which the performance prediction is required, i.e. based on: the number of blades, blade area ratio, foil section, face pitch ratio and speed range. (Carlton 2012) reviews many of these series discussing their advantages and disadvantages, including the: Japanese AU, Gawn, KCA, Lindgren (Ma-Series), and Newton-radar series. The Wageningen B-screw series is considered one of the most extensive and widely used propeller series (Carlton 2012) and was used for the development of the SOPP model presented in Chapter 9.

The Wageningen series was first presented by Troost in the late 1940's and therefore it is also sometimes referred to as Troost's series (Troost 1950). (Oosterveld & Ossannen, 1975, Lammeren, Manen, & Oosterveld, 1969; Carlton 2012) further developed the series to account for known unfairness in the results due to model testing methods. The Wageningen B4-series is best suited for 4 bladed, fixed pitch, non-ducted propellers with a face pitch ratio is in the range of 0.6 to 1.4. The calculations for the series to predict the thrust and torque coefficients of the propeller, from which the open water efficiency can be calculated, are given in E.12 to E.16 in Appendix A.

However, the open water performance of the propeller (including the open water efficiency and thrust and torque coefficients) changes in different operational conditions, due to:

- A change in the advance coefficient
- A change in propeller open water efficiency (i.e. due to propeller surface roughness and degradation.

- **A change in the advance coefficient**

The advance coefficient changes with the ratio between the speed of the ship and propeller RPM. However it is also influenced by the wake fraction which depends on the boundary layer of the ship. The boundary layer is predominantly dictated by the underwater geometry of the ship (particularly at the stern), including the influences of draft, trim. It can also be influenced by currents and ship motions due to the ship's response in wave and wind conditions, and by changes in the hull roughness due to surface degradation. (Yabuki, Saaki, Hiwatashi 2013) performed full scale trials and conclude that an increase in propeller loading due to operation in wind and waves has a small impact on the wake coefficient, whilst the displacement and trim is likely to have a greater impact.

An estimate of the wake fraction is usually determined during the propeller open water tests; however this is only provides a value for the test conditions. In operational conditions the wake fraction could be calculated from measured speed through water, shaft torque and RPM; but only if the open water diagram has been corrected for propeller roughness (Hasselaar 2010). Alternatively, (Moody 1996) discusses some relatively simplistic methods established for estimating the wake fraction including the D.W Taylor's, Hecksher equation and Schiffbaukalender equations. Empirical formulae based on regression analysis offer more complex methods for estimating the wake fraction, such as using the Holtrop and Mennen formulae, used to calculate the wake fraction in the SOPP model described in

Chapter 9. The calculation of wake fraction using the (Holtrop & Mennen 1982) method (E.17: Appendix A) takes account of the draft of the ship fore and aft, the underwater and waterline form of the ship, appendages and the diameter of the propeller, However, it does not account for hull fouling, nor weather induced ship motions. Additional methods for calculation include those presented by the British Ship Research Association (BSRA) suitable for ships with a Block Coefficient (C_B) in the range 0.55 to 8.5 and Froude number within 0.12 and 0.36, and the Harvald method, for ships with a C_B lower than 0.75: (Molland et al. 2011). It is also cautioned by (Schneekluth & Bertram 1998) that prediction of the wake fraction using scaled model tests can contain large errors (typically over predicting) due to the complexity in scaling flow characteristics.

- **A change in propulsion open water efficiency**

If a constant RPM and wake fraction (and hence advance coefficient) is assumed, the propeller open water efficiency is decreased with an increase in propeller surface degradation and fouling (i.e. roughness), along with the thrust coefficient, but the torque coefficient is increased. These results are demonstrated in (Wan, Nishikawa and Uchida 2002) using full scale trial results for a training ship. The trials were carried out with different propeller roughness (50μ, 150μ and 250μ: the former two roughness values correspond to before and after a dry dock). The full scale results are compared to corresponding model test results and the results provided by a developed numerical model. Subsequently, using the results presented in (Wan, Nishikawa and Uchida 2002), which were determined using a torque and thrust meter, (Uchida & Nishikawa 2005) presented a method for correcting the thrust coefficient based on the proportional change in torque coefficient, with different propeller roughness. The advantage of this method provided a way to account for propeller roughness in service without requiring a torque meter. However, it is susceptible to errors in logged ship speed and would also require determination of the initial roughness relationships (i.e. knowledge of open water characteristics and self propulsion factors, as well as propeller roughness). Therefore, at present there remains no practical analytical method to separate hull and propeller roughness effects unless a torque and thrust meter is installed. If a torque and thrust meter is installed, the previously mentioned method presented in (Townsin et al. 1985) can be used to determine the power penalty due to hull and propeller roughness separately. If just a torque meter is installed it should be cautioned that the performance changes due propeller roughness will be revealed as a reduction in the advance coefficient, in which case the calculation of wake fraction based on measured results may be inflated. Nevertheless, as (Logan 2011) points out, it is fuel economy that ship operators are most concerned about which is due to the combined effect of hull and propeller performance. Thus separation of the two is less critical than providing a method for monitoring of both.

2.4.5 Performance Prediction and Monitoring Methods

▪ **Introduction**

In early research it was reported that predominantly model tests were used to identify changes in ship performance, with 'gains from full scale testing provided little input to an important field of unexplored research.' (Telfer 1926). However (Clements 1957) identified that research into ship performance prediction was expanding to look at in-service conditions compared with sea trial 'measured-mile trial performance'. Direct and empirical models based on full scale tests in trial and operational conditions became more popular for predicting ship operational performance, along with the development of analytical method: as will be discussed. Still today, the typical methods for SOPM tend to include the comparison of in service recorded data (operational datasets) with ship performance predicted by an operational performance prediction model.

Despite significant advances in computational ability, sophistication of technology and advances in many areas of ship resistance and propulsion research; the same rate of advancements do not appear to have been translated to SOPM, although they have recently gathered increased interest. This view is shared by (Logan, 2011) who 'spent nearly seven years researching the subject during the oil crisis of the 1970's (Logan et al. 1980; Logan, 2011), and after pursuing other areas was surprised to learn that practical techniques for assessing the performance of a ship at sea have changed relatively little during the past 35 years'. However, this is not to say that no advances have been made, on the contrary, the later part of this sub-section examines the more recent research developments.

- **Simple performance relationships and regression methods**

(Telfer 1926) was one of the first to present a practical method for identifying ship performance in operation and use it for monitoring ship performance over time. The principal of his method was to consider the propeller as a power absorption dynamometer and construct a Mean Referred Pressure (MRP)[12] diagram, which could then be converted to a Generalised Power Diagram (GPD). The assumptions made were that the mean referred pressure is proportional to torque, and that the torque of a propeller at constant real slip varies with the square of its revolutions. Furthermore, the calibrated GPD developed for the individual ship will only be valid for one wake fraction condition. Therefore as the wake fraction changes with hull fouling and degradation (discussed in the previous sub-section), the GPD should be recalibrated. The benefit of the GPD is that it allows for either the power, speed or RPM to be predicted, given that the other two parameters are known (i.e. measured).

Telfer tested the accuracy of the calibrated GPD for a case study ship by collecting 20 or so service cards completed with 'considerable care' by a chief engineer. Comparing results it was found that the accuracy of power prediction was within half a percent. By performing the same process for different case ships Telfer concluded

[12] *Break Mean Effective Pressure (BMEP) = Indicated Mean Effective Pressure (IMEP) – Frictional Mean Effective Pressure (FMEP)*

that the same accuracy could be observed for several ships. Indicator diagrams can be used to determine the mean indicated pressure and they can be produced on all ships. Therefore this method could be used widely within the world fleet. However, the process of calibrating the GPD for wake fraction, given that it cannot be measured in operation, limits the practical application somewhat. Furthermore, whilst indicator diagrams are produced and analysed by the seafarers in the engine room, the measurement values are not usually recorded in operational datasets.

Telfer then proposed a method for SOPM by utilising the GPD. Ship log data was used as the operational dataset, where the recorded RPM and ship speed and the GPD were used to predict power. Telfer also used the draft recorded at the end of each voyage to determine ship displacement. He then averaged all log entry results to calculate one averaged set of results for each voyage. Then by filtering over a weather intensity scale, the voyage average Admiralty coefficient (E.24: Appendix A) was determined. The Admiralty coefficient was then plotted over time to observe performance changes. The weather intensity scale proposed by Telfer was not widely used although his method provided a foundation for subsequent developments in the field.

(Carlton 2012) discusses that plotting the Admiralty coefficient is one of the traditional methods used by ship owners and managers to assess ship performance over time. This is because it is relatively simple to calculate. The Admiralty coefficient is also often plot against slip. If a measurement or prediction of power is not available, the fuel consumption ratio (E.25: Appendix A) has also been commonly used, based on a similar form to the Admiralty coefficient: where the draft is used instead of the displacement and fuel consumption instead of the power. Filtering of data for different operational conditions can reduce scatter, however the Admiralty coefficient and fuel consumption ratio both produce results with a large amount of scatter due to the uncertainties in the input data and equation assumptions.

Like Telfer, Bonebakker focused on using slip as a key parameter in determining ship power. The method presented in (Bonebakker 1951) demonstrates the use of linear regression analysis based on model test data to predict the coefficients a and b for the relationship between the power ratio (P/N^3) and apparent slip (Sa): where it is again assumed that the wake fraction remains constant.

$$\frac{P_D}{N^3} = a \times Sa + b$$

Where: P_D is the delivered power at the tail shaft, Sa is the apparent slip, N is the propeller revolutions per minute, and a and b are constants to be determined.

Having determined the coefficients a and b, Bonebakker rearranges the equation to plot the power against N^3(axSa)+b. Adding an additional term to account for the constant torque to overcome main engine and or shaft efficiency, Bonebaker presents the following equation for power prediction.

$$P_{S\ or\ I(HP)} = N^3(a \times Sa + bN^{-2} + c)$$

Bonebakker determined the above coefficients for a single screw steamer in both ballast and laden. Comparing the predictions with recorded power records, he reported a mean deviation of the prediction to be 1.9% for laden and 3.1% for ballast. For the ballast case Bonebakker found the term bN^{-2} to be so small that it could be neglected. Following this Bonebakker also performed the regression analysis not splitting the service data into ballast and laden but he also included a term for draft (shown below). The mean deviation was found to be 2.4%: highlighting that draft is an important parameter to consider in ship performance prediction.

$$\frac{P_{S(HP)}}{N^3} = a \times Sa + bN^{-2} + cT + d$$

In his 1954 paper Bonebakker presents further full scale comparisons and discusses the importance of taking simultaneous measurements (Bonebakker 1954). He criticises the methods based on constant wake fraction which are only true under constant speed, draft, trim and roughness; but for practical purposes (which is the objective) the assumptions are tolerable.

(Clements 1957) presents yet another method based on similar regression methods to those of Telfer and Bonebakker, but presents the power ratio as a function of time out of dry dock (T_D) and weather intensity (W):

$$\frac{P_{S(HP)}}{N^3} = aT_D + bW + c$$

However, the above assumes that the power ratio varies linearly with time out of dry dock, which Clements found to not necessarily be true: particulary for tankers that spend a relatively short period of time in port. Thus he presents a quadratic relationship with time out of dry dock included, highlighting it as an important parameter to consider:

$$\frac{P_{S(HP)}}{N^3} = a{T_D}^2 + bT_D + cW + d$$

(Logan 2011) discusses a similar method based on the principals presented by (Telfer 1926) and (Telfer 1964; Logan, 2011) but more closely following the work of (Bustard 1978; Logan, 2011). Logan again utilises power ratio, but plotted it against the slip ratio (V/n). To perform a linear regression it was assumed that in the normal range of operation, the torque coefficient has a relatively linear relationship with advance coefficient. Logan filtered the operational data to best remove influences of current, weather, rudder angles and transient conditions. The remaining influence on slip left in the data was identified to be due to propeller pitch: a controllable pitch propeller (CPP) was being modelled. Therefore Logan proposes two linear regression equations taking account of propeller pitch:

$$\frac{SHP}{n^3} = c_1 + c_2 H$$

$$\frac{V}{n} = c_3 + c_4 H$$

The reciprocal of these relationships were found to provide better predictions for the in-service data and were subsequently used to determine the coefficients of regression. (Logan 2011) found his model to be within 1.8% absolute error for the speed prediction and 0.9%) for the shaft power. Whilst this method demonstrates improved accuracy compared to the previous mentioned methods, it is required that shaft power is measured. Therefore at present this method is not feasible on a large scale due to the installed torque meters or indicated power recorded regularly in operational datasets.

- **Empirical and analytical methods**

(Journée 2003) reports results from trials that were carried out in 1985 on a semi-submersible heavy lift vessel. The trials were carried out unloaded and at 16 combinations of draft at midship and trim, at a range of speeds. The trials were restricted to calm water and to beam or following seas. In addition to providing a valuable contribution to full scale trails in a full range of draft and trim conditions, the aim of the research was to 'investigate the feasibility of a computer based shipboard monitoring, prediction and surveillance system, to ensure safe and economic ship operation.'. The recorded input data to the model included the propeller pitch, propeller RPM, displacement and loading, and environmental conditions. The model itself was based on ship specific model experiments; established hydrodynamic and propulsion relationships, empirical and analytical formulae and methods (including those of Isherwood, Gerritsma and Beukelman, & Boese); ship specific polynomials developed using the full scale data.

An example of one of the derived polynomials was for the equivalent wake fraction which was based on full-scale measurements in each draft and trim combination. The average deviation of the measured equivalent wake fractions compared to the polynomial prediction value was within 3.5% deviation. A conclusion of the study was that the trim only had a small impact on wake fraction; only slightly higher than the prediction deviation. It was also determined that the impact of rudder motions and yaw motions were relatively small and could have been ignored in the overall model; although they were not. A conclusion from the full scale results was that a 10% reductions in fuel was achieved by switching off one main engine at lower ship speeds. The ship owner described many practical benefits of using the SOPM system, including the generation of good, accurate and reliable information to help support operational decisions, particularly for a management overview and for use during onboard voyage planning and post voyage processing. A comment made by a captain also emphasised the benefit of using the system for increasing awareness about ship performance and encouraging recognition of improvement opportunities and generating motivation to achieve them. Due to the benefits of the system the payback period was expected to be around 1 year. (Journée 2003).

It would not be feasible to carry out comparable trials on all commercial ships as described in (Journée 2003); even though it was identified that significantly less than 200 trials would be needed to calibrate the model. However, the conclusions identified are beneficial for consolidating energy efficiency best practice knowledge and supports the identified need to provide reliable SOPM systems with supporting training and documentation.

Similarly the aim of the study carried out by (Hasselaar 2010) was to ‘investigate the feasibility of developing an advanced (online) ship performance modelling and analysis system for typical merchant ships'. His focus was on improving data accuracy and providing Key Performance Indicators (KPI's) for direct and useful feedback on ship operation. Hasselaar's method utilises onboard measured data, then, using a deterministic method, corrects the measured data to a standardised condition. The measured datasets used were collected from a research and Very Large Crude Carrier (VLCC) vessel; both with Fixed Pitch Propellers (FPP) and equipped with a range of sensors and tailor made data acquisition systems, installed by Hasselaar himself.

As data accuracy was a priority, the uncertainty associated with measured data variables was discussed at length (Hasselaar 2010). A key point highlighted is that, whilst the Speed Through Water (STW) measured by a Doppler log provides a more accurate measurement than Speed Over Ground (SOG), it too contains great uncertainty due to influences such as: ship motions, improper location, aerated water, water depth; salinity, incorrect calibration. Thus Hasslaars suggested the use of a GPD (as first proposed by (Telfer 1926)) to predict speed most accurately: i.e. because power and RPM can be measured more accurately. However the accuracy, will only remain if the GPD is calibrated periodically for changes in the wake fraction.

The SOPP method presented by Hasselaar included using measured propeller blade roughness to correct the propeller open water diagram. Then, with the corrected open water diagram, measured ship speed, RPM and torque, the thrust coefficient could be calculated. With the thrust deduction factor (available through tests), the total measured resistance ($R_{measured}$) could be determined, and then using well established empirical and analytical methods to determine total added resistance (R_{added}) (including components for wind, waves, shallow water and viscosity) the standardised resistance was calculated as follows:

$$R_{standardised} = R_{measured} - R_{added} + R_{air}$$

Where R_{air} was deducted during the added resistance calculation and therefore must be added back for the standardised condition

(Hasselaar 2010) reversed the calculation process to convert the resistance back to power. The smooth propeller open water characteristics could then be used to determine the power in the standardised condition (i.e. with a smooth propeller) and then the results could be compared to find the difference due to hull roughness.

(Hasselaar 2010) used the model to determine real-time, semi real-time and long term performance indicators. The conclusions included that the method described is very sensitive to the accuracy of speed and torque. To reduce the impacts of this sensitivity Hasselaar suggests that STW and SOG should be measured and compared to remove data records where currents are evident. This is because the STW measurement is more susceptible to error in the presence of currents. The approach presented in (Hasselaar 2010) provides a valuable method for accurately predicting ship performance without using typical statistical methods, and for improving data accuracy. However it requires the instalment of a torque meter and for propeller roughness measurements to be taken. Therefore in the short term, the practical effectiveness of wide scale application is reduced.

Using a similar concept although different modelling approach (Aas-Hansen 2010) utilises several empirical and analytical methods to calculate calm water resistance and the components of additional resistance due to waves, wind, steering and operation in shallow water. He then presents a method for considering the additional resistance due to fouling as the difference between resistance derived from measured power and predicted calm water resistance and the additional resistance components: as shown in the following equation.

$$\Delta R_{Fouling} = R_{measured} - (R_{calm\,water} + \Delta R_{AW} + \Delta R_{Wind} + \Delta R_{Draft} + \Delta R_{rudder} + \Delta R_{yaw})$$

(Hansen 2011) presents another study focusing on the establishment of a reliable index for ship performance evaluation. Data was collected for a Post Panamax containership in service over 1 year. A thrust measurement was included. Most sensor information was logged at 10 second intervals, apart from draft which was logged once a day. Corresponding noon data reports were also available along with hindcast data for weather conditions, obtained through a subscription of data from Buoyweather Inc.

A Bond Graph method was used to construct the SOPP model: which 'describes the energy system and flows in a dynamic system.' Empirical methods based model and full scale results were utilised to form each element in the Bond Graph. The primary elements of the model included: propulsion based on shaft power and the propeller; hull performance based on wake and thrust deduction at varying speeds, drafts and trim; ship resistance at varying speed draft and trim; wind resistance; wave resistance.

Different levels of data filtering were examined to demonstrate the benefit of ship performance analysis using only data points with increased reliability, albeit at the reduction of data sample size. The benefits of the filtering processes were particularly evident when observing ship performance in open water conditions compared to confined waters. It was also concluded that the scatter in noon data did not allow for the detection of propeller cleaning performance as the saving made was within the scatter of the data. The automatically logged data reduced this scatter considerably. An example of how logged speed varies with speed over ground can be seen in Figure 7 where the scatter is due to environmental operating conditions, measurement method and measurement errors.

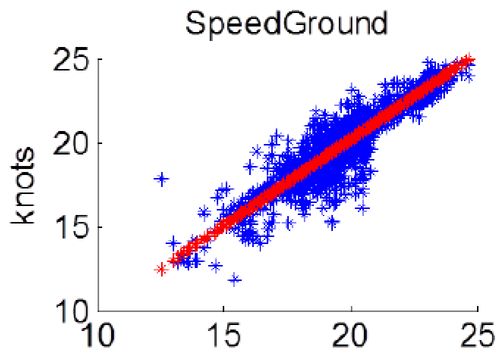

Figure 7: Speed over ground against speed log (Hansen 2011)

(Hansen 2011) made an evaluation of each of the identified performance indices *(footnotes 13, 14 and 15*) against each of the measured input parameters, including: heave, air temperature, mean draft, trim, RPM, sea water temperature, rudder angle, speed over ground, logged speed, true wind speed. The evaluation provided identification of performance relationships that had not been captured within the existing model. The following two relationships were demonstrated to be important but not accounted for in the model:

- Power percentage decreases with sea water temperature
- Speed percentage decreases with rudder angle.

This result makes it evident that ship power and ship speed are influenced by the change in sea water temperature and induced rudder angles retrospectively, and thus should be considered a SOPP model if possible.

Based on these findings the model was updated or improvements were suggested for future work. The updated model was used to assess the performance impact of propeller cleaning. No maintenance was applied to the hull as it was considered to have negligible fouling and thus was not considered to be a factor in the performance evaluation. It was concluded that a 2% increase in power[13] could be obtained from a

[13] Power percentage: the difference between the model predicted and measured power, over the model predicted power.

propeller polish. This was demonstrated to correspond to a 1.5% increase in speed[14] and a reduction in added roughness[15] of 80µm. The performance gains were shown to have returned to the level prior to the propeller clean within 6 months.

Looking more to statistical methods, (Bocchetti et al. 2013) presents a study using multi linear regression to predict average voyage fuel consumption based on the nautical miles travelled, average speed and displacements, which were recorded by sensors, and Beaufort Number recorded in the noon reports. The regression analysis was applied to data collected for two cruise ships. Whilst the modelling samples for the two case study ships demonstrated coefficients of determination at 98.9% and 98.7%, with a standard deviation of 3 and 3.7 retrospectively, no indication was given as to the performance of the testing sample.

(Pedersen & Larsen 2009) used measured data from a 110,000 dwt tanker to develop a ship specific empirical model to predict propulsion power. The collected measured data for analysis included: power, using a shaft torsion meter; speed through the water, using a Doppler speed log; relative wind speed and wind direction, using an anemometer; air temperature, using a weather station unit; sea water temperature measured by the engine crew. The cube of speed was used to as an input to the model to capture its relationship with power. Air temperature was subsequently removed from the model as the measurements were considered to be too unstable. Measurements of speed and power were made every 13 seconds and every second for the other parameters. The time series was then split into 10 minute samples for performance analysis: where samples demonstrating excessive ship heading changes were removed from the datasets: ‘even small changes (less than 1°) of the heading, had significant influence on the measured propulsion power’.

[14] Speed percentage: the difference between the model predicted and measured speed (from the speed log), over the model predicted power.

[15] Average hull roughness is derived from comparing the predicted speed percentage based on the AHR with no fouling, to the speed percentage with hull roughness; utilising on the definitions of dC_F given by (Townsin 2003) but substituting logged speed instead of model test speed

The data was divided into four datasets for four loading conditions based on draft measurements. It was considered that two of the four samples were representative of calm water conditions. This is because the measured wind speeds in the dataset were 16 knots or less, corresponding to a Beaufort Number 5 or less, and hence wind surface waves of 2 meters or less: where it was considered that added resistance due to waves starts to have influence above 2 meters.

Analysis of the standard deviation and relative standard deviation of the power, speed and wind direction measurements in each data set revealed low variation in power and speed measurements (in the range of 1%) but much larger variation for wind speed (up to 18%). This wide variation and uncertainty is something to consider when developing further models based on similar measurement data.

The developed model by (Pedersen & Larsen 2009) used an Artificial Neural Network (ANN): an advanced form of non-linear regression. A one hidden layer network was selected, along with a non liner regression model with additive Gaussian noise and trained with a Bayesian learning scheme. The results of the model determined that propulsion power could be predicted with 2.7% cross validation error. Comparing well established empirical methods by (Harvald 1983, cited in Pedersen & Larsen, 2009) and (Holtrop 1984), the cross validation error was within 23% and 28% retrospectively, demonstrating the much improved prediction. However, it is noted by the author of this thesis that the empirical methods used were developed for calm water prediction and it is not if wind resistance corrections by (Isherwood 1972, cited in Pedersen & Larsen, 2009) were applied, or to what level of detail the other required inputs variables for the empirical formulae were known.

It was highlighted in (Pedersen & Larsen 2009) that requirements of the ANN model include: the availability of sufficient variables; a sufficiently large dataset to train and cross validate with; transformation of the variables to 'hide' the units. It has already been discussed that most shipping companies have limited recorded data for variables such as power and speed through water, amongst others. It should also be highlighted that ANN approaches do not allow for the contribution of each variable in the model to be explored, as this part of the model is 'hidden'.

Extending the research on the ANN modelling, (Pedersen & Larsen 2013) present results from the development of a Gaussian Process (GP) model: a 'non-parametric model that provides a flexible framework for regression'. The regression input variables take on a Gaussian distribution with an identified mean. An Automated Relevance Determination (ARD) routine was then used to train the data by finding the optimum covariance function for the hyperparameters (i.e. the length-scale feature of the input variable's distribution).

A focus of the (Pedersen & Larsen 2013) paper was to compare the use of different data variables, and different combination of variables, as inputs to the GP regression. Noon data was collected from five sister containerships over 10 years, encompassing dry dock and hull cleaning maintenance events. Hindcast weather data was also collected from an independent company. The data was processed to remove irrelevant data. It was stated that the data 'seems to be very consistent, especially the manual observation of the wave height and direction and wind speed and direction'. For the final comparison of results between the sister ships power determined via torsion meter measurements, but where a torsion meter was not installed the specific fuel consumption was used as an input instead.

The results of the comparison demonstrated that the best combination of parameters provided a model with a relative cross validation prediction error around 4%. Removing time increase as an input to the model (i.e. considered representative of hull and propeller fouling) the error increased up to 2.4% (i.e. to around 6.4%). The best model using noon data alone, including time, provided a cross validation error of 4.9%; increasing to around 7% with no time input included. It is interesting to note that the model that provided the best prediction (5.5%) was based on solely on noon data and not including time, included only speed through the water, sea water temperature and mean draft as the input variables. However, it is considered that care should be taken to interpret results purely based on statistics as true relationships can be masked, thus as further evaluation would be required before considering this a conclusion. It is concluded (Pedersen & Larsen 2013) that the variables with the most influence on power prediction, if the time is not included in the model are the ship speed (through water and over ground), hindcast wind speed and direction, and significant wave height. Time also has a great influence, as well as altering the identified contribution by the other inputs. Recognition of the contribution of the input variables helps understanding of the importance of inputs to a successful model.

Comparison of the GP regression model developed in (Pedersen & Larsen 2013) with the ANN model in (Pedersen & Larsen 2009) using the same container ship noon data, reviled the cross validation error when comparing the predicted and measured data was lower for the GP regression method. Nevertheless, whilst the GP model was relatively quick, using it with a large number of inputs could increase its complexity and thus it should not be used with large datasets. This could be a concern for the practical application to larger datasets; although it is not specified what size dataset would provide a robust enough model without compromising complexity. An advantage of the ARD function of the GP regression over the ANN model is that it allows for identification of each input variable's relevance to the prediction.

As a final part to the paper, the GP regression models were then used to investigate the detection of hull and propeller fouling represented as a performance loss. A result presented in (Pedersen & Larsen 2013) has been reproduced in Figure 8: where the 17 model does not include time. The error in prediction is plot over time.

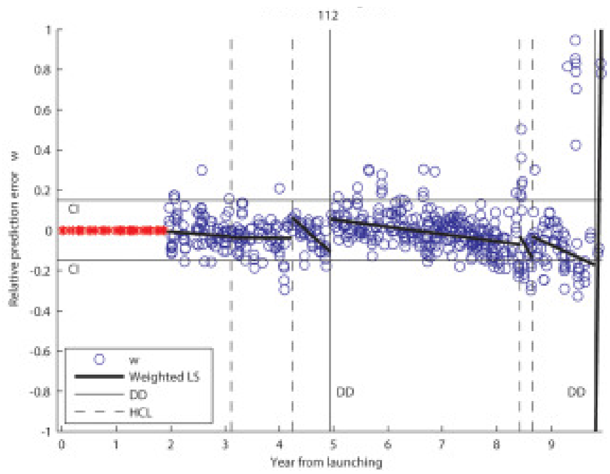

Figure 8: Performance trends using the Gaussian Process model, 1 ship example (Pedersen & Larsen 2013)

As the model is constructed based on the mean of each distribution, it should represent the average performance over the complete dataset used to train the model: with equally distributed error each side of the mean. Thus the positive error represents an over prediction by the model, i.e. when the hull and propeller surface is in better conditions, and negative error represents an under prediction, where the hull and propeller surface condition requires increased power to overcome the additional resistance. It can be seen that most of the error falls within 0.2 % although there is scatter. Nevertheless, trend lines drawn between each dry dock and hull clean make the impact of the maintenance carried out clear. For the full discussion regarding the trends the differences refer to (Pedersen & Larsen 2013). Conversion of the prediction error to performance impact in terms of power or resistance would be of interest.

(Petersen 2011) developed a statistical model of the main propulsion parameters of a ship for utilisation as an onboard ship energy efficiency performance optimisation tool. To support the study data was collected for a ferry operating on a daily route. This data was made publically available (Petersen 2011) as it was concluded that a limitation for comparing different published SOPP and SOPM results, is that the results cannot be compared unless the same data is used: where different data sets (even for the same ship or company) will contain different uncertainties.

Petersen highlights the differences between static and dynamic models. The advantages of a static model[16] are that it enables: anomaly detection, benchmarking, comparisons, capture of drift in the residuals, data-mining[17.] However, a static model does not capture the fact that ‘a change in a control variable may affect several variables, including inputs to the model and not only the outputs of the model’.

(Petersen 2011) discusses the following static models: Gaussian Process (GP) regression model; Artificial Neural Network (ANN) model; Gaussian Mixture Model (GMM). This is followed by a machine learning approach using a instantaneous ANN, and then the application of a Tapped-Delay Neural Network (TDNN) to introduce a dynamic model. The highlighted advantages of using an ANN included that it is a well known and successfully utilised model, and that its computational demands are relatively low. However, the major disadvantage of the ANN is that it does not provide uncertainty measures associated with the results. On the contrary, the advantage of a GP model is that it does provide uncertainty measures. However, the non-parametric nature of the model limits its application to large datasets or data with high dimensionality. The advantages of using a GMM model were identified to be that it has reduced computational demands compared to the GP and that it assesses uncertainty (in terms of data set areas without data, with noise, and modelling errors).

The TDNN and GMM networks were applied to the case study ship and it was concluded that the GMM network performed well and it is a promising method for decision support application with further improvements. Further recommendations were made for the TDNN model.

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[16] *A static (or instantaneous) model predicts performance for a given set of input (control) parameters and doesn’t take into account previous outputs or the impacted change on the rest of the inputs given a change in one or more.*
[17] *Generation of information about model characteristics related to the data inputs.*

Conclusions and key points identified in (Petersen 2011) highlighted that the success of a SOPP model depends on the size of the collected dataset, quality of data collected and the nonlinearity in the collected variables. Petersen also identifies that key aspects of a SOPP and SOPM model are: how well they provide a generalised prediction for scenarios outwith the training set; how well the results can be interpreted; what is the best compromise between improving predictive performance (i.e. via data collection and computational complexity) and data and result requirements. A further conclusion given in (Petersen 2011) is that further work is required on regression based models as they might be better suited for some, non dynamic applications.

Lastly, from a practical application view point, (Petersen 2011) discusses the use of performance models for trim optimisation. He highlights that if an impractical solution is found and presented by the SOPM system, this could 'under certain circumstances undermine the crew's confidence in the system.' This remark is considered important by the author of this thesis as similar opinions of seafarers were shared during discussions. As one example, a seafarer did not like to use a weather routing system as it had not taken practical safety consideration into account: such as going the other way round an island because in the event of loss of speed (e.g. due to engine failure), the likelihood of a high risk accident (e.g. such as grounding) is minimised considerably. This highlights the need to provide a full understanding about a SOPM system to the user, including its limitations and its benefits.

CHAPTER SUMMARY

International pressure to mitigate Climate Change by reducing carbon dioxide emissions is the driver towards energy efficiency regulations within the shipping industry. The first International Maritime regulations on energy efficiency entered into force in 2013, including the Ship Energy Efficiency Management Plan to improve ship operations. However, there are several recommended practices that still require the development of tools and procedures to assist in their effective achievement, such as: a standardised method for performance monitoring; education and training; goal setting and motivational techniques.

Public scepticism regarding Climate Change exists. This could be improved by generating awareness and knowledge about the vast amount of Climate Change science now available, with increased certainty regarding the impacts. This knowledge and awareness should be provided to all stakeholders within the shipping industry.

There are many operational measures available to the shipping industry to help realise improvements in energy efficiency, yet there are also several barriers to their implementation, including split incentives and lack of: integrated operations and human factor awareness, knowledge and skills; methods to quantify ship operational performance and savings; performance feedback mechanisms.

Whilst Maritime Education and Training (MET) on energy efficiency is available as an IMO model course, it is considered that there is still scope for improvement in the following areas: inclusion of a wider base of energy efficiency best practices; focus on human factors awareness and skills development; focus on integrated operations.

The operating profile of a ship should be taken into account in operational decisions that affect ship energy efficiency; such what type of antifouling paint to select, or *when to perform hull and propeller maintenance. However, the analysis of operating profiles is not a common practice industry wide.*

Methods for ship operational performance prediction (SOPP) and monitoring (SOPM) have been proposed since early 1900's, yet no standardised methods for data collection for SOPM have been established, and it is required within the industry.

Recently there have been developments in SOPM focusing on the improvement of data collection and modelling techniques: both are necessary for advances in the field. However, whilst advances to improve data accuracy and sophisticated modelling are required, there is also a need to provide a method of SOPM that can be widely used by all ships in the short term (i.e. without the need for investment in onboard sensors and measurement devices) to enable carbon emission reductions as soon as possible.

A method for SOPM that can be widely used in the world fleet could be based on Ship Reports (SR's) as they are an operational dataset recorded by all ships, typically once a day. This is providing that the inherent uncertainties in the recorded values are taken into consideration.

Improvements in ship operational energy efficiency do not only require MET and SOPM to be addressed; changes in existing ship operational procedures and management techniques (e.g. company objectives, and transparency of operations) are also required. Thus all of these aspects should be addressed to achieve practical operational energy efficiency improvements.

3. RESEARCH AIM AND OBJECTIVES

3.1 Aim

The aim of this research is to contribute towards energy efficiency in the shipping industry through improved operational practices that reduce fuel consumption, hence exhaust emissions and the amount of carbon dioxide released into the atmosphere; in line with meeting global emission reduction targets and the mitigation of Climate Change.

3.2 Objectives

To achieve the research aim the following six objectives were identified:

Objective 1

Identify current energy efficiency practices and perceptions in the shipping industry, the best energy efficient operational practices to implement, and the key enablers and barriers to their implementation.

Objective 2

Develop an Operational Framework for improving ship energy efficiency; supported by field studies and the collection of data and information on operating practices. The Framework includes: Maritime Education and Training, Operating Profiles Analysis, and a Ship Operational Performance Prediction model.

Objective 3

Develop a Maritime Education and Training (MET) Course on Energy Efficiency based on knowledge gained from company visits, field studies, and collected information and operational data. The course material will then be populated to demonstrate the potential for full development, testing and delivery and its applicability for generating energy efficiency awareness, knowledge skills and motivation.

Objective 4

Identify trends in ship operating profiles and the key influences on ship performance, by analysing the operational data from more than 21 vessels; including oil tankers, bulk carriers and container ships.

Objective 5

Develop a Ship Operational Performance Prediction (SOPP) model using statistical data analysis techniques and taking into account operating profiles and environmental conditions. The developed model will be suitable for utilisation as part of a Ship Operational Performance Monitoring (SOPM) system.

Objective 6

Demonstrate the benefit of the proposed Framework for improving the energy efficiency of operational strategies by applying the developed SOPP model and the analysis of operating profiles to a series of case studies, focusing on: ship performance tends; hull and propeller maintenance decisions; the provision of ship performance feedback to the stakeholders concerned with ship operation.

4. RESEARCH METHODOLOGY

CHAPTER INTRODUCTION

The aim of this chapter is to provide details of the method that was used to ensure that the research aim and objectives were addressed. A flow diagram of the method is presented followed by a brief description of each method task.

4.1 Methodology Description

Figure 9 demonstrates the tasks undertaken to complete the research presented in this thesis and to meet the research aim and objectives.

Task 1.1 Review of Maritime Energy Efficiency Regulations

Task 1 was accomplished by reviewing current literature and information about maritime energy efficiency regulations. The discussion around the reviewed literature and information has been presented in the Critical Review, Chapter 2.

Task 1.2 Review of current energy efficiency practices

To help comply with the energy efficiency regulations, increase energy efficiency and hence reduce the amount of carbon emission emit by shipping, several best practice methods have been identified in the literature. These best practices are highlighted and discussed briefly. This task was again accomplished by a review of literature and information, and is presented in the Critical Review, Chapter 2.

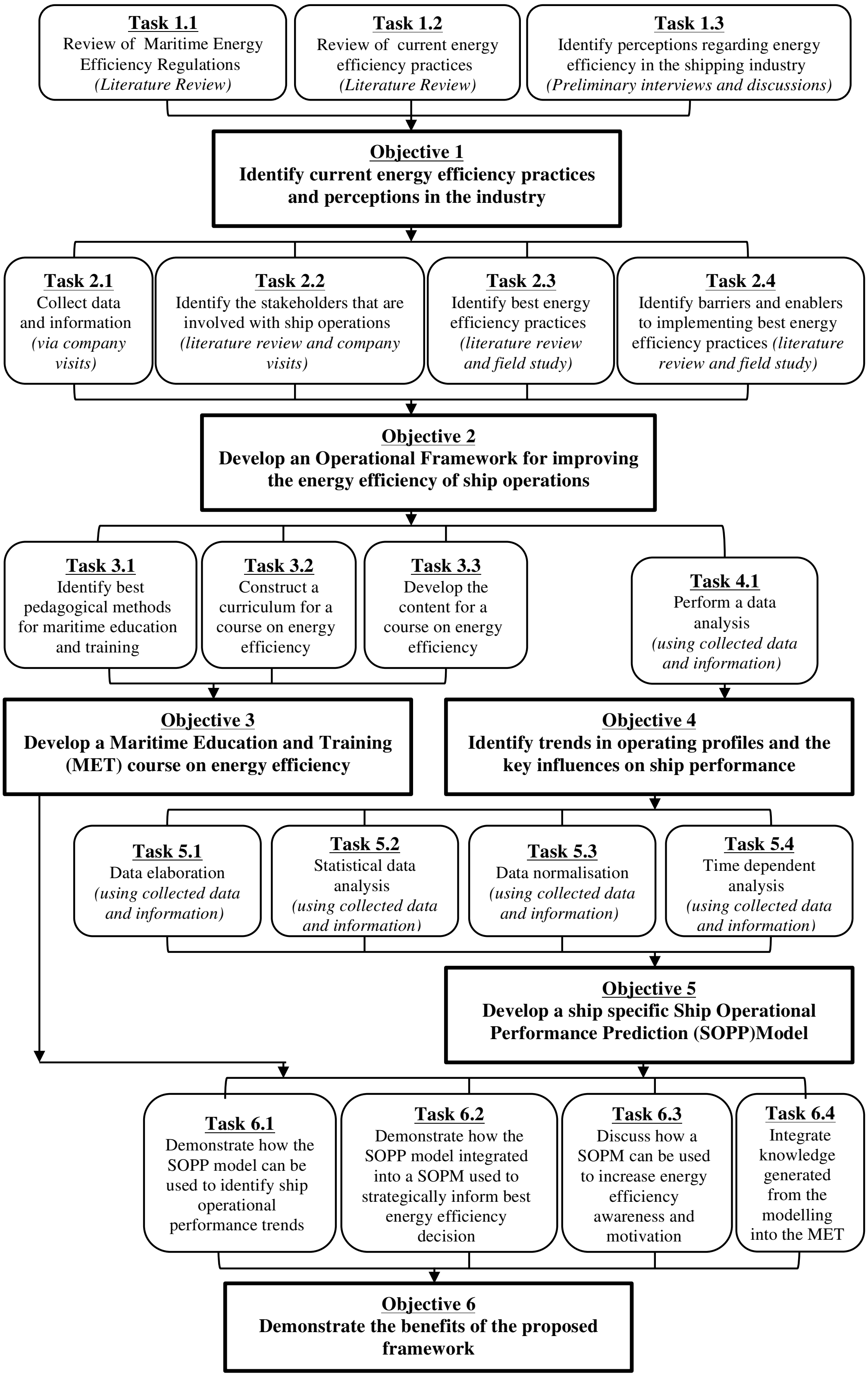


Figure 9: Method flow diagram

Task 1.3 Identify perceptions regarding energy efficiency in the shipping industry, preliminary interviews and discussions

Task 1.3 was to carry out preliminary interviews and discussions with as many personnel related to the shipping industry as possible. These personnel included: personnel working within shipping industry both on shore and at sea (met during company visits, conferences, events and collaboration projects); researchers with knowledge in the same or similar fields of research. The outputs of this task are included throughout the Critical Review, Chapter 2, and also in Chapter 5 where the field study company visits are detailed.

Task 2.1 Collect data and information

The collection of data and information related to ship operations and or energy efficiency was carried out during company visits (detailed in Chapter 5) and continuing correspondence. The data and information collected predominantly included in daily Ship Reports (SR's) and additional ship particular and design documents. The collection and pre-processing of the data is described in Chapter 7.

Task 2.2 Identify the stakeholders that are involved with ship operations

Task 2.2 included a review of literature to identify the key internal and external stakeholders in the shipping industry that have direct and indirect influence over the implementation of energy efficient ship operations: presented in the Critical Review, Chapter 2. This review was also supported by knowledge gained from field study exercises, and by working with people who have had practical experience working in the industry. A network of stakeholders was prepared and is presented in Chapter 5.

Task 2.3 Identify best energy efficient practices

In addition to the identification of energy efficiency best practices (Task 1.2), field studies and a more in depth literature review was undertaken to better understand practical implementation of best energy efficient ship operation. Specifically, a field questionnaire distributed amongst a seafarer target group helped to identify the best practices believed to be the most important for short and long term energy efficient ship operation: Chapter 5.

Task 2.4 Identify barriers and enablers to implementing best energy efficiency practices,

The review of literature (Chapter 2) and field study results (Chapter 5) identify the barriers and enablers that different stakeholders in the shipping industry face towards implementing ship operational best energy efficiency practices.

Task 3.1 Identify best pedagogical methods for maritime education and training

Conclusions from Tasks 1 and 2 were used to identify a specification for a Maritime Education and Training (MET) course on energy efficiency. Different pedagogical methods were reviewed to support the development of the course structure, curriculum and material. This task is discussed in Chapter 6.

Task 3.2 Construct a curriculum for a course on energy efficiency

The structure and curriculum was developed for three courses on energy efficiency and they have been presented Chapter 6.

Task 3.3 Develop the content for a course on energy efficiency

Based on Task 3.2 the content of one of the course on energy efficiency was developed. The key aspects of the developed material related to practical and effective implementation of energy efficiency best practices is included in Chapter 6.

Task 4.1 Perform a data analysis

Utilising the collected and processed ship operational data, as described in Chapter 7, the operating profiles of the case study ships were analysed: discussed and presented in Chapter 8. As a preliminary investigation for ship operational performance prediction, as series of relatively simple modelling techniques were assessed: presented Appendix D. These investigations supported the conclusion that an improved method for the analysis Ship Report (SR) datasets is required.

Task 5.1 Data elaboration

A data elaboration was carried out to calculate additional parameters (such as resistance) from the existing data variables contained in the SR datasets. In addition to the SR datasets, hull form parameters are required from the Trim and Stability booklet and the Holtrop and Mennen method was utilised along with Wageningen propeller B-series. The data elaboration process is presented in Chapter 9.

Task 5.2 Statistical data analysis

The data variables recorded in the SR dataset, along with elaborated data variables, were used in a non-linear regression analysis to determine the prediction equations (one for laden and one for ballast sailing) for the specific case study ship. The prediction equations in this task did not include a time variable. The statistical analysis is presented Chapter 9.

Task 5.3 Data normalisation

The performance prediction equations were used to predict the ship resistance for each SR record based on the operational input conditions in each record. The resistance apportioned to the difference between each of the operating input conditions compared to the baseline input conditions was identified, and then used to normalise the calculated resistance (determined during the data elaboration processes, Task 5.1). The data normalisation is presented in Chapter 9.

Task 5.4 Time dependent data analysis

The residual error between the normalised resistance and sea trial resistance (corresponding to the baseline) was plot over time to identify time dependent performance changes: i.e. changes due to hull and propeller surface degradation and fouling. The time dependent change identified was then described as a function of time and added to the performance prediction equations to form the final SOPP model. This task is presented in Chapter 9.

Task 6.1 Demonstrate how the SOPP model can be used to identify ship operational performance trends

A case study example for how the SOPP model was used to identify ship operational performance trends, such as power increase and speed loss in different operational conditions, presented in Chapter 10.

Task 6.2 Demonstrate how the SOPP model integrated into a SOPM used to strategically inform best energy efficiency decision

A case study example, presented in Chapter 10, was used as an example of how the SOPP model can be utilised for a life cycle analysis to support operational decisions; such as hull maintenance decisions.

Task 6.3 Discuss how a SOPM can be used to increase energy efficiency awareness and motivation

Case study examples were used to demonstrate how operating profiles and ship performance can be presented to raise awareness of ship performance, which is expected to help generate motivation towards the implementation of energy efficiency improvements. This is presented in Chapter 10.

Task 6.4 Integrate knowledge generated from the modelling into the MET

A discussion is held in Chapter 11 regarding the key aspects of knowledge generated from Tasks 1, 2, 4 and 5 that are utilised within the Maritime Education and Training (MET) course on energy efficiency (Task 3).

5. OPERATIONAL FRAMEWORK

CHAPTER INTRODUCTION

This chapter describes field studies that were undertaken to better understand the barriers and enablers to best operational practices. The field studies include discussions and interviews with stakeholders working in the industry, and the distribution of a questionnaire. A network of stakeholders was constructed to visually demonstrate the complexity of operational structures. Based on the abovementioned, a framework is presented for improving the energy efficiency of ship operational practices. This chapter has been organised into the four following sections:

5.1 Field Studies to Attain Knowledge of Ship Operation

To support attainment of research objectives 1 and 2, the author made a review of literature and spent as much time as possible speaking to experienced individuals and visiting different companies. The company visit field studies were considered important to: gain knowledge about the structure of different shipping companies; how they function to achieve the successful operation of their fleet; to discuss best energy efficiency practices. The companies ranged in size from small-medium to very large. Visits were also made to a number of Maritime Education and Training (MET) institutes, and conferences and collaborative work was undertaken. The benefits gained from visiting each company and the MET institutes are described in Table 4:

Table 4: Company visit field studies

Primary company type	Primary ship type / expertise area	Objective of the visit	Opportunities and benefits gained from the visit
Short Company Visits (1 to 4 days)			
Ship owner & operator	Passenger ferry	• Survey for a another research project • Gathering specific details for the purpose of this research	• Interviews and discussions with seafarers about perceptions, experiences and recommendations for energy efficiency best practices. • Informal meetings in the engine room and on the bridge whilst under sail: allowing observation of working environments. • Familiarisation with standard office based operating procedures related to voyage procedures and maintenance • Distribution of the field study questionnaire
Ship owner & operator	Tanker ships	• Gathering specific details for the purpose of this research	• Interviews and discussions with ship management and technical management personnel about perceptions, experiences and recommendations for energy efficiency best practices. • Introduction to the company's sustainability and energy efficiency management plans and existing procedures and systems used to monitor ship performance. • Visit and tour of a tanker ship that had docked. • Collection of operational datasets and ship information for use within this research • Distribution of the field study questionnaire
Ship owner & operator	Tanker ships	• Gathering specific details for the purpose of this research	• Informal meetings with onshore management personnel about current efforts towards energy efficiency best practices. • Collection of operational datasets and ship information for use within this research

Ship owner & operator	Container ships	• Gathering specific details for the purpose of this research	• Informal meetings with onshore management personnel about current efforts towards energy efficiency best practices and options for improvement. • Introduction to procedures, systems and plans for energy efficiency • Collection of operational datasets and ship information for use within this research
Ship Operator	Bulk and container ships	• Gathering specific details for the purpose of this research	• Collection of operational datasets and ship information for use within this research
Ship owner & operator	Bulk and container ships	• Gathering specific details for the purpose of this research	• Meetings with Commercial, Technical and Ship Management personnel about perceptions, experiences and recommendations for energy efficiency best practices. • Interviews and discussions with Commercial, Technical and Ship Management personnel about their job roles and responsibilities. • Introduction to energy efficiency procedures and plans, ship management procedures and the opportunity for questions and discussions. • Collection of operational datasets and ship information • Visit and tour of a ship yard, gaining an insight into yet another stakeholder within the shipping industry
Canadian MET University	MET	• Gathering specific details for the purpose of this research	• Discussion with a MET instructor about experiences and recommendations for MET and how energy efficiency is being considered and introduced. • Review and feedback on a draft of the developed MET material (Chapter 6) by the instructor.
2 MET Universities in Vietnam and 1 in the Philippines	MET	• Delivering energy efficiency presentations and conducting question and answer sessions	• Observations of different teaching and learning styles and familiarisation with the different facilities available at the MET institute for training cadets in the deck and engineering disciplines
UK MET Institute	MET	• Gathering specific details for the purpose of this research	• Distribution of the field study questionnaire
Danish MET Institute	MET	• Gathering specific details for the purpose of this research	• Observations of different teaching and learning styles and familiarisation with the different facilities available at the MET institute for training cadets in the deck and engineering disciplines • Preliminarily questionnaire field study interviews and discussions • Distribution of the field study questionnaire
Longer Company Visits (1 week to 1 month)			
Indian MET University	MET	• Tutoring Naval Architecture classes	• Observations of different teaching and learning styles and familiarisation with the different facilities available at the MET institute for training cadets in the deck and engineering disciplines • Preliminarily questionnaire field study interviews and discussions • Distribution of the field study questionnaire

Ship owner & operator	Tanker Ships	• Work experience	• Several interviews and discussions with personnel from the Commercial, Technical and Ship Management personnel (some whom had previous sea experience) about their perceptions, experiences and recommendations for energy efficiency best practices. • Informal meetings with Commercial, Technical and Ship Management personnel about their job roles and responsibilities. • Introduction to energy efficiency procedures and plans, ship management procedures and the opportunity for questions and discussions. • The collection of operational datasets and ship information for use within this research • Distribution of the field study questionnaire
Other collaborative work			
	Ship's Agent	• Supporting the research project of a summer intern whom had been a ship's agent in his previous job.	• Discussions on the direct and wider stakeholder network within shipping related to ship operations. Specific discussions focused on job roles, communication links and opportunities for energy efficiency improvement.
Conferences			
	Industry perspective	• Green Ship Technology Conferences in 2012 and 1013	• Continued discussions with several of the contacts made during the company visits • Networking and discussions with many people from different stakeholder groups: providing an insight into their roles, perceptions, and the barriers and enablers towards energy efficient shipping. The stakeholder groups included: ship brokers, banks and classification societies. • Updates from presentation and workshops on latest developments and opinions, primarily from an industry perspective.
	Research advances	• Low Carbon Shipping Conference 2011 and 2012	• Updates from presentation and paper on advances in research related to energy efficiency related to design, operational and regulatory measures.

The author maintained communication with several of the personnel in the different companies who continued to provide support by sharing knowledge, opinions, experiences as well as useful data and information.

5.2 Stakeholders Concerned with Ship Operations

Based on the literature review presented in Section 2.3, and the field study visits described previously, a network of stakeholders was constructed. This helped to identify the stakeholders with direct and indirect influence over a ship's operation, and to visually demonstrate the complexity of these influences. As discussed in Section 2.3, it is the stakeholders with direct influence over ship operations that have been the focus of this research. However, many operational boundaries are set by the external stakeholders and it is the role of the internal stakeholders to work within these boundaries. Therefore the influences, boundaries and communications between stakeholders must be understood, including consideration of stakeholder; job role objectives, responsibilities, communications, and improvement opportunities. Each of these aspects have been considered within the developed network of stakeholders that can be seen in Figure 10.

It was acknowledged that each company and series of companies has a different organisational structure and therefore the network shown in Figure 10 was constructed to represent a generic structure: it will not be applicable any one company in whole. Furthermore, the generalisation has been done so that each entity (single black line box) can be considered as an independent company or combined with another, for example: the ship owner may also be the ship manager; the charterer may be the same as the ship manager; the commercial management may be the same as the ship management; or not. It is not expected the network includes every stakeholder or communication link; however it provides a demonstration of the complexity of communication flows between the many of the stakeholders involved with ship operations.

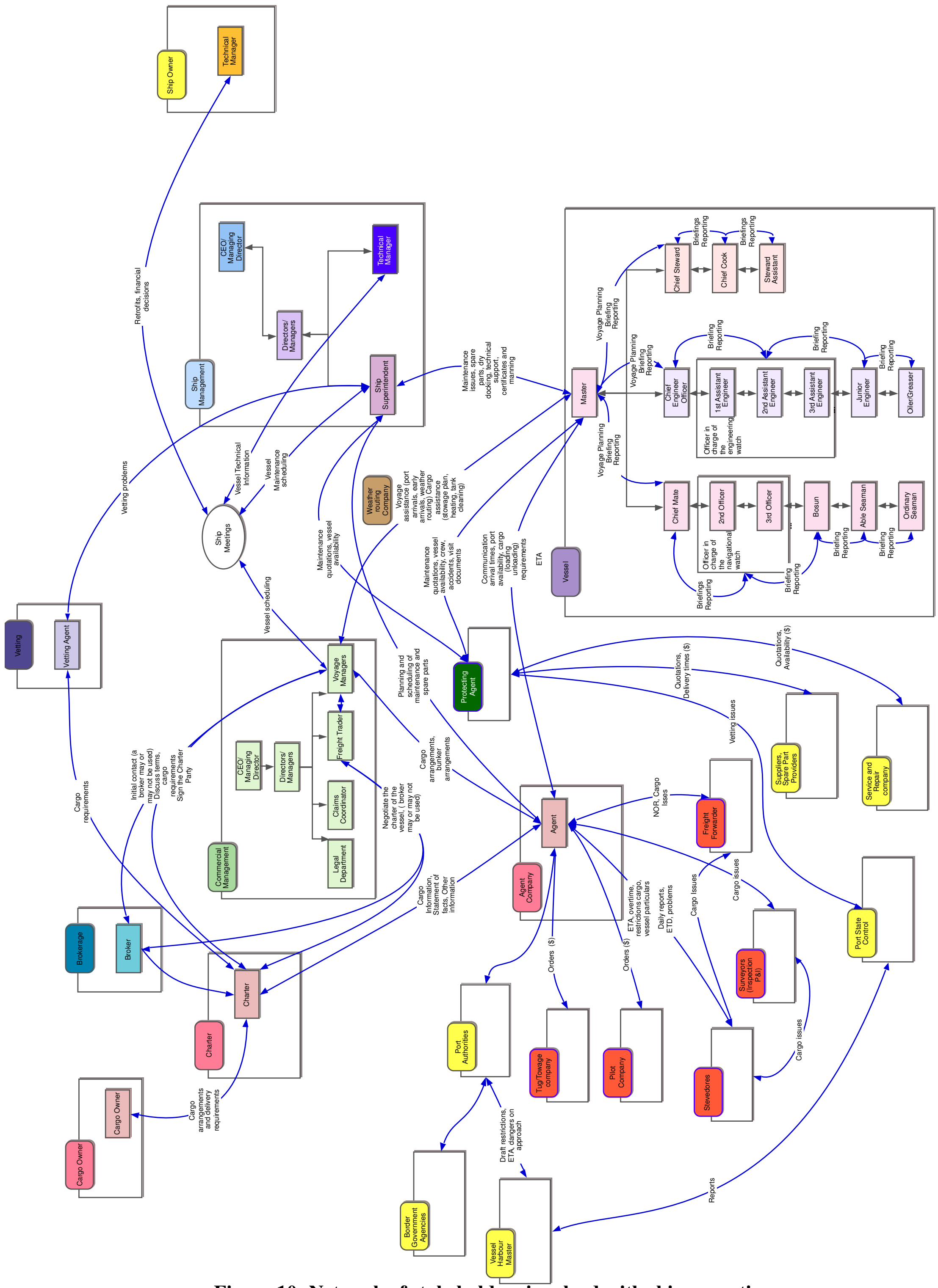


Figure 10: Network of stakeholders involved with ship operations

▪ **The job role tasks of stakeholders related to ship operation**

To simplify the following explanation of stakeholder job roles and responsibilities corresponding to Figure 10, a tramp shipping service is considered with a charter party arrangement (such as a time charter).

The Cargo Owner communicates with the Cargo Purchaser to agree on the amount and type cargo to be transported in a given time frame. The opportunities to influence energy efficiency lie with the importance placed on achieving an energy efficient supply chain, and can be realised through communications for the contractual agreement. In a similar way, the Cargo Owner (who may or may not be the Charterer) provides the Charterer with the cargo requirements and delivery information. The Charterer (who may or may not use a Broker) communicates with the Voyage Manager in the to *fix* a ship and agree upon the charter party. The job roles and responsibilities of the Cargo Owner, Purchaser, Charterer and hence Broker are focused around economic efficiency. Therefore increasing energy efficiency will be important to each of these stakeholders if it reduces costs (i.e. refer to the discussion on split incentives, chapter Section 2.3); or if a specific stipulation has been placed on environmental benefits. These stakeholders should be influenced to place higher importance on environmental issues, such as CO_2 emission reductions, by raising awareness and knowledge and putting mechanisms in place.

The Charterer communicates with the Vetting Agent regarding cargo requirements; and with the ship's Agent (who looks after the ship whilst she is in a specific port) regarding cargo information and the Statement of Facts (i.e. loading and unloading details, including delays and the reasoning why). The role of the ship's Agent will be discussed further in a later paragraph.

Focusing on the communication between the Voyage Manager and Charterer (with or without a Broker): it is the responsibility of the Voyage Manager to select the best ship to fix and negotiate the charter party, aiming to maximise energy efficiency by considering the following within the charterer's terms (which may be restricted by the Cargo Purchaser's requirements):

- Maximise utilisation of the fleet of ship's: taking a holistic view
- Select the best suited ship to fix by ensuring correct awareness of the actual fuel consumption performance of the ship: discussed in the next paragraph.
- Negotiate the laytime (i.e. the time allowed for the voyage) to allow for best economic and energy efficient fleet utilisation (i.e. maximising transport work) and average voyage speed (i.e. optimising for minimum fuel consumption by balancing speed, and time for the given route)

The Vessel Management should communicate with the Ship Superintendent (who may or may not be the Technical Manager) regarding the ship's actual fuel consumption performance. It was highlighted during the field studies that there is often a difference between the understood fuel consumption performance of a ship between the Commercial, Ship and Technical Management departments. This is a barrier to effectively achieving best energy efficient integrated operations. Thus regular communication regarding actual ship performance should be incorporated into company procedures. This could be supported by the use of a Ship Operational Performance Monitoring (SOPM) system to quantify ship performance and provide feedback to each of the stakeholders mentioned. Not only will this provide the knowledge of ship performance, it will also help to raise awareness regarding the implementation of energy efficient practices.

Meetings and communications between the Vessel Manager, Vessel Superintendent, Technical Manager and the Ship Owner (and their technical manager) are highlighted in Figure 10. For specific ship discussions the Master of the Ship may also be included. It should be noted that these stakeholders may belong to one or various companies and such procedures may or may not already be in place. The discussions should not only include topics on ship fuel consumption performance, but also:

commercial scheduling; maintenance scheduling; commercial performance; vessel technical performance. The benefit of achieving transparency of each topic is that it supports identification of practical solutions and decisions for best ship operations, e.g. related to: machinery maintenance; dry docking; hull and propeller maintenance; new operational practices; technology retrofits. Each of the stakeholders can contribute expert knowledge about the ship's performance from their job role perspective and identify their implementation barriers and responsibilities: all necessary for practical achievement of best economic and energy efficient ship operation.

The Voyage Manager communicates with the Master of the ship who has overall responsibility of the ship, or with the Officer On Watch (OoW) who communicates with the Master. Details discussed include the requirements for the voyage: i.e. departure and arrival ports, laytime and laycan, voyage assistance, cargo assistance, other information. Often it is the OoW that prepares the voyage plan, with or without the assistance of an internal or external Weather Routing Company. The stowage, heating and tank cleaning plans are prepared onboard and communicated to the Voyage Manager. At this point there is the opportunity to optimise energy efficiency by considering (not a finite list): weather routing, voyage speed profile optimisation, cargo heating arrangements. During the field studies visits it was reported that quantifiable fuel savings had been achieved by adjusting voyage speed when a delay was identified at the discharge port and by optimising cargo heating arrangements. These best practices were suggested for implementation by seafarers based on their expertise. They were then trialled and included into company procedures. This type of consultation, recognition of contributions, and follow through with successful actions is a good example of effective personnel resource management and engagement: further discussed in Sub-section 2.3.4.

The Master takes overall responsibility and management of the ship although the Deck OoW and the Engineering OoW have an important roles in implementing the voyage operations and communications. The Deck and Engineering OoW also manage sub-teams onboard in the deck, and engineering departments. The chief steward manages their team. Thus it is highlighted that seafarers are not only required to have a high level of technical skills, they are also required to be good team managers, leaders, team members and communicators. These skills are particularly important for encouraging an energy efficiency culture onboard and for completing procedures and communications as effectively as possible.

The ship's Master or the OoW communicates with the Ship Superintendent regarding maintenance issues, spare parts, scheduled dry docking and technical information. The Ship Superintendent then communicates the planning and scheduling of maintenance and spare parts with the ship's Agent, and the Master or OoW. The Master or OoW also communicates the maintenance, vessel availability and quotations with the Protecting Agent, who in turn also communicates with the Ship Superintendent. It is the Protecting Agent who then organises the quotations and delivery for maintenance issues and spare parts with the Spare Part Providers and Repair Companies. Crew accidents and documentations are also discussed during the communication. Additionally, any vetting issues that are raised are communicated between the Vetting Agent, Master and Ship Superintendent. This description of communications demonstrates how complicated the network of stakeholders is for organising maintenance and other operations. It is made clear that the external stakeholders can create operational barriers (i.e. due to the late supply of spare parts or repair providers) that prevent the internal stakeholders (i.e. the Ship Superintendent and Master or OoW) from completing the most energy efficient ship operation. Nevertheless, good communication by the internal stakeholders can help to reduce issues.

Similarly, the Ship Superintendent and the Master, or the OoW, communicates arrival times, port availabilities, cargo loading and unloading requirements with the ship's Agent who then commutates with the Port Authorities, the Tug and Towage company, Pilot Company, Stevedores, Surveyors, P&I Inspectors and Freight Forwarders. Again it is highlighted that the efficient operation of the ship is susceptible to delays with any one of these external stakeholders. Furthermore, it is highlighted that the ship's Agent and the communications with the Ship Superintendent and the Master or OoW are important for organising the most energy efficient port stay and loading and unloading procedures. The recognition and communication of port delays provides the opportunity for ship speed optimisation. Whilst not within the scope of this research, the external stakeholders mentioned present a group of personnel important for considering energy efficiency ship operational improvements.

Concluding the discussion above, the developed stakeholder network visually demonstrates the complexity of the communications and operations between internal and external stakeholders with direct and indirect influences over energy efficient ship operations. Improved human factor skills were identified as enablers to energy efficient communications, operations and promoting an energy efficient culture. Transparency of ship performance between internal stakeholders (namely the Commercial, Ship and Technical Management departments) achievable by meetings and good communication and supported by a Ship Operational Performance Monitoring System, can help achieve integrated energy efficient operations. Furthermore, all stakeholders should contribute their job role expertise towards finding practical solutions for energy efficient operations, where identification of best practices should be recognised and incorporated into operating procedures.

5.3 Field Study Questionnaire

5.3.1 Motivation to Carry Out The Field Study Questionnaire

Chapter 2 has discussed existing research into the barriers to energy efficient ship operations, which has predominantly been carried out from the view point of management and investment level stakeholders. However, it is acknowledged that seafarers operate the ships on a day to day basis. Therefore, whilst the decision making level is often with onshore management, seafarers play a critical role in putting changes into practice, making the real-time onboard decisions, and operating the machinery and technologies installed onboard. As no published research to investigate the views, opinions and knowledge requirements of seafarers regarding energy efficient ship operations was identified, a field study was undertaken using a questionnaire.

5.3.2 Objective of the Field Study

The objective of the preliminary investigation and questionnaire field study was to investigate seafarers' and cadets (i.e. training to be seafarers) levels of awareness, knowledge and motivation towards carbon emissions in general, shipping carbon emissions, and towards making reductions. The questionnaire also aimed to investigate the participants' views on the most important ship operations to improve for increased energy efficiency, along with their preferred learning methods.

5.3.3 Preliminary Investigation

Prior to the design of the questionnaire a preliminary investigation was carried out at Maritime Education and Training (MET) institutes in the following countries: UK, Netherlands, Turkey, Greece, Finland, Denmark and Sweden. A few industry people were also contacted. In addition to formal and informal interviews, a first design of the questionnaire was distributed and feedback was gathered. The results for the questionnaire were used to test the questionnaire analysis process. The preliminary investigation was carried out in 2011, prior to the introduction of the maritime energy efficiency regulations.

Summarising the key findings from the preliminary investigation, it was concluded that in 2011 there was very little awareness or education available regarding: CO_2 as a greenhouse gas; energy efficient ship operation to reduce CO_2; and the up and coming energy efficiency regulations that were being discussed at MEPC meetings. The only awareness of energy efficient ship operation at the time focused on operational cost saving benefits. There was little motivation to improve energy efficiency whilst completing operations in line with existing rules and procedures. There was a lack of awareness about how energy efficiency can be achieved without compromising safety. Furthermore, it is a concern that too much programmed maintenance and operations can reduce motivation and the opportunity for seafarers to trial and implement best energy efficient practices.

Whilst energy efficiency knowledge is taught amongst other topics during Maritime Education and Training (MET) courses, it is not addressed as a specific subject. This has lead to low seafarers' awareness regarding knowledge application of best energy efficiency practices in every day ship operation. Group discussions, class exercises and simulator training are effective ways to observe practices and develop interest, knowledge and motivation towards the subject. Knowledge and skills that a specific course on energy efficiency should address, include: energy efficiency best practices, hands on work skills, problem solving skills, and problem solving confidence. Training also needs to be continue once working on a ship to ensure that the purpose of energy efficient procedures is fully understood, along with how to carry them out effectively, and how to find support if it is required. As a final point, education and training is not sufficient alone. Application of knowledge requires the support of the company in terms of operating procedures and encouragement to make changes. For a full report of the preliminarily investigation refer to (Banks et al. 2011).

5.3.4 The field Study Questionnaire

The questionnaire was designed and distributed towards last quarter of 2011 and over the first quarter of 2012: previous to the enforcement of the Energy Efficiency regulations on the 1st January 2013. 317 responses were received in total from a target group of seafarers and cadets.

To distribute and receive adequate responses to the questionnaire contacts were established with management personnel in four different shipping companies. Cooperation with these personnel was significantly beneficial as they were able to distribute the questionnaire to their seafaring staff with directed authorisation and encouragement to participate. The participating shipping companies were predominantly larger companies already proactively working on increasing environmental awareness. The questionnaire was also distributed to a class of seafarers undergoing continual professional training at a MET institute, and to two student cadets groups undergoing their initial seafarer education at MET institutes.

Results from written answers that contributed to some of the conclusions made in the following discussion have been included in Appendix B – Quotes from the Questionnaire Analysis, for further reference.

- **Questionnaire Results**
  - **Profile of Questionnaire Participants**

It was concluded that the questionnaire participants had been educated and trained in a large range of countries and thus the responses given can be considered to include views from a global maritime community; including a range of educational and cultural differences. The results are most likely to be based on tanker operations as this was the most common ship type that participants' had sailed on. 84% of participants had more than 1 year of sailing experience and therefore the results can be assumed representative of the opinion of seafarers working at sea. 35% of the questionnaire participants worked in the bridge team (Master/Captain and Deck Officer) and 33% from the engineering team (Chief Engineer and Engineer): thus opinions and expertise from both operational groups were captured.

- **General Awareness And Knowledge of Carbon Emissions**

The largest proportion of the questionnaire participants believed that they were aware of the effects that carbon emissions have on our world: 20% had the confidence to say they were *very aware* but 23% believed they were only *fairly* or a *little aware*. They considered their knowledge to be less: only 6% believed they were *very knowledgeable*. It is considered that without this awareness and knowledge, how can it be expected that seafarers will form a motivation towards making improvements.

Figure 11 demonstrates the evident benefit of knowledge about carbon emission. It shows that that the participants with increasingly more knowledge, consider they have tried increasingly more to make energy efficiency improvements onboard. [The result for *no knowledge* can be ignored as it is based on only 1 response (N) and thus is reflective of a personal opinion rather than of seafarers in general].

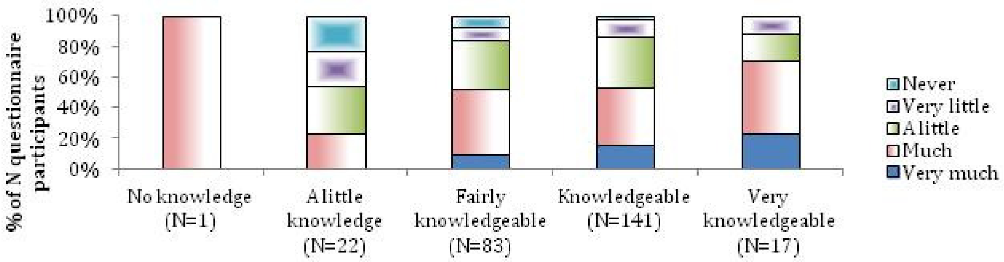


Figure 11: Participants improvement efforts considering their level of knowledge about the effect carbon emissions have on our world

Some written responses (such as Quotes 1: Appendix B) demonstrate that a wider awareness as to why energy efficient implementation efforts are required by everyone, and what efforts are being made by others. This is to avoid a build up of resentment or feelings of being targeted for efforts which both reduce motivation to provide efforts. It should be recognised that personnel in different job roles have influence over operational changes with varying impact on energy efficiency improvements. However, it should also be stressed that all small efforts are accumulative and that efforts are required from everyone. Methods to encourage efforts at all levels include increasing transparency of common company objective and goals, and the efforts being made by different personnel groups: particularly efforts with larger improvement potential to demonstrate that the smaller efforts are also needed. Recognition of efforts can also encourage personnel engagement as discussed in Sub-section 2.3.4.

- **Knowledge Sources For Low Carbon – Energy Efficiency Knowledge**

Figure 12 demonstrates that the most common method for current knowledge acquisition about the effects of carbon emissions is via newspapers followed by TV documentaries, TV news and magazines. It is known that the knowledge content within these sources is not comprehensive, nor specific, to carbon emissions, particularly to shipping, and thus these sources do not provide the knowledge levels required for effective shipping carbon emission reductions.

It was demonstrated that less than half of the participants had discussed carbon emission with others, indicating that it was not a topic of focus and hence discussion: particularly when considering that 'share and discuss' was quoted as an effective method for learning in many response. Figure 12 also demonstrates that only 20% of 311 participants had gained knowledge about the effects of carbon emissions via a MET course. The participants who had undertaken such courses were asked to provide additional details. No comments appeared specific to the subject of energy efficiency or carbon emissions; although awareness of other GHG's (sulphur oxide and nitrogen oxides) appeared to be increasing.

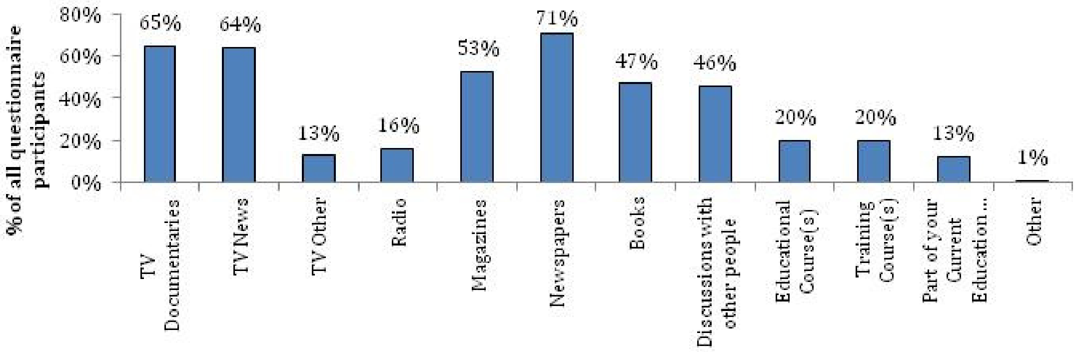


Figure 12: Methods for the acquisition of knowledge on the effects that carbon emissions have on our world (N= 311).

- **Technical Awareness And Knowledge About How To Achieve Carbon Emissions Reductions**

Participants were asked how they think carbon emissions reductions can be achieved during ship operation (see examples of reoccurring comments in Quotes 2). The written responses contained many reoccurring, generalised comments that lacked in technical content. Whilst this could be indicative of a lack of awareness and knowledge about ways to increase the energy efficiency of ship operation, it could also be the case that the participants could expand answers further given the opportunity and or a non written response format.

In addition to the suggested improvements in Quotes 2 (including: fuel quality, availability of spare parts for maintenance; voyage scheduling; voyage handling; cargo handling; good plant management; training) the participants were asked to rank listed improvement areas in order of which need most improvement to achieve the maximum carbon emissions reductions. It was identified that all areas need improving and the ranking order was as follows:

- Low carbon technologies (1st – most improvement needed)
- Management decisions (2nd)
- Low carbon regulations (3rd)
- Improvement of onshore performance support (4th)

- Reliability of onboard tools (decision support, monitoring devices)(5^{th})
- The improvement of crew awareness and motivation (5^{th})
- Onboard available material and information (7^{th})
- Crew initiative and problem-solving skills (8^{th}– less improvement needed)

Similarly, participants were asked to rank a list of stakeholders in the order of most influence over achieving maximum carbon emission reductions:

- The shipping company (1^{st} - more influence)
- The engineering team (2^{nd})
- The shipper (3^{rd})
- Onshore shore support (4^{th})
- The voyage contract department (5^{th})
- The bridge team (6^{th})
- The deck team (7^{th}- less influence)

A somewhat surprising result was the low ranking of the bridge team, particularly in comparison to the engineering team. This is because suggested methods for improving operational energy efficiency include good voyage planning and handling; which fall under the job roles of the bridge team. These practices are also highlighted in the SEEMP guidelines previously discussed in Sub-section 2.2.2.

The high ranking of management decisions and onshore performance support in the above two question responses was further emphasised by written responses. The provision and utilisation of support between ship and shore (going both ways) was highlighted as important for operational improvements. Participants were asked how much they would request information from onshore support. Whilst 60% of the participants responded that they would request information *often* or *very often*, 40%

of participants would request it *sometimes*, *not very often* or *never*. Measures to improve resource and expertise sharing should be investigated and improved: awareness should be increasing about what support is available, and beneficial support for provision should be identified. One enabler to providing support is the use of a Ship Operational Performance Monitoring (SOPM) system that can be used to identify performance problem areas. The analysis could be done onshore, minimising analysis and administrative burdens onboard, and solutions to improve low performance should be discussed utilising all expertise.

Written quotes (such as those in Quotes 3, Quotes 4 and Quotes 5: Appendix B) highlight communication and teamwork between all stakeholders as important for energy efficient operations: including between department onboard, onshore and with external stakeholders: see Figure 10 for communications in the stakeholder network. An example communications with external stakeholders identified for improving energy efficiency is the arrangement of spare parts.

Improved communications, teamwork, and resource and expertise sharing between stakeholders is required for maximising integrated operations and maximum energy efficiency improvements. An enabler to this is increasing personnels' awareness and knowledge of other stakeholders' job roles, expertise, skills, responsibilities and efforts: see Quotes 3, mentioning that seafarers in the deck and engineering departments should be at least familiar with the other discipline.

- **Importance and Possibility Motivation and Incentive towards energy efficiency**

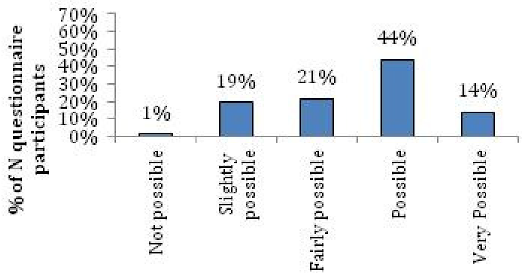


Figure 13: How possible participants believe it is for crew to help reduce shipping carbon emissions (N=314)

On average the participants' demonstrated a positive view to how important they think it is to reduce carbon emissions: 65% of participants though it was *very important*, 29% *important*, 4% *neither important nor unimportant*, and 2% considered it *very unimportant*. There was a slightly less positive view for how possible it is to reduce carbon emissions emit by shipping. However the mode of participants still thought it is possible. Shown in Figure 13, there was a wide distribution of opinions as to how possible the participants thought it is for seafarers to help reduce carbon emissions. It cannot be expected that crew will make conscious effort to reduce carbon emissions if they do not think it is important or possible. Therefore awareness needs to be created about why it is important and the ways in which seafarers can contribute towards energy efficient ship operations. This will include background knowledge about Climate Change and the regulatory drive (out with and within the shipping industry) and technical knowledge.

Some reoccurring comments regarding why participants had not tried to implement energy efficiency practices are shown in Quotes 6 and Quotes 7, including: lack of knowledge, training; lack of motivation to use existing knowledge and available information; it is considered a low priority; limited by operating requirements and resources (including time and man power). Responsibility shifting was identified as one reason for low motivation. Without motivation it cannot be expected that improvements will be implemented, even if the knowledge is known.

In addition to increasing knowledge, the introduction of regulations and incentives were mentioned as important for increasing motivation to implement improvements. The majority of participants (94%) believed it was *important* or *very important* to introduce shipping carbon emissions regulations. Introducing low carbon regulation was ranked as the third most important area that needed achieve effective carbon emission reductions. Company policy and operating procedures were also strongly commented on in written answers. The general impression given is that without mandatory pressure to carry out energy efficiency improvements, it will not happen due to existing high workloads and other priorities (Quotes 7). This is indicative of an unestablished energy efficiency culture. Participants were asked if a company reward would affect how much they try to make energy efficiency improvements onboard. The results indicated that although a reward is likely to make a positive difference towards motivation, opinions varied considerably and thus it may not be as effective as hoped. Another company procedure that was highlighted several times as a key motivator towards making energy efficiency improvements included providing useful feedback (see Quotes 8).

It was determined that 74% of participants would like to know *more* or *a lot more* about how crew can help reduce shipping carbon emissions; demonstrating positive motivation to learn. However, 27% would only like to know *some* or *a little*. This demonstrates a lack of motivation that could be due to any one of the following: low motivation to learn in general; lack of interest in the subject; a reluctance to learn additional tasks to implement; belief that improvements are not possible. Crew also may think that they will end up with extra workload in addition to their overloaded work. Methods, such as those previously discussed, should be used to addresses these motivational issues.

- **Effective Learning Methods**

Participants were asked to rank a list of learning methods in order of most effective. The methods identified as most effective include practical workshops, simulator training and onboard training: where practical workshops were ranked as more effective than simulator training. Whilst classroom based MET is fundamental for delivering the factual content of a subject, practical workshops and simulator training are extremely important for allowing 'trial and error' practices to be implemented, and for demonstrating (quantify) potential savings that can be achieved. This is important for increasing understanding at a practical level and encouraging a personal appreciation of the task: most likely to result in improved awareness, knowledge, skills and motivation. Simulator training should be highlighted as it provides an opportunity to practice best operational practices in an environment that provides a holistic overview of how systems and people operate together. This can promote situational awareness (Quotes 9).

Along with workshops, simulator training provides an environment where focused attention and feedback can be given on a specific subject, such as energy efficiency. This may be more difficult during onboard training with the requirements of other workload tasks. Onboard learning will also be influenced by the supervisor's knowledge and motivation towards energy efficiency: where it has been established that an existing energy efficient culture is not evident.

- **Questionnaire Conclusions**

Summarising the main conclusions from the questionnaire, knowledge needs to be provided to seafarers, containing the necessary technical detail with specific focus on best energy efficient practices for ship operations. Awareness of knowledge application in practical scenarios needs to be addressed, along with the drivers towards energy efficiency (i.e. carbon emission reductions), to help to generate understanding and motivation towards changes. Increased knowledge about carbon emissions has been demonstrated to have a beneficial impact on the effort made to improve energy efficiency onboard. Seafarers with sailing experience can offer practical knowledge about how to make energy efficiency improvements, contribution to a technical level of details may be provided more easily via group discussions than written responses.

In general there is positive motivation towards energy efficiency improvement of ship operations, and to learn more about how to achieve them. However, it is indicated that an energy efficient culture onboard is not widely established yet. Barriers to its establishment include existing high workloads, procedures and negative motivations from some seafarers. Key enablers to improving energy efficiency include the introduction of regulations and mandated procedures, the implementation of new technologies and improved onshore support. Thus communications between personnel should be improved and understood on both sides of the communication link. Communication improvements can be achieved by increasing: related human factor skills; transparency of goals and efforts; transparency of job role objectives and improvement opportunities; performance feedback enabled by the use of a ship operational performance monitoring system. Furthermore, motivation to implement improvements can be encouraged with incentives, performance feedback and effort recognition.

As a final conclusion, both Maritime Education and Training (MET) and improved company practices are required to for most effective improvements. The most effective methods for delivering MET have been identified to be practical workshops, simulator training and onboard training.

For further details and discussion on the questionnaire results refer to (Banks et al. 2014).

5.4 The Operational Framework for Energy Efficiency Improvements

Based on conclusions identified in Chapter 2 (page 107 for the Chapter Summary) and those from the field studies, particularly the questionnaire, a Operational Framework for achieving practical energy efficiency improvements is identified in this Section.

5.4.1 The Objective and Aims of the Framework

The objective of the Framework is to set up a systematic and generalised process that can be applied widely in the industry to effectively identify and implement practical, best, energy efficient ship operations: to assist in the attainment of shipping carbon emission reductions, in line with reduction targets.

To achieve this objective, and the implementation of best practices, the following aims were identified:

- Increase the target groups awareness, knowledge and skills (both technical and non-technical) and motivation towards energy efficient ship operation.
- Provide the tool considered necessary to achieve the above aim

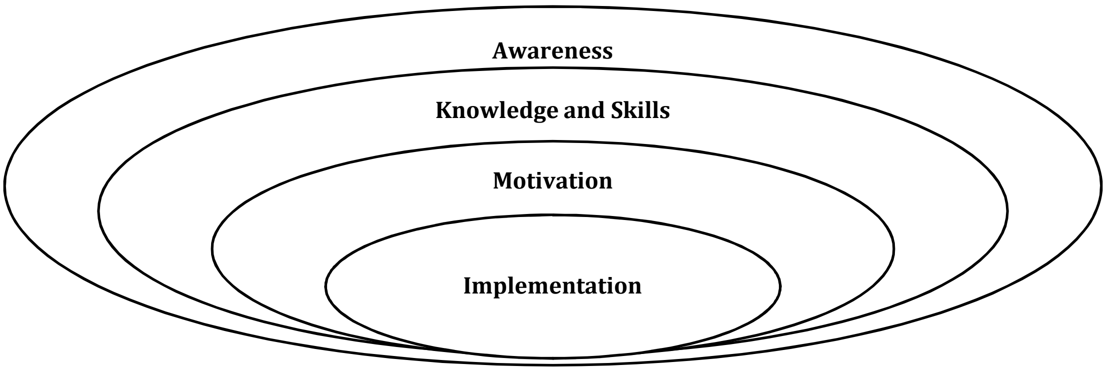


Figure 14: Aims of the Framework

Demonstrated in Figure 14, the generation of awareness is the first and encompassing aim as it is the starting point, trigger, for the use of knowledge, skills and motivation to implement energy efficient operations. Two key aspects of awareness include:

- An appreciation of the requirements for energy efficiency, CO_2 reductions and Climate Change mitigation, within and outwith the shipping industry
- What are the best energy efficiency practices

Knowledge and skills are then necessary for development, including: a higher level technical skills; a holistic appreciation of the ship's performance; human factors (such as resource, behavioural, communication, teamwork and leadership management). If awareness and motivation are gained without the correct knowledge and skills of best energy efficiency practices, then implementation of poor practices could occur.

Motivation can be developed at any stage but is considered to be the third critical task towards the implementation of energy efficiency improvements. Development of awareness, knowledge and skills can be enablers to motivation along with other mechanism introduced in to company procedures: such as feedback, incentives and procedure changes.

5.4.2 Target Groups Considered in the Framework

The target group of the Framework have been previously been referred to as internal stakeholders, including; seafarers and personnel working in the commercial, ship and technical management departments (see Figure 10 the network of stakeholders for further references). In addition to seafarers working at sea, cadets have also been introduced as target groups. This is because there is a career progression that often exists through the target groups: i.e. cadets become seafarers, seafarers take up onshore management positions. Its important to introduce an energy efficient culture and knowledge at the earliest stage possible. Each target group is described:

- **Cadets**

Cadets are considered to be students completing their initial seafarer training, typically in a MET institute. The cadets could be training to be part of the deck or engineering department.

- **Seafarers**

Seafarers of primary focus in the Framework are those in the deck and engineering departments. The deck department refers to the officers that typically work on the bridge (such as the Master and Deck Officers). The engineering department includes the Chief Officer and Engineering officers. Ratings and other seafaring staff shown developed stakeholder network (Figure 10) have not taken a primary focus within Framework. This is because their awareness, knowledge, skills and motivation towards an energy efficiency, and development of an energy efficiency culture, can be encouraged and developed via good team management by the Officers on Watch. Hence why development of good leaderships skills are required to be taught in a MET course on energy efficiency.

- **Commercial Ship and Technical Management Departments**

The Commercial, Ship, Technical Management departments include Vessel Managers, Vessel Superintendents and Technical Managers, amongst other personnel in different specific company scenario. They all have direct influences over ship operations although their job role objectives and expertise areas differ. Each are important for achievement of best energy efficient integrated operations for energy efficiency.

- **Business Management**

Business management stakeholders are considered to be the management personnel who have influence over higher level business and strategic decision; such as investments.

- **Maritime Education and Training (MET) Trainers**

Consideration of MET trainers is important for the delivery of MET to cadets or any of the other stakeholders. This is to ensure that they have the required awareness, knowledge, skills and motivation towards energy efficiency; particularly as it has been highlighted that an energy efficiency culture is not yet established.

5.4.3 The Framework

To action the objective and aims of the Framework it was considered that the following elements need to be developed:

- Maritime Education and Training on energy efficiency
- Analysis of ship operational profiles (a key part of SOPM and improving operational strategies)
- A Ship Operational Performance Prediction (SOPP) Model (required to support SOPM)

Based on these development it was then considered that the following can be then be considered to action the objective and aim:

- Ship Operational Performance Monitoring (SOPM) for feedback distribution and supporting operational strategic decisions
- Updates, changes and additions to Operating Procedures

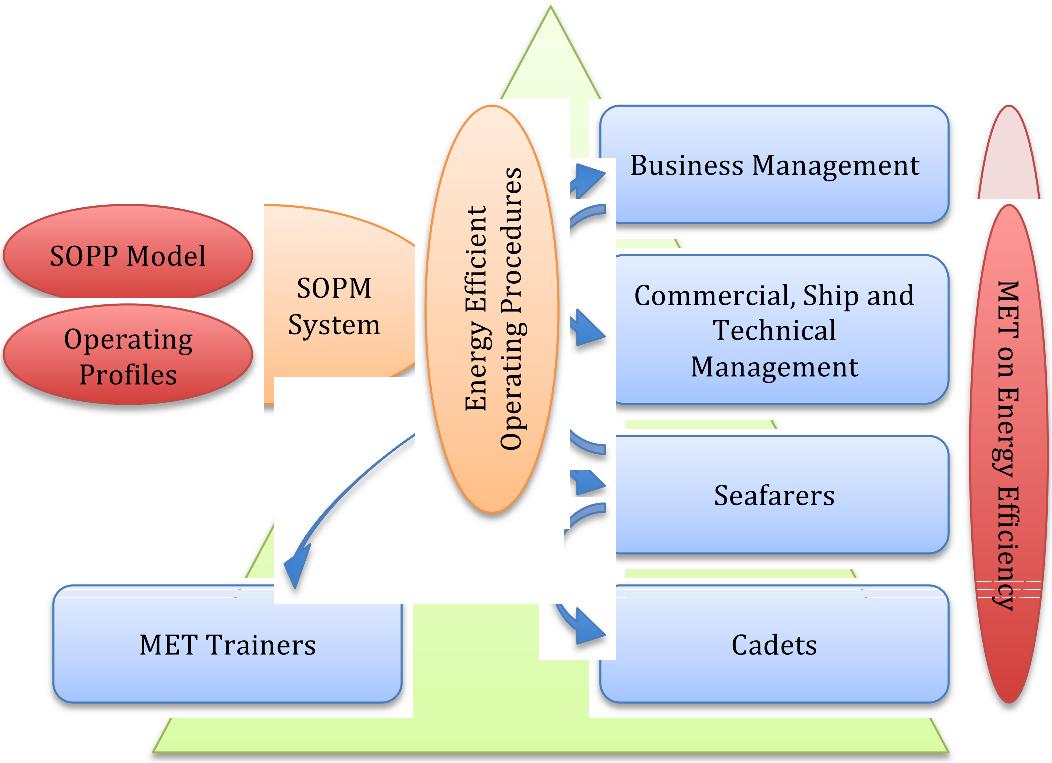


Figure 15: The Operational Framework for improving ship energy efficiency
Where: SOPM Ship Operational Performance Monitoring, SOPP Ship Operational Performance Prediction, and MET is Maritime Education and Training

Figure 15 demonstrates the Framework where the following aspects have been captured:

- The green background pyramid demonstrates the flow of common company operational structures, and career progression. The progression of some seafarers and management department personnel to MET trainers is also captured.

- The red shows the elements of the Framework that have been developed (as described in following chapters). MET is shown to be important for all target groups. However a faded extension of the MET is shown for business management as they are not a primary target group considered for the delivery of MET within the Framework. This is because much of the existing MET developed by industry stakeholders such as classification societies, is aimed at this target group. They also have different technical skill requirements to seafarers and the Commercial, Ship and Technical Management personnel (i.e. they are not concerned with the daily operation of the ship). Nevertheless, the MET material developed within the Framework can be used for delivery of MET to business management, selecting the most relevant details and selecting the most appropriate delivery format.

- Orange shows the key features of the Framework that can be supported by the developed elements. Ship Operational Performance Monitoring (SOPM) should support the quantification of ship performance, including for fuel consumption and carbon emissions. Feedback should be generated and distributed in the format correct to each of the Management departments and seafarers. Operating procedures should be updated to include processes for feedback. Processes should be established for recognising and distributing good efforts and best practices for energy efficient operation in all departments. Methods to increase awareness and knowledge in addition to ensuring MET for personnel should be considered (e.g. regular bulletins, company forums, etc.). Company objectives could be updated to ensure common goals for safe and energy efficient best practices. All of the above should help achieve transparency of ship performance and operations and help contribute to staff engagement, awareness, knowledge, skills and motivation towards operational energy efficiency.
- The communication and information flows are shown very simply by the arrows in the Framework.

A specification of each of the three development features is given in the following Sub-sections; again based on the discussion and conclusions presented from Chapter 2 and field studies.

5.4.4 Maritime Education and Training Specification

A focus identified for the MET developed within the Framework was to build upon existing MET and the IMO model course (noting that the IMO model course was not published at the time when this research started). Specifically it was identified that the following should be addressed in an MET course on energy efficiency: human factors; job role objectives; emphasis on the need for integrated operations. The following specification for the development of a MET course was identified:

- Develop a comprehensive set of material and exercises by collating knowledge of best practices gained from industry experience and research.
- Include a focus on job role objectives, responsibilities and communications
- Include a focus on barriers and enablers to energy efficient best practices in different practical scenarios.
- Include a focus on the human factors related to energy efficiency and promote skills development (specifically: teamwork, leadership, communication, situational awareness).
- Promote discussion on how to practically achieve energy efficiency best practices; not only allowing for solutions to be identified, but also development of higher level cognitive skills (e.g. problem solving)
- Clearly present the benefits of implementing energy efficiency, including but not limited to, cost savings.
- Provide comprehensive material, knowledge, skills and motivation to trainers around the world, taking into account that an energy efficiency culture may not yet be established.

The development of the MET is presented in Chapter 6.

5.4.5 Analysis of Operating Profiles Specification

The following specification was identified for the analysis of operating profiles:

- Include the following profiles related to energy efficiency:
  a. Passage type profles (i.e. time spent in ballast, laden, port)
  b. Speed profiles
  c. Cargo load and trim profiles
  d. Dry docking and hull and propeller maintenance trends
- Include analysis for average profiles (i.e. yearly, fleet wise) and ship specific (i.e. daily, voyage) profiles.

The analysis of operating profiles is presented in Chapter 8.

5.4.6 Ship Operational Performance Prediction Model Specification

The following specification was identified for the functions the SOPP to be developed as part of the Framework:

- Utilise ship operational datasets that are already collected by most, or all, shipping companies to allow for a practical and wide spread solution for Ship Operational Performance Monitoring in the short term.
- Identify performance impacts due to weather conditions and time dependent performance changes (such as hull and propeller fouling and surface degradation).
- Assess ship performance in terms of fuel consumption and fuel cost so that it can be integrated into an economic model to assess the cost effectiveness of different operational decisions.

- Assess ship Performance in terms of should also be assessed in terms of energy efficiency and CO_2 indicators so that environmental impacts can be assessed.
- Provide an estimate (prediction) of ship performance given known operational conditions (i.e. input data).
- Evaluate past performance of the ship over: possible if a historic operational data is available.
- Utilising both historic and continually collected data (i.e. daily) to assess changes in ship performance.

The development of the SOPP model is presented in Chapter 9.

CHAPTER SUMMARY

The benefits of field study visits were described, contributing to better understanding of: operational structures, best energy efficient practices and the barriers and enablers to best operational practices.

A network of stakeholders was developed to visually demonstrate direct and indirect influence over a ship's operation, and to visually demonstrate the complexity of communications and cooperations.

A field study questionnaire was carried out to investigate seafarers' and cadets levels of awareness, knowledge and motivation towards carbon emissions in general, shipping carbon emissions, and towards making reductions. The results from 317 responses were analysed and discussed.

Based conclusions from chapter 2, the field study visits and the field study questionnaire, an Operational Framework to improve ship energy efficiency was developed, with the objective to increase energy efficiency awareness, knowledge, skills and motivation.

Key elements of the Framework highlighted for development include:

- *Maritime Education and Training on energy efficiency*
- *Analysis of ship operational profiles (a key part of SOPM and improving operational strategies)*
- *A Ship Operational Performance Prediction (SOPP) Model (required to support SOPM)*

Development of these elements were identified as enablers to the following features of the Framework.

- *Ship Operational Performance Monitoring (SOPM) for feedback distribution and supporting operational strategic decisions*

- *Updates, changes and additions to Operating Procedures*

A specification was written for each Framework elements, which will be addressed in the following chapters.

6. MARITIME EDUCATION AND TRAINING FOR ENERGY EFFICIENCY

CHAPTER INTRODUCTION

The aim of this chapter is to describe the Maritime Education and Training (MET) that was developed as part of the Framework to improve the energy efficiency of ship operations. The research presented focuses on the key aspects of the MET design related to energy efficiency, and those not currently evident in other MET courses. The research related to the development of the MET but not specific to energy efficiency is given in Appendix C. There are four sections to this chapter as follows:

<u>*Section*</u>

6.1 Addressing the Specification

6.2 The Courses

6.3 Course Content

6.4 Material Design and Development

Chapter Summary

6.1 Addressing the Specification

The specification for the development of Maritime Education and Training (MET) was presented in Section 5.4.4. The aim is to increase the awareness, knowledge, skills and motivation of the target groups, including cadets, seafarers, onshore management personnel. Each target group is described in Section 5.4.2 and teaching requirements considered specific for each have been identified and presented in Appendix C3.

To achieve the aim of the MET, it was identified that it was necessary to focus on the provision of comprehensive material that can be used by the trainer of the course, to ensure that they have a level of required awareness, knowledge, skills and motivation regarding energy efficiency and best practices (see Section 5.4.4 for the MET specification). It was considered that only once the trainer has the required awareness, knowledge, skills and motivation themselves, they can teach and pass the knowledge on to their trainee group. This is important considering that it was concluded in Chapter 5 that an energy efficiency culture does not currently exist and energy efficiency is not addressed as a specific focus topic within MET.

It was also identified that the developed MET on energy efficiency should include topics that promote the development of human factor skills in relation to energy efficiency. These skills (i.e. teamwork, leadership, communication, work load management and decision making) are the same topics that are included in existing Maritime Resource Management (MRM) courses. The focus of most of the existing MRM courses is on safety. Nevertheless, it was considered that a lot could be learnt from feedback on these courses regarding the successful teaching of human factor skills. Conclusions from the review of an informal discussion related to various MRM courses, contributed to by MET trainers, seafarers and other personnel in the shipping industry sharing their experience and opinions, is presented in Appendix C1.

A key feature of the developed MET material for energy efficiency is that it should focus on the implementation of high level technical and non-technical skills. Different knowledge and skill levels can be accounted for by describing desired learning objectives. Table 5 provides examples of three types of learning objectives at different levels.

Table 5: Examples of learning objectives for different attainment levels

<table>
<tr><th colspan="2">Cognitive Objectives: what thinking process will the student undertake?</th></tr>
<tr><td rowspan="3">Lower Level
Higher Level</td><td>Remembering factual information</td></tr>
<tr><td>Evaluating, Analysing</td></tr>
<tr><td>Creative Recognition, Problem solving</td></tr>
<tr><th colspan="2">Active Objectives: what feeling and attitudes will the student undergo?</th></tr>
<tr><td rowspan="3">Lower Level
Higher Level</td><td>Paying attention</td></tr>
<tr><td>Attach value to learning</td></tr>
<tr><td>Change in life-style and outlook</td></tr>
<tr><th colspan="2">Psychomotor Objective: what physical actions and activities will the student have to perform?</th></tr>
<tr><td rowspan="3">Lower Level
Higher Level</td><td>Use a screw driver</td></tr>
<tr><td>Dismantle a part</td></tr>
<tr><td>Fix and fine tune a part</td></tr>
</table>

The type of cognitive learning objectives that a MET course on energy efficiency should aim to address is the development of the evaluation and analytical skills: e.g. to identify where energy efficiency can be improved. In particular the course should be looking to develop creative recognition and problem solving skills. This is because energy efficiency improvement scenarios will be different depending on different company procedures, ships and ship operations. It has already been identified from the questionnaire field study results in chapter Section 5.3 that 'problem solving skills and initiative' require improving.

Regarding active objectives, it is the primary aim that awareness towards energy efficiency is delivered. However the desire is that the trainees not only recognise the energy efficiency problem, but also they develop an understanding and motivation by placing a value on it. The overall aim is therefore to achieve a higher level of lifestyle and outlook change that the trainees will apply in both their working environment and home: i.e. the development of an energy efficiency culture.

It is considered that the lower level psychomotor skill will have been taught to the trainees in previous education and training (i.e. according to STCW requirements). The developed MET course on energy efficiency should therefore focus on the fine tuning and application of skills required to maximise ship operational energy efficiency. Nonetheless, during delivery of the developed course, it should be ensured that founding knowledge and skills are known before attempting to develop the higher levels.

The MET learning requirements for each of the target groups were identified and have been presented in Appendix C3. Then based on the learning requirements and the review in the previous paragraphs, a specification was written for the design and development of the MET course: presented in Appendix C4. This specification differs and is in addition to the one presented in Section 5.4.4 in that it focuses on MET development not necessarily specific to Energy Efficiency.

To support the development of the MET course, a pedagogical review was carried out in (Appendix C2) including the review of: curriculum development, educational approaches, delivery platforms and assessment approaches. A framework was then constructed to integrate the identified pedagogical methods relevant to MET on energy efficiency and the training material; including theory, exercises and practical example scenarios. This framework for the MET course on energy efficiency was presented in Appendix C5. Its purpose is to allow for flexible and best delivery of the course, depending on the MET resources available in the training environment and the specific trainee groups’ requirement.

6.2 The Courses

6.2.1 Introduction

Deck and Engineering Officers and onshore personnel must all work together to achieve integrated energy efficient operations, but it is also acknowledged that they have very different job roles and expertise. Particularly the Deck and Engineering Officers require a high level of technical knowledge in their job role areas; e.g. voyage planning for Deck Officers and main engine maintenance for Engineering Officers. Thus it was considered that three courses need to be developed, as listed below.

- **Energy Management for Engineering**

Specific for cadets and seafarers related to the engineering department (of officer rank: i.e. Chief Engineer, Engineering Officers)

- **Energy Management for Deck Officers**

Specific for cadets and seafarers related to the deck department (of officer rank: i.e. Master, Deck Officers)

- **Energy Resources Management (ERM)**

Specific for cadets or seafarers (of officer rank) and onshore management concerned with ship operations (i.e. Voyage, Vessel and Technical Managers)

Participation of all the different trainees identified for the ERM course is emphasised as important (if possible), particularly in company delivered courses. This is because it will provide added value to the course by allowing for job roles, responsibilities, and decision making procedures to be discussed openly. This way each trainee becomes increasingly more aware of the practical considerations associated with energy efficient operations the issues that require discussion between all personnel to identify solutions. Furthermore it will start the process of identifying integrated best practice solutions for energy efficient ship operation.

It was explained in Section 5.4.2 that there are other groups of seafarers (such as Able and Ordinary Seaman; refer to the network of stakeholders in section 5.2) that have not been addressed in the Framework (Section 5) and hence the MET development. This is because they do not need the same level of technical engineering or deck management skills; thus the focus on the course would not be appropriate. Furthermore the Energy Resource Management Course is focused on developing the management skills of the trainees, specifically communication and leaderships. Within this, the objective of educating others onboard and encouraging an energy efficiency culture through good communication and management is emphasised. Hence the educational needs of those not included directly in the MET target trainee groups are indirectly considered.

6.2.2 Course Structure

Table 6, Table 7 and Table 8 present the time tables for each of the courses. The key features of these time tables include:

- Each column represents a day, where the ERM course is a shorter course lasting 3 days and the Energy Management for Engineers and Deck Officers courses are a week.
- Considering an 8 hour working day, each block represents 2 hours of MET delivery; inclusive of theory, exercises and practical activities (e.g. workshops).
- Each module topic is shown with a bold heading. The primary subject areas addressed in each topic are listed below.
- Each course shares common modules with the other courses (shown in light grey shading in the time tables). [If the ERM course was to be run in parallel

with either the Energy Management course for Engineers or Deck Officers, the common modules would only need to be taught once.]

- The uncommon modules for each course focus on the comprehensive delivery of the related technical and non technical knowledge and skills. However, an overview of these specific modules can be seen as integrated into modules within the other course to provide awareness to all trainees but not at a technical level too high for all personnel attending the course (i.e. from different operational departments).

Table 6: Energy Resource Management, Course Time Table

Day 1	Day 2	Day 3
Introduction - Course Introduction - Carbon emissions - Carbon emissions from shipping	**Operational Measures** • Operational measures to improve energy efficiency	**Energy Efficient Integrated Procedures** Continued
Carbon Regulation • EEDI • SEEMP • EEOI • MRV • Regulatory Initiatives • Industry Initiatives	**Integrated Operations** • Management structures • Job Roles and Responsibilities • Communications and decision making flows	**Energy Efficient Integrated Procedures** Continued
Communication **Attitudes and Perceptions Towards Energy Efficiency** • Importance • Current attitudes, perceptions and opinions • Improvement considerations	**Energy Efficient Integrated** Operational measures, focusing on: • Leadership • Teamwork • Situational awareness • Workload Management • Decision Making	**Energy Management** • Electrical • Water • Waste • HVAC **Assessment** • Data records • Ship • Team/ department • Personal
Energy Awareness • Energy Demand • Resistance and Propulsion Principals • Operational Profiles	**Energy Efficient Integrated** Continued	**New Technologies** • Wind assist • Hydrodynamic retrofits • Rudder types • Waste Heat Recovery • Alternative Fuel types • Ship design

Table 7: Energy Management for Deck Officers, Course Time Table

Day 1	Day 2	Day 3	Day 4	Day 5
Introduction • Course Introduction • Carbon emissions • International Actions Carbon emissions from shipping	**Integrated Operations** • Management structures • Job Roles and Responsibilities • Communications and decision making flows	**Route Planning** Continued	**Voyage Operations and Manoeuvring** • Pitch optimisation • Shallow water operation • Steady shaft power • Autopilot control (steady rudder and heading control • Acceleration, deceleration • Systems management for manoeuvring	**Extended Performance Awareness** • Engineering department performance overview • Hull and propeller performance • Performance monitoring • Fuel quality
Carbon Regulation • EEDI • SEEMP • EEOI • MRV • Regulatory Initiatives Industry Initiatives	**Integrated Operations** Continued	**Cargo Planning** • Cargo handling and storage optimisation • Ballast operation optimisation	**Voyage Operations and Manoeuvring** Continued	**Extended Performance Awareness** Continued
Energy Awareness • Energy Demand • Resistance and Propulsion Principals • Operational Profiles	**Route Planning** • Routing Practices • Weather routing • Speed optimisation • Systems planning	**Cargo Planning** Continued	**Voyage Operations and Manoeuvring** Continued	**Energy Management** • Electrical • Water • Waste • HVAC **Assessment** • Data records • Ship • Team/ department Personal
Energy Awareness Continued	**Route Planning** Continued	**Cargo Planning** Continued	**Arrival Management** • Estimated time of arrival management, • Virtual arrival	**New Technologies** • Wind assist • Hydrodynamic retrofits • Rudder types • Waste Heat Recovery • Alternative Fuel types • Ship design

Table 8: Energy Management for Engineering Officers, Course Time Table

Day 1	Day 2	Day 3	Day 4	Day 5
Introduction • Course Introduction • Carbon emissions • International Actions • Carbon emissions from shipping	**Integrated Operations** • Management structures • Job Roles and Responsibilities • Communications and decision making flows •	**Main Propulsion Engine** Continued	**Boilers Economizers and Heat Exchangers** • Boilers • Economiser • Other heat exchange systems	**Auxiliary Systems** • Electric Motors • Pumps • Refrigeration • Heating, ventilation & air conditioning (HVAC) systems • Onboard equipment • Cargo systems
Carbon Regulation • EEDI • SEEMP • EEOI • MRV • Regulatory Initiatives • Industry Initiatives	**Integrated Operations** Continued	**Main Propulsion Engine** Continued	**Boilers Economizers and Heat Exchangers**	**Extended Performance Awareness** • Deck department performance overview • Hull and propeller performance • Performance monitoring
Energy Awareness • Energy Demand • Resistance and Propulsion Principals • Operational Profiles	**Maintenance** • Maintenance philosophies • Monitoring techniques • Monitoring tools • Maintenance scheduling • Integrated Operations	**Fuel** • Fuel Quality • Fuel Quality monitoring • Fuel Additives	**Diesel Generators/ Alternators** • Diesel generators • Diesel generators lubrication • Diesel generator operational optimisation • Integrated operation • Diesel Electric	**Energy Management** • Electrical • Water • Waste • HVAC **Assessment** • Data records • Ship • Team/ department • Personal
Energy Awareness Continued	**Main Propulsion Engine** • Main engine system • Main engine lubrication • Scavenging and supercharging systems • Main engine operational optimisation • Integrated operation • Overview of other prime movers	**Propulsion and Transmission Systems** • Shaft Components • Propeller • propulsion and transmission operational optimisation; • Integrated operation	**Diesel Generators/ Alternators** Continued	**New Technologies** • Wind assist • Hydrodynamic retrofits • Rudder types • Waste Heat Recovery • Alternative Fuel types • Ship design

6.3 Course Content

6.3.1 Energy Resource Management Course

The training material for the Energy Resource Management (ERM) Course took the focus of the training material developed in this research for the following reasons:

- It has focused modules related to the human factor subjects identified as required but are not currently addressed in relation to energy efficiency in existing MET.
- It contains common modules with the Energy Management for Engineers and Deck Officers courses, thus the modules will be developed for all three courses in parallel.
- The technical material collected, collated and developed in this research can be used to populate the modules in the ERM course requiring technical content. However to achieve the extended high level technical content required for the Energy Management for Engineers and Deck Officers courses, personnel working in the industry should be included in the development.

The rest of this subsection describes each of the modules for the ERM course in more detail:

- **Introduction**

Module Aim: Increase awareness and motivation towards: Climate Change; the need for energy efficiency improvements within the shipping industry; learning on the course about energy efficiency

The module includes the following subjects:

- *A course introduction*
- *Climate Change and Carbon Dioxide Emissions*
- *The International drivers towards Carbon emission reductions*

- *The shipping industry's drivers towards energy efficiency improvements, hence carbon emission reductions*

The course introduction is included to ensure that the trainees know what to expect from the course at the beginning, including the aim and objectives and the material and resources available to them. The introduction also includes an overview of the course content and identifies the potential benefits of completing the course: these benefits are discussed in the Sub-section 6.3.2. It is hoped that this will encourage motivation to learn and participation during the course. Also included is an introduction to: Climate Change; carbon dioxide emissions; international drivers towards emission reductions; shipping's contribution to global anthropogenic carbon emissions. This content is not dissimilar to that summarised in Section 2.1, but much more comprehensive to ensure that the trainer of the course has a complete understanding of Climate Change, even if they had no previous knowledge. The theory content covers a comprehendible introduction, to a review of State-of-the-art Climate Change Science. Reference sources are provided to check for future updates: noting that it is an ever changing research area. Examples and exercises are also included to provide interactive option for the course delivery if desired, an example from the material is given below:

4) EXERCISE: CLIMATE CHANGE, VIDEO AND TUTORIALS

Aim: To emphasise the effects and impacts of Climate Change and to provide more details about how climate change is expected to affect different regions of the world.

Example:

Blow is a link to an online video and tutorial that uses **Google Earth** to present climate change.

http://www.google.com/landing/cop15/

The tour is also available in several languages.

- **Carbon Regulation**

Module Aim: To ensure that trainees understand the maritime regulations, their expected impact, and how they can be achieved.

The module includes the following subjects:

- *Energy Efficiency Design Index (EEDI)*
- *Ship Energy Efficiency Management Plan (SEEMP)*
- *Energy Efficiency Operational Indicator (EEOI)*
- *Regulatory Initiatives*
- *Industry Initiatives*

This module introduces an overview and then a more in depth examination of the international shipping regulations. This is supported by exercises to ensure that the calculation processes are understood. Industry initiatives are also included: much similar to Section 2.2 and additional resources are given for future updates.

- **Attitudes and Perceptions Towards Energy Efficiency**

Module Aim: For trainees to understand the importance of, and further develop, positive attitudes and perceptions towards energy efficiency

The module includes the following subjects:

- *Why are attitude and perceptions important*
- *Current attitudes and perceptions towards energy efficiency*
- *Improvement considerations and methods*

This module introduces the importance of a positive attitude and perception towards energy efficiency; i.e. demonstration of an energy efficiency culture. Methods to encourage this are discussed; such as knowledge acquisition. Poor attitudes and perceptions of trainees should be identified (e.g. scepticism, lack of effort demonstrated by others, additional stresses in already busy workloads) so they can be addressed throughout course delivery. Example and exercises are provided, led by the presentation of questionnaire results revealing the opinions of seafarers; i.e.

generated from the field study questionnaire analysis in Section 5.3. An example is provided below.

8) EXERCISE– QUESTIONNAIRE, AWARENESS AND KNOWLEDGE

Aim: To identify trainees and seafarers in generals' current levels of awareness and knowledge about carbon emissions and their reduction.

Brief: Before presenting the results of the questionnaire ask the trainees what their responses' would be (either before the start of the course or now having completed the previous chapters to this course).

The responses of the trainees may be different from the questionnaire results. However, it is important to discuss the questionnaire results in order to identify the general opinions of other seafarers (i.e. who may not have undertaken such a course). This will be important to understand when developing leadership and teamwork skills as well as promoting motivation towards energy efficiency.

- Questionnaire form -

- **Once the responses to the questionnaire have been presented ask trainees to comment on what they thought:**

- Do the responses match the trainees responses
- Are the trainees surprised at any of the results
- Do trainees agree that the questionnaire results probably represent the view of most seafarers
- How do trainees think onshore managements' opinions differs

Debrief: Any questions, points and negative attitudes and behaviour (e.g. scepticism) identified should either be addressed in the discussions within this chapter or noted for attention during the rest of the course.

▪ Communication

Module Aim: For trainees to understand the importance of good communication for achieving energy efficient operations, and then develop good communication skills.

The module includes the following subjects:

- *Communication for energy efficient ship operation*
- *Skills for achieving good communication*

There are many different types of communication between different key personnel on board and in onshore management departments: as discussed in Sub-section 5.2. Communication also exists between humans and systems, or between personnel via technology. The importance of these communications for energy efficient operation is identified and stressed: as done so in Sub-section 5.2. This module addresses the different types of communication links relevant to ship operations. It identifies the barriers to good communication (e.g. language barriers, different locations and knowledge) and then discusses key skills for improvement.

▪ **Energy Awareness**

Module Aim: To ensure that trainees have awareness and understanding of the importance of operating profiles, and how energy demand changes during different operations and in different conditions.

The module includes the following subjects:

- *Energy demand and usage onboard*
- *Resistance and propulsion principals*
- *Operational profiles*

The module on Energy Awareness identifies where and how energy is used on board and therefore where there is potential to improve energy efficiency. Resistance and propulsion principals are included in the theory to ensure a fundamental understanding by all trainees, but also to emphasise the changes in power demand and fuel consumption when sailing in different operational conditions. The Ship Operational Performance Prediction (SOPP) model developed in this research (described in Chapter 9) was used to populate suggested examples and interactive exercises (see for some of the ways that the SOPP model can be used in Chapter 10) for delivery of this module. Results from the Analysis of Operating Profiles presented in Chapter 8 were also used to populate the theory, examples and exercises in this material. A holistic overview of ship performance is stressed in this module. Furthermore, a focus is placed on how changes in fuel consumption and power demand impact on both carbon dioxide emission and costs. Noting that cost savings are a large motivator for the implementation of energy efficient operations.

▪ **Operational Measures**

Module Aim: For trainees to know what are the operational measures that should be considered for improving energy efficiency.

The module includes the following subjects:

- *Industry recommended operational measures*
- *Data recording*

This module introduces the industry recommended operational measures at an overview technical level (i.e. including all measures recommended in the SEEMP regulation guidelines). Operational barriers to the measures are identified for further elaboration in following modules. It is also highlighted that not all measures will be applicable to all ships or all scenarios, again for further discussion in subsequent modules.

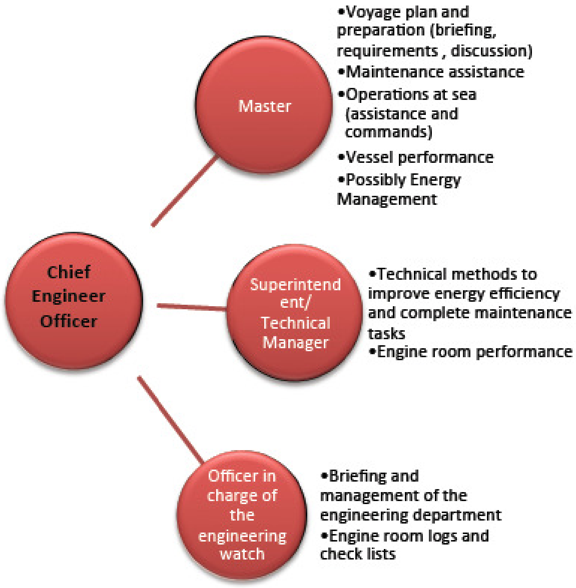
▪ **Integrated Operations**

Module Aim: For trainees to recognise and understand their own, and other personnel's, roles and responsibilities for energy efficient ship operation, and the restrictions and opportunities to implementation.

The module includes the following subjects:

- *Management Structures, Job roles and responsibilities*
- *Integrated operations to increase energy efficiency*
- *Data collection*

This module introduces management structures, decision making flows and integrated operations as vital enablers to practical implementation of energy efficient operations. Communication flows (as addressed in the third module) is again emphasised as important. The network of stakeholders presented in Section 5.2 is used for discussion. Different management structures are identified along with job roles and responsibilities for energy efficiency. The communication flows related to operational decision making are identified for each stakeholder (see example below). Where energy efficiency improvements can be made is emphasised and split incentives are also introduced (See section 2.3 for explanation).



▪ **Energy Efficient Integrated Operations**

Module Aim: For trainees to develop awareness of integrated operations and how human factor skills can be used to enable achievement.

The module includes the following subjects for energy efficient operations:

- *Leadership*
- *Teamwork*
- *Situational awareness*
- *Decision making*
- *Work load management*

The new content introduced in this module is related to why each of the human factor skills listed above are important for the implementation of energy efficient operations, and how these skills can be enhanced. The key emphasis of the module is to select the operational measures covered in the previous module (Operational Measures) one at a time, and identify practical implementation solutions for different ship types and scenarios, developing the human factor skill in question (i.e. through good leadership). This could be achieved through interactive sessions such as group discussions. The benefits intended from the activity include: the encouragement of innovative thinking for different scenarios; recap and knowledge reinforcement of operational measures and human factor skills; the integrated application of technical and non-technical skills.

- **Energy Management**

Module Aim: For trainees to understand and know how to manage and optimise different energy systems onboard.

The module includes the following subjects:

- *Electrical*
- *Water*
- *Waste*
- *HVAC*

The content of this module identifies each of the listed systems, their energy demands and how energy efficiency can be optimised. The potential improvements expected from these systems are discussed, using industry based case study scenarios (collected during field company field visits Section 5.1) as examples. Smaller savings are emphasised as important along with larger savings, mentioning that savings are accumulative and all efforts raise awareness of the subject and help contribute to the generation of an energy efficient culture.

▪ **Assessment**

Module Aim: For trainees to understand the benefit of energy efficiency assessment and implementation techniques, even if no performance monitoring systems are installed.

The module includes the following subjects:

- *Data Records*
- *Ship*
- *Team/department*
- *Personal*

Data records are introduced in this module as important sources of information for performance assessment. The data sources discussed include; continuous monitoring datasets, Ship Reports (noon data); onboard logs; additional records of specific performance parameters. The benefits of data analysis onboard or onshore is discussed, along with the importance of performance feedback and distribution. To encourage motivation to collect and record data careful and accurately, its value and the different ways in which it can be used for performance assessment and monitoring are identified (such as the method presented in Chapter 9 for the development of the SOPP model). Common types of performance monitoring systems utilised by companies are discussed, along with technique for ship, team or department, and self-assessment in terms of energy efficiency performance. The identified methods range from performance monitoring systems to daily consideration of efforts made.

▪ **New Technologies**

Module Aim: For trainees to be aware of the technologies being developed in the industry to address the required energy efficiency improvement in shipping.

Includes:

- *Wind assist*
- *Hydrodynamic retrofits*

- *Rudder types*
- *Waste Heat Recovery*
- *Alternative Fuel types*
- *Ship design*

This module was developed with a focus on raising trainee's awareness rather than gaining technical knowledge. Nevertheless a comprehensive review of the technologies is given in the training material to ensure that the trainer of the course has knowledge resource for each technology. It is considered that trainees should be aware of developments in the industry for the following reasons: they may have to operate (or adjust other existing operations to optimise overall systems efficiency) if such technologies reach implementation maturity and are installed; to gain a wider perspective of the energy efficiency efforts in the industry.

6.3.2 Key Benefits of the Course

In the first module of the ERM course (Introduction) the benefits of completing the course are described. It was considered important to include not just the carbon emission reduction benefits to support the mitigation of Climate Change, but also the benefits to the shipping company and individual trainees. The considered potential benefits from completing the MET course on energy efficiency and implementing the practices during daily operation are presented in Table 9.

Table 9: The benefits to undertaking the MET course on energy efficiency

BENEFICIAL OUTCOMES TO MANKIND	
Beneficial outcome	**Achieved by**
Mitigation (avoidance) of Climate Change	1. By increasing energy efficiency, reducing fuel consumption and hence reducing CO_2 will contribute towards the mitigation of Climate Change. This will help to reduce predicted impacts of Climate Change, including health concerns and loss of current living environments. The benefits of Climate Change mitigation will be observed both in our lifetime and for future generations if action is taken now.

BENEFICIAL OUTCOMES TO THE TRAINEE	
Beneficial outcome	**Achieved by**
Continual professional development	2. The awareness, knowledge, and skills delivered in this course will contribute to professional development training. Development of non-technical as well as technical knowledge and skills for energy efficiency is increasing in value as we move into a lower carbon, more energy efficient, and environmentally aware future. Further to this, recognition of these skills and demonstration of the ability to contribute towards energy efficiency savings is expected to increase employability.
Compliance with regulations	3. The course will provide trainees with the knowledge about the maritime energy efficiency regulations, and how compliance can be achieved. This supports point 2 as part of continual professional development.
Ease of Workload	4. Workload management could be improved along with achievement of energy efficiency if the skills covered within this course are implemented: i.e. (good communication, leadership, teamwork, situational awareness and workload management, and decision-making) are demonstrated and expertise and work tasks are well distributed, communicated and utilised, (both onshore and on board) .
Increased safety	5. In some cases energy efficiency and safety operations and decisions are contradictory. The course identifies and discusses how both objectives can be achieved simultaneously. 6. Many of the key skills required for energy efficiency (good communication, leadership, teamwork, situational awareness and workload management, and decision-making) are similar to those required to increase safety. Therefore, by developing these skills further for energy efficiency it is also likely to increase safety skills as well. 7. A good working environment and job satisfaction (see points 8, 9 & 10) are known to increase attention on the job, and hence reduce accidents.
Improved working environment	8. If the good practices for energy efficiency (good communication, leadership, teamwork, situational awareness and workload management, and decision-making) are employed, and the energy efficiency roles, responsibilities, restrictions and expertise of all personnel are known, then efficient and good interactions between people are likely to be observed. This has the potential to increase motivation (working together towards common objectives) and result in an improved working environment.
Increased job satisfaction	9. The benefits of continual professional development (point 2), ease of workload (point 4), increased safety (points 5, 6 and 7), improved working environment (point 8) and mitigation of climate change (point 1 - self satisfaction resulting from participation) may help to increase moral and job satisfaction in the

	workplace. 10. Maximising energy efficiency requires utilisation of an individuals most advanced knowledge and skills within their stream of expertise and problem solving. This itself, along with a sense of achievement, may drive interest, motivation and job satisfaction: particularly if performance monitoring, review and feedback are implemented.
Job security	11. A contribution to fuel cost savings will arise from increased energy efficiency. This will either increase profitability if the company is paying the fuel bill, or, provide the vessel with a competitive advantages over less efficiently run vessels; attracting charter. A more profitable company will provide increased job security. 12. Point 2 regarding employability in the context of energy efficiency skills also applies to job security.
BENEFICIAL OUTCOMES TO THE SHIPPING COMPANY	
Beneficial outcome	**Achieved by**
Cost savings	13. Reiterating point 11, a contribution to fuel cost savings will arise from a decrease in fuel consumption resulting from energy efficient operation. 14. Additional cost savings may also be realised via reduced maintenance (as a result of condition maintenance for optimal energy efficiency) and other operational savings.
Compliance with regulations	15. Reiterating point 4, crew and personnel trained in energy efficient ship operations will help the shipping companies to implement energy efficiency regulations (such as the Ship Energy Efficiency Management Plan). This will aid achievement of current and future carbon emission reduction strategies, targets and regulations.
Green competitive advantage and customer satisfaction	16. 'Greenness' is becoming a much more competitive attribute within and out with the shipping industry due to emphasis on supply chain environmental impacts. 17. Point 16 may contribute to customer satisfaction and attract a charter, if the customer knows they are supporting an efficient means of transport, thus contributing to social responsibility to reduce Climate Change (Point 1).
Reduced accidents	18. Reiterating the benefits described in points 5, 6 and 7, a reduction in accidents will also benefit the shipping company by protection of crew and cargo and ship (also reducing a reduction of damage costs, insurance claims, etc.).

6.4 Material Design and Development

6.4.1 Strategy and Structure

A course structure similar to the IMO courses was selected for the following reasons and benefits:

- The structure and intentions of the IMO model courses fit well with the specification identified for a MET course on energy efficiency in Sub-section 5.4.4.
- Using a similar format will increase compatibility of the developed MET courses on energy efficiency with existing MET.
- Using a similar format to the IMO model course may allow for easier assessment and certification of the course in the future.
- Observation of other IMO model courses can provide experience to what is assumed to work well for MET.

6.4.2 Model Course

A model course document was prepared for each course, including the following:

- Introduction
- Course framework
- Course outline
- Suggested time table
- Training syllabus

The suggested time tables have presented previously in Table 6, Table 7 and Table 8. The training syllabus lists the same course modules as the course outline and shown in the time tables, and for each module the learning objectives are identified. The learning objectives were selected carefully using verbs (such as; state, understand, recognise, demonstrate, calculate) to support the future development of an assessment scheme. Two examples are shown in Figure 16 .

1. INTRODUCTION

1.1 COURSE INTRODUCTION

- Understand what will be covered in the course and the post course material that will be available
- Recognise the energy efficiency philosophy **STiPAD** (1. maintain Safety 2. work as a Team 3. implement Personal contribution 4. Assess performance 5. collect Data accurately)

2. CARBON REGULATION

2.1 ENERGY EFFICIENCY DESIGN INDEX, EEDI

- Understand what is the EEDI; including advantages and limitations
- Demonstrate calculation of the EEDI and understanding of how it can be effected
- Recognise the expected effects that EEDI will have on onshore management
- Recognise the expected effect that EEDI will have on seafarer

Figure 16: Learning objectives in the developed MET course on energy efficiency, example

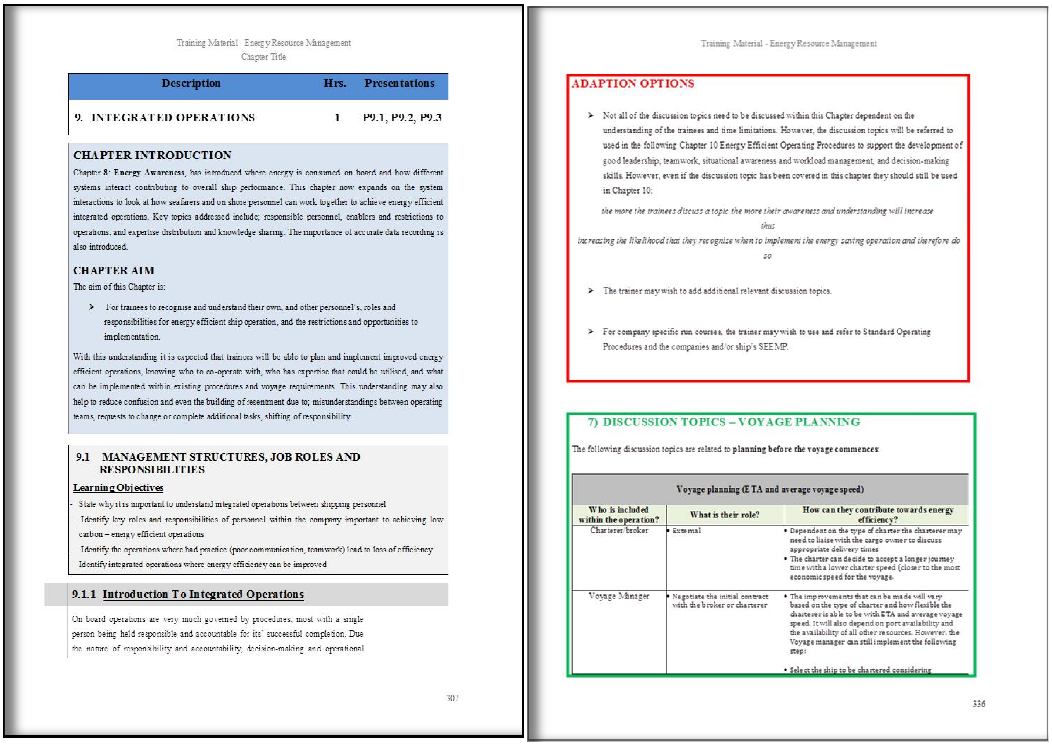
6.4.3 Training Material

The content of the training material has been described in the previous chapter section. However a few points about its format and design are identified here:

- The format was designed for easy use by the trainer, including clearly marked sections for: Module Introduction; aims and learning objectives of the subjects; the comprehensive theory; examples and exercise; trainer notes; suggested resources; company specific adaption options. An example of some of these sections can be seen in Figure 17.
- The theory section of the training material provides the trainer with knowledge, information and material for teaching each learning objective for each topic.

- It is intended that once the trainer has read the training material for a module, they can select what they considered to be the best platforms and specific content to deliver to the trainee group, based on the trainee groups' learning requirements.
- The written theory includes text, quotes, references, pictures and diagrams and it is based on technical and scientific information collected during the literature review (Chapter 2) and field studies (Section 5.1) for this research. The theory and exercises are also populated with the outputs of this research as identified during the description of each module in the previous chapter section.
- The training material itself has been written in an easy reading format so that trainers using the document all over the world (i.e. where English may not be their first language) should be able to understand and absorb the knowledge.
- The layout of the theory content includes a margin to the left separated with a vertical grey line and a larger space (blank margin) to the right. This was done base on feedback from a MET instructor who mentioned it would be practically beneficial if the trainers were able to make their own notes next to the content.

The Training Material document, containing 12 chapters for each module, was produced during this research. A comprehensive document was produced as a resource document (Banks 2014).



Training Material - Energy Resource Management
Chapter Title

Description	Hrs.	Presentations
9. INTEGRATED OPERATIONS	1	P9.1, P9.2, P9.3

CHAPTER INTRODUCTION

Chapter 8: **Energy Awareness**, has introduced where energy is consumed on board and how different systems interact contributing to overall ship performance. This chapter now expands on the system interactions to look at how seafarers and on shore personnel can work together to achieve energy efficient integrated operations. Key topics addressed include; responsible personnel, enablers and restrictions to operations, and expertise distribution and knowledge sharing. The importance of accurate data recording is also introduced.

CHAPTER AIM

The aim of this Chapter is:

- For trainees to recognise and understand their own, and other personnel's, roles and responsibilities for energy efficient ship operation, and the restrictions and opportunities to implementation.

With this understanding it is expected that trainees will be able to plan and implement improved energy efficient operations, knowing who to co-operate with, who has expertise that could be utilised, and what can be implemented within existing procedures and voyage requirements. This understanding may also help to reduce confusion and even the building of resentment due to; misunderstandings between operating teams, requests to change or complete additional tasks, shifting of responsibility.

9.1 MANAGEMENT STRUCTURES, JOB ROLES AND RESPONSIBILITIES

Learning Objectives

- State why it is important to understand integrated operations between shipping personnel
- Identify key roles and responsibilities of personnel within the company important to achieving low carbon – energy efficient operations
- Identify the operations where bad practice (poor communication, teamwork) lead to loss of efficiency
- Identify integrated operations where energy efficiency can be improved

9.1.1 Introduction To Integrated Operations

On board operations are very much governed by procedures, most with a single person being held responsible and accountable for its' successful completion. Due the nature of responsibility and accountability, decision-making and operational

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Training Material - Energy Resource Management

ADAPTION OPTIONS

- Not all of the discussion topics need to be discussed within this Chapter dependent on the understanding of the trainees and time limitations. However, the discussion topics will be referred to used in the following Chapter 10 Energy Efficient Operating Procedures to support the development of good leadership, teamwork, situational awareness and workload management, and decision-making skills. However, even if the discussion topic has been covered in this chapter they should still be used in Chapter 10:

the more the trainees discuss a topic the more their awareness and understanding will increase thus increasing the likelihood that they recognise when to implement the energy saving operation and therefore do so

- The trainer may wish to add additional relevant discussion topics.
- For company specific run courses, the trainer may wish to use and refer to Standard Operating Procedures and the companies and/or ship's SEEMP.

7) DISCUSSION TOPICS – VOYAGE PLANNING

The following discussion topics are related to **planning before the voyage commences**:

Voyage planning (ETA and average voyage speed)		
Who is included within the operation?	**What is their role?**	**How can they contribute towards energy efficiency?**
Charterer/broker	• External	• Dependent on the type of charter the charterer may need to liaise with the cargo owner to discuss appropriate delivery times • The charter can decide to accept a longer journey time with a lower charter speed (closer to the most economic speed for the voyage.
Voyage Manager	• Negotiate the initial contract with the broker or charterer	• The improvements that can be made will vary based on the type of charter and how flexible the charterer is able to be with ETA and average voyage speed. It will also depend on port availability and the availability of all other resources. However, the Voyage manager can still implement the following step: • Select the ship to be chartered considering

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Figure 17: Energy Resource Management Training Material, example

6.4.4 Other Material

Further developments of the MET course for future work, include the completion and review of the training material for all courses and development of the following:

- Training aids: i.e. a set of presentation corresponding to each chapter and section within the Training Material. Modifiable by the trainer
- The Course Notes: i.e. a summarised version of the Training Material (highlighting the key points and leaving room for self notes) that can be distributed to trainees
- Assessment Scheme

CHAPTER SUMMARY

This chapter has identified that three courses are needed to address the specification set out in Section 5.4.4. The three courses identified for development include:

- *Energy Management for Engineering*
- *Energy Management for Deck Officers*
- *Energy Resources Management (ERM)*

The time tables for each course have been presented demonstrating the Module topics and subjects within the topics that are included.

The content of the developed training material is described for each module in the Energy Resource Management course. Specifically, the inclusion of research outputs presented in other chapters of this thesis, are highlighted for enhancing theoretical understanding and providing example and exercise material.

The module topics within the Energy Resource Management course specifically (but also in the other two courses) address the need to include non-technical human factor knowledge and skills in addition to technical. This was concluded as a requirement in Chapter 5 but one that is not currently addressed in existing MET related to energy efficiency.

The benefits that could be gained from completion of the developed MET courses and implementation of the lessons learned are identified at three levels: benefits to mankind (i.e. the mitigation of Climate Change); benefits to the trainee; benefits to the shipping company. Identification of level is important for encouraging motivation towards energy efficiency improvements.

7. DATA COLLECTION AND PROCESSING

CHAPTER INTRODUCTION

The aim of this chapter is to describe the data and information that was collected for use in the data analyses presented in Chapter 8 and Chapter 9. This chapter has three sections as follow:

7.1 Data Collection

Operational datasets were required to analyse ship operating profiles and to develop the Ship Operational Performance Prediction (SOPP) model, as identified in the Framework (Section 5.4). A requirement for the dataset type was that it had to be widely available to all or most of the ships in world fleet in order to meet the specification for the SOPP model (Sub-section 5.4.6). The different types of operational datasets available were discussed in chapter Sub-section 2.4.2, identifying the two main types as: Ship Reports (SR's) also commonly known as Noon Reports, and Continuous Monitoring. SR's were selected as they are typically collected for all commercial ships.

The data and information was collected from several from industry contacts: namely ship owner and operating companies. The collection was enabled by the many filed study company visits that were carried out, previously described in Section 5.1.

Due to the range of industry contacts that responded to the data request, data and information was collected for a number of tanker, bulk carrier and container ships: as shown in Table 10..

All case study ships listed in Table 10 were included in the analysis of ship operating profiles presented in Chapter 8. Case study ship T1 was used to develop the SOPP model and demonstrate the case study examples in Chapters 9 and 10.

Table 10: Collected datasets

Case Ship Reference	Number of sister ships	Ship Type	Size classification	Ship Reports	Approximate years of data	Loading condition/ mean draft	Sea trial power-speed curve	Ship Particulars	Machinery and propeller details	Important dates	Paint type	Other documents
T10	1		Handysize	✓	2		✓	✓	✓	✓	✓	
T6, T7	2		Aframax	✓	7	✓	✓	✓	✓	✓	✓	
T8, T9	2	Tanker	Aframax	✓	7	✓	✓	✓	✓	✓	✓	Sea Trial Document Trim & Stability Booklet, Propeller Particulars
T1, T2, T3	3		Suezmax	✓	7	✓	✓	✓	✓	✓	✓	
T4, T5	2		Suezmax	✓	7	✓	✓	✓	✓	✓	✓	
C1, C2	2		Post Panamax	✓	9	✓	✓	✓	✓	✓	✓	
C3, C4	2	Container	Post Panamax	✓	6	✓	✓	✓	✓	✓	✓	
C5, C6	2		Post Panamax	✓	6	✓	✓	✓	✓	✓	✓	
B1	1		Capesize	✓	3			✓		✓	✓	
B2	1		Capesize	✓	3			✓		✓	✓	
B3	1	Bulk Carrier	Capesize	✓	3			✓		✓	✓	
B4	1		Capesize	✓	3			✓		✓	✓	
B5	1		Capesize	✓	3			✓		✓	✓	
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The additional data and information to the SR operational datasets identified in Table 10 is described below:

- **Loading Condition/ Mean Draft:** The mean draft (considered as an indicator of the cargo loaded) either recorded in the SR dataset, made available via collected loading report datasets.
- **Sea Trial Power-Speed Curve:** The plot showing the power-speed curve in the sea trial document was collected, but the full Sea Trial Document was not. No data tables were provided so the power-speed data was read from the plot.

- **Sea Trial Document**: Included the power-speed curve (as described above) as well as the full Sea Trial Document, providing tabulated results for each of the Sea Trial tests and runs.
- **Trim and Stability Booklet:** provided a tabulated table of the following ship form parameters at varying average draft at midship values: waterline length, longitudinal centre of buoyancy, block coefficient, prismatic coefficient, waterplane coefficient, midship section coefficient and displacement.
- **Propeller Particulars:** Not only where the propeller details given but also the torque and thrust measurement values for a specified RPM and power test. These results will be described for use in the SOPP model development in Sub-section 9.2.4.

7.2 Data Description

The data variables typically contained in a SR dataset were listed and briefly discussed in Sub-section 2.4.2. Table 11 elaborates on the discussion to describe each variable, how it is typically measured and starts to identify the possible sources of uncertainty in its measurement. These points are important to identify and understand for the following reasons. SR datasets are considered to be a relatively low quality dataset due to their uncertainty. However, they are widely collected and have been for many years providing a time history of data: thus provide a source of useful operational data that can be used for SOPP modelling (as will be demonstrated in 9). Therefore, if SR's are to be used for SOPP and Ship Operational Performance Monitoring (SOPM), company procedures should be revised to reduce the uncertainties as much as possible (i.e. update existing operating procedures: a task highlighted in the Framework for improving the energy efficiency of ship operations, Section 5.4). Demonstration and explanation of how SR data is used for SOPP and SOPM, the benefits that SOPP and SOPM can provide, hence the importance of taking due care when making a SR record entry, should be used to raise seafarer's awareness and help encourage implementation motivation.

Table 11: Data variables recorded in operational data sets

Data variable	Description	Measurement method	Sources of uncertainty
Typically included in a SR dataset			
Date/time	The date and time that the record entry is made.	Observation from clock and calendar	• Resolution of digital or analogue time measurement • Time Zone corrections not considered • Not making the observation and recording simultaneously
Report duration	Whilst not always recorded in a Ship Report, it can be calculated from the Date/time of consecutive reports to provide the duration of time that the report entry refers to.	Calculation from consecutive report date/time entries	• The sources of uncertainty listed for Date/time that are hence carried though in the calculation. • Calculation error
Location	The location of the ship	GPS (Global Positioning System)	• GPS measurement error

Heading	The direction that the ship is heading relative to North	Based on either of the following observations:	• Lack of clarity of what method is used to make the measurement • If several measurements are taken and averaged over the report duration, or if one instantaneous measurement is made at the time of recording.
		The compass on the bridge	• Changes in magnetic north • Measurement resolution and accuracy
		GPS	• Lack of clarity to which north is used, possible settings include: True North, Grid North, Magnetic North, or User North • GPS measurement error
Report Type	Describes the type of report but the description varies between companies. For example, the entry may be a N or P (for noon at sea or port), or an N, P, A or D could be used (for noon at sea, port, arrival or departure)	Observation	• Recording error
Passage Type	Describes the ship's loading condition, typically in two categories, B or L (Ballast or Laden)	Observed from one of the following	• Lack of clarity of what method is used • Does not account for variations in draft
		Carrying cargo or not	• The amount of cargo is not specified
		Draft	• See uncertainties given for average draft at midship below.
Distance	The distance travelled in the reporting duration	Based on either one or the other following methods:	• Lack of clarity of which method is used
		GPS	• Lack of clarity of which north is used, possible settings include: True North, Grid North, Magnetic North, or User North • GPS measurement error
		Chart distance	• Deviations from actual voyage path • Measurement accuracy
Ship Speed (Over Ground)	The speed of the ship over ground	Based on either of the following:	• Lack of clarity as to whether an instantaneous or averaged speed is recorded
		Calculated from the reported dates/times/duration and distance (V=S/T)	• Does not capture speed variations
		GPS	• Lack of clarity to which north is used, possible settings include: True North, Grid North, Magnetic North, or User North • GPS measurement error

Beaufort Number	This describes the weather and sea conditions The Beaufort Number is an ordinal scale.	Based on either or a combination of both the following methods:	• Lack of clarity to which method is used to make the observation • Resolution error using the Beaufort Scale
		Visual observation of the sea state outside	• Subjective error • Observation error
		Measurement of wind speed (see method for measuring wind speed below)	• Wind measurement errors as described for wind speed below
		Forecast data	• Variation from experienced Beaufort Number
Wind Direction	This is typically used to describe the direction that the wind and sea conditions are coming from	Based on one or more of the following :	• Lack of clarity as to whether the wind direction is relative to north, (in which case it needs to be considered with the vessel heading), or relative to the ship.
		Anemometer	• Measurement error due to placement of the anemometer • Measurement fluctuations • Measurement error
		Forecasts	• Differences with experienced conditions
		Visual observation	• Errors due to subjectivity
Fuel Consumpti on	The fuel consumed during the report duration	The fuel consumed is typically measured in any one of the following ways	• The use of a shaft generator or other such technology should be identified • The total consumption accuracy to the record date/time/duration.
		Fuel Tank Soundings usually made using a sounding tape and bob, but could also use an electronic mechanical sounding device	• Sounding measurement error • Calculation and rounding error in deterring the trim and list of the vessel , and hence the volumetric content in the tank • Includes or doesn't include the spill tank fuel • Inclusion of fuel used or obtained from other systems than the main engine
		Fuel Flow Rate measurement typically using one of the following sensor types:	• Sensor measurement error
Sometimes included in a SR dataset			
Ship Speed (through water)	The ship's speed through the water	Using a speed log (e.g. a Doppler log (most common), Electromagnetic or acoustic correlation)	• Lack of clarity as to whether an instantaneous or averaged speed is recorded for the report duration • Sensor measurement error
Engine RPM	The speed of the main engine	Determined by either of the following methods	• Lack of clarity of which method is used
		Determined from the fly wheel using a tachometer. The average RPM is determined by comparing the RPM counter values at the start and end of an observation period and dividing by the time between the values.	• Lack of clarity as to whether an instantaneous or averaged recording has been made • Measurement taken simultaneously or not with the power record (if recorded). • Measurement error (of RPM and duration if an average is provided) • Calculation error

		Integrated pulse sensor and frequency counter into a shaft torque meter	• Sensor measurement error
Brake power	Shaft power is determined from the shaft meter and corrected using the calibrated efficiency to brake power.	Using a shaft meter (e.g. based on strain gage measurement or optical)	• Sensor measurement error • Sensor measurement calibration
Draft at midship	The average draft at mid ship	Determined by either of the following:	• Variations in the average draft at midship vary over the reporting duration due to consumption of fuel • Lack of certainty in the procedure
		Draft marks	• Resolution of measurement • Accuracy of observation • Lack of clarity if the draft is measured from aft, forward or midship draft marks, or an average is taken of all three.
		Loading computer	• Measurement error
		Draft gauges	• Sensor measurement error
Draft Fore	The draft at the bow of the ship	Measured in the same ways as described for draft	• The same uncertainty considerations as listed for Draft
Draft Aft	The draft at the stern of the ship	Measured in the same ways as described for draft	• The same uncertainty considerations as listed for Draft
Trim	The trim of the ship	Determined from:	• Lack of clarity of what method is used
		Calculation from the fore and aft draft (if provided	• Encompasses the uncertainties with the draft measurements • Calculation error
		The loading computer	• Accuracy of measurement
Wave Height/ Force	Typically corresponds to surface wind generated waves.	The surface waves, swell and currents, force and direction, may be represented by an ordinal (Beaufort Number) scale or continuous scale (meters). They may be measured in the following ways:	• Lack of clarity as to which method(s) are used
Wave direction		Observation	• Subjective error • Observation error
Swell Height/ Force	Referring to the developed sea waves		
Swell Direction		Forecasts	• Variation from experienced conditions
Current Force	Wave currents		
Current Direction		Radar	• Sensor observation error

Wind Speed/Force	The speed of the wind. It could be given in scale units (such as meters per second) or represented by a Beaufort Number	Based on one or more of the following :	• Lack of clarity as to which method(s) are used for measurement • Measurement resolution error related to the use of a (Beaufort Number) or continuous (meters per second) scale.
Wind Direction		Anemometer	• Measurement error due to placement of the anemometer • Measurement fluctuations • Measurement error
		Forecasts	• Differences with experienced conditions
		Visual observation	• Errors due to subjective
Atmospheric pressure	Barometric pressure	barometer	• Resolution of observation • Sensor measurement error
Atmospheric temperature	Barometric temperature	thermometer	• Resolution of observation • Sensor measurement error

Additional uncertainty is inherent with all manually entered SR data variable due to human error. Human error may also be inherent in any data transfer processes or transcription processes. It is recommended for future work that an uncertainty analysis is undertaken in attempt to quantify the uncertainties expected when utilising the data.

The data variables recorded in a SR record depend on company procedures, measurement equipment and sensors available onboard and individual crew methods used to make the record, at the time of recording each one. Therefore, it was not surprising that the data variables collected for each ship SR dataset varied between companies, ships and even for the same ship.

Table 12, Table 13 and Table 14 therefore provide a list of the data variables contained in the datasets collected for each ship type. The number of records within the SR datasets with specific variables recorded is identified. Where only most or a few records in the dataset contained the variable this may have been due to: missed entry by the seafarer completing the record; a change in operating procedures to record or not record a variable; installation or availability of new measurement equipment or sensors. However, for all SR variables and datasets, there were some instances individual values were missing.

Table 12: Description of data collected, CS tanker ships

Data Variable	Additional details	No. of records in the SR dataset	Format, units or category options
Date/Time		All	dd/mm/yyyy hh:mm
Duration	The time since the last SR record. Calculated during the data processing described in the next chapter section.	All	hours
Voyage type	Corresponds to the type of record entry: i.e. at noon whilst sailing or in port, or, an additional record on arrival and departure of port.	All	Arrival, Port, Departure, Sailing
Passage type		All	Ballast, Laden
Distance travelled		All	Nautical miles
Port or position		All	Place name, GPS coordinates
Destination		All	Place name
Ship Speed	Ship speed over ground. Calculated by dividing the distance travelled by the duration of the reporting interval.	All	Knots
Forward draft		Few	Meters
Aft draft		Few	Meters
Average draft at midship		Most	Meters
Beaufort number		All	1,2,3,4,5,6,7,8
Wind direction	The wind direction provided was in relation to the ship. The direction was coded into 8 categories corresponding to 45 degree interval in 360 degrees. The port and starboard degrees were combined in the data standardisation processes to generate the format shown here.	Most	Head seas Bow quartering seas Beam seas Stern quartering seas Following seas
Slip	The apparent slip calculated from the recorded ship speed and observed main engine RPM. Presented as a percentage factor.	Most	%
Main engine HFO consumption	The total heavy fuel oil consumed by the main engine over the report duration	All	Tonnes
Total fuel(s)[18] consumption	This is the total of all fuels consumed over the report duration	All	Tonnes
Power, brake[21 (pg 188)]	Torque meter measurement	Few	Horse Power
RPM	Torque meter measurement	Few	
Comments	There was no specific format for the comments and it very much differed between captains. In many cases no comments were made.	Few	e.g. Against currents of X knots, Adverse weather, Proceeding at economical speed, drifting

[18] *Fuels: Heavy Fuel Oil (HFO), Low Sulphur Fuel Oil (LSFO), and Marine Diesel Oil (MDO).*

Table 13: Description of data collected, CS container ships

Data Variable	Additional details	No. of records in the SR dataset	Format, units or category options
Date/Time		All	dd/mm/yyyy hh:mm
Duration	The time since the last SR record. Calculated during the data processing described in the next chapter section.	All	hours
Voyage type	Only sailing reports were included in this data set	All	Sailing
Passage type		All	Ballast, Laden
Distance travelled		All	Nautical miles
Port or position		All	Place name, GPS coordinates
Destination		All	Place name
Estimated time of arrival		All	dd/mm/yyyy hh:mm
Ship Speed	Ship speed over ground.	All	Knots
Wind direction		All	Degrees
Wind force		All	Beaufort force scale
Sea direction		All	Degrees
Sea force		All	Beaufort force scale
Current direction		All	Degrees
Current speed		All	Beaufort force scale
Swell direction		All	Degrees
Swell forces		All	Beaufort force scale
Vessel course		All	Degrees
RPM		All	
Slip	This was given as the slip factor	All	%
Main engine HFO consumption	This a total of the fuel consumed by the main engine over the report duration	All	Tonnes
Other machinery fuel(s)[19] cons.	This is the total of all fuels consumed over the report duration	All	Tonnes
Comments	There is no specific format for the comments and very much differ between different captains. In many cases no comments were made.	Few	

Table 14: Description of data collected, CS bulk carrier ships

Data Variable	Additional details	No. of records in the SR dataset	Format, units or category options
Date/Time		All	dd/mm/yyyy hh:mm
Duration		All	hours
Voyage type	A report was made typically at noon each day whilst sailing or in port. Additional reports were also made on arrival and departure of the port.	All	Arrival, Port, Departure, Sailing
Passage type		All	Ballast, Laden
Distance		All	Nautical miles

[19] *Fuels means a spate value for marine heavy fuel oil, HFO, low sulphur fuel oil, LSFO, and marine diesel oil, MDO.*

travelled			
Port or position		All	Place name, GPS coordinates
Destination		All	Place name
Estimated time of arrival		All	dd/mm/yyyy hh:mm
Ship Speed	This is ship speed over ground as an average of the reporting period	All	Knots
Forward draft		All	Meters
Aft draft		All	Meters
Wind direction		All	Degrees
Wind force		All	Beaufort force scale
Sea direction		All	Degrees
Sea force		All	Beaufort force scale
Current direction		All	Degrees
Current speed		All	Beaufort force scale
Swell direction		All	Degrees
Swell forces		All	Beaufort force scale
Vessel course		All	Degrees
Slip	This was given as the slip factor	All	%
Main engine HFO consumption	This a total of the fuel consumed by the main engine over the report duration	All	Tonnes
Total fuel(s)[20] consumption	This is the total of all fuels consumed over the report duration	All	Tonnes
RPM		All	

The main observations and differences between the datasets collected included:

- Brake power[21] was only recorded for the tanker ships. However, the records were only made for approximately the last 1/3rd of the dataset: i.e. after the installation of a torque meter.
- RPM was recorded for all ships, but only in the same 1/3rd of the dataset for the tanker ships in which brake power had been recorded.
- The SR data sets for the container and bulk carrier ships were the only ones that had records for the force and direction of the wind, sea current and swell individually.

[20] Fuels means a spate value for marine heavy fuel oil, HFO, low sulphur fuel oil, LSFO, and marine diesel oil, MDO.

[21] The variable recorded in the SR data set was labelled Brake Power. However, it is known that the power was measured by a shaft torque meter (providing a measurement of shaft power). It is not known if the shaft power measurement had or had not been corrected by the gearbox efficiency to brake power before being recorded in the SR record. This is a demonstrated uncertainty in SR datasets. Due to this unknown it was assumed that the recorded power is brake power, although it is considered that this might not be the case.

- Average draft at midship was only recorded in most of the tanker SR's dataset. However, loading report datasets were available for the containership's and therefore this information could be found.
- The SR datasets collected for the containers ships were only for when the ship was sailing. The tanker and bulk carrier ships had records for sailing and whilst in port.
- The recording of comments variable was sporadic throughout the SR datasets.

7.3 Data Processing

Data processing was carried out prior to the analysis to collate the collected SR datasets in a standardised database, from which the data could be analysed and compared.

7.3.1 Database Construction

▪ **Software**

There are several dedicated database design, construction and utilisation software packages available and used within industry, including; Microsoft Access (Microsoft n.d.), Oracle (Oracle n.d.), and IBM (IBM n.d.). Nevertheless a spread sheet software package was selected (Microsoft Excel (Microsoft n.d.)) as: the dataset size was not too large: the computational flexibility and capabilities of a spread sheet software package outweighed those of the database packages: programming applications (such as Visual Basic) were available: ease of import and export with statistics software packages.

▪ **Database Design**

Three database tables (spread sheets) were created each containing the data variables shown in Figure 18. A unique ID was created for each record in each table, as described in Table 15. The unique ID's were used to link[22] the tables and avoid redundancy of stored data.

It should be noted that not all variables contained in SR's have been included in the Reports table: only those of direct relation to the analyses presented in this research.

[22] *The one (1) to many (∞) links between the tables, via the unique ID's can be seen in Figure 18.*

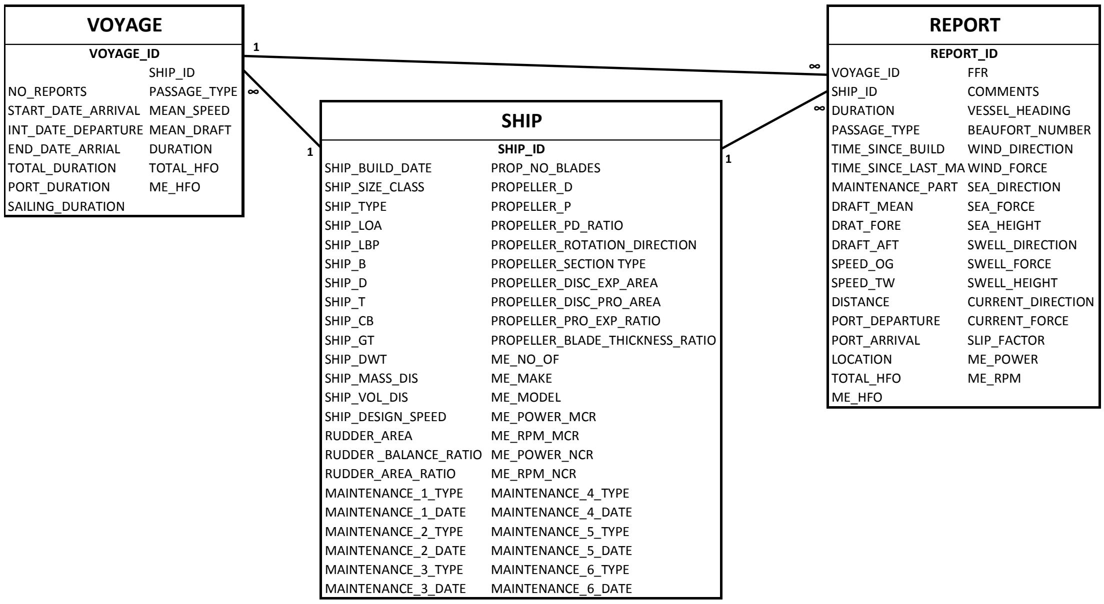

Figure 18: Database table design

Table 15: Unique ID creation

ID	Description	Format	Example for case study ship T1
SHIP_ID	Each case ship was given a reference ID in Table 10. The first letter indicates the type of ship (T = tanker, C = container, B = bulk carrier) The number and letter combination is unique	SX	T1
VOYAGE_ID	A voyage was defined from the ship departing port to departing the next port, i.e. including the unloading port time. For the tanker and bulk carrier case study ships, this was calculated by ordering all SR’s in data order and considering the sequence of the *passage type* value recorded in each report. For the container case study ships it was calculated by observing the change of destination place name. Each voyage was identified in this way for all case ships to provide consistency in the definition of a voyage. The voyage ID was then formed using the ship ID followed by a numeric value assigned to each voyage in chronological order; this combination providing a unique voyage ID.	SX_VXX	T1_V67
REPORT_ID	Each individual SR recorded (report) collected was given a numeric value in chronological order. Combining this with the corresponding voyage and ship ID the report ID was generated.	SX_VXX_RXXX	T1_V67_R1046

7.3.2 Database Standardisation and Population

It has been emphasised that there is considerable variation between the data variables recorded in the same or different SR datasets. Therefore great care was taken to only combine data variables from the individual SR datasets under the same data variable heading (a list of the heading were shown previously in Figure 18.). An example of this was not to confuse ship speed over ground with ship speed through water: in this case data variable headings had to be created.

In addition to the data variables listed in Table 12, Table 13 and
Table 14, additional data fields had to be defined or calculated as described here.

▪ **Separation of SR's into voyages**

A voyage was defined from the ship arriving at port to arriving at the next port. Each voyage therefore includes unloading or unloading and port time.

For the tanker and bulk carrier case study ships, this was calculated by:

- **a)** Sort the SR's for a case study ship in date order
- **b)** Use the PASSAGE_TYPE value recorded in each report to determine when the ship arrived at port

For the container case study ships:

- **a)** Sort the SR's for a case study ship in date order
- **b)** Use a change in PORT_DEPARTURE value to identify a new voyage

▪ **Matching voyage data to SR data**

For the container ships the average draft at midship was made available for each voyage via loading reports. The mean draft provided in these reports therefore had to be matched with the corresponding voyage in the SR dataset, and entered for each SR record for that voyage (assuming that the average draft at midship does not change over the voyage, which is not true but assumed for the recorded average draft for the other case study ships). This was achieved via the following steps:

a) Collate the average draft at midship and the corresponding date recorded in each loading report into one spread sheet.

b) Look up the date from the loading reports with the date of the SR's and transfer the corresponding average draft at midship to the SR dataset

c) Expand the average draft at midship for all records in the identified voyage

- **Calculate DURATION**

The duration of each SR record was assumed to be the difference between the date and time of the record entry, and the data and time of the previous record entry. This duration is the period of time that the data variable corresponding to average values (i.e. average speed) were considered averaged over.

- **Calculation of Fuel Flow Rate of the main engine (FFR)**

The Fuel Flow Rate (FFR) is the tonnes of HFO consumed by the main engine per day. It was calculated as follow:

$$\boldsymbol{FFR} = \frac{\boldsymbol{ME{,}HFO\ Cons._{rec.}}}{\boldsymbol{Duration_{cal.}}} \times \mathbf{24} \qquad \textit{Units:} \frac{\textbf{tonnes}}{\textbf{day}}$$

- **Weather direction**

The weather direction was provided relative to the ship for the tanker case study ships. However this was not the case for the container and bulk carrier ships. Therefore the wind direction relative to the ship was calculated from the recorded vessel heading and wind direction.

For the case study tanker ships the wind direction was categorised into 8 degree values (0° [head seas], 45°, 90°, 135°, 180°, 225°, 270° & 315°). A ship is considered symmetrical, therefore to increase the number of data points for each wind direction for analysis, the port side records were combined with the starboard to form 5 categories of wind direction: head (0°), bow quartering (45° or 315°), beam (90° or 270°), stern quartering (135° or 225°) and following (180°).

- **Define Maintenance Part (MP)**

Defined by:

a) The count the number of previous maintenance event carried out

e.g. for case study Ship T1, MP1 corresponds to the time period between ship build and the first propeller polishing. MP2 to the time period between the propeller polishing and the first dry dock, and MP3 from the first dry dock to the second dry dock.

- **Calculate Time since build**
  a) Date/time for the SR record, less the data of the ship build. Given in months
- **Calculate Time since last maintenance**
  a) Date/time for the SR record, less the date of the last maintenance event

7.3.3 Data Filtering

A simple data filtering method was used to remove SR records from the datasets to produce data samples relevant for each analysis. Two levels of data filtering were thus carried out for this research, one to identify the data sample for the analysis of operational profiles, and the other to identify the data sample for the SOPP model development.

The filters for the analysis of operating profiles are identified with the presentation of results for each profile in Chapter 8. The filters applied for the SOPP model development data samples are given in Table 16.

For the development of the SOPP model the reports matching the following criteria were removed:

Table 16: Data filters applied for the SOPP model development

Filter (removed)	Reasoning
Report type not *Sailing*	To remove reports corresponding to in port, or in arrival and departure modes of operation (which may include transient operations due to manoeuvring, or operation in shallow water)
Records with a duration of 20 hours or less	Considered to potentially not be in the full away sailing condition and therefore may include transient operations due to manoeuvring, or operation in shallow water)
No ship speed value recorded	This variable was required as an input for the SOPP model development.
Recorded speed lower than 10 knots	Considered to potentially represent operation not in the full away sailing condition and therefore may include transient operations due to manoeuvring, or operation in shallow water)
No Passage type value (i.e. *Ballast* or *Laden*)	This variable was needed to split the
No main engine fuel consumption, and hence FFR, value recorded	This variable was required as an input for the SOPP model validation.
No Beaufort Number value recorded	This variable is required as an input to the SOPP model.
No wind direction value recorded	This variable is required as an input to the SOPP model.
No average draft at midship value recorded	This variable is required as an input to the SOPP model.
No slip recorded	This variable was required as an input for the SOPP model development.

CHAPTER SUMMARY

The data and information that was collected for use in the data analyses presented in Chapters 8 and Chapter 9, has been described in this chapter. The data processing methods to ensure the construction of a standardised database and to calculate addition variable, were described.

It was identified that there is no standardisation of the data variables recorded in SR datasets. Moreover there is great variability between companies, between ships, and for the same ship.

The common methods of measurement or observation for each data variable typically recorded in a SR dataset were identified, along with the associated uncertainties.

Improvement of the quality of SR records was identified as important. This is because they provide a widely collected data source that has been collected for many years (providing a time history of data): hence prove beneficial for SOPP and SOPM (as will be demonstrated in Chapter 9). It is recommended that company procedures should be revised to reduce the uncertainty in SR record as far as possible. A suggested method to raise seafarers' awareness and motivation towards improving SR record data entry was to demonstrate and explain: how SR data is used for SOPP and SOPM; the benefits that SOPP and SOPM can provide; hence the importance to take due care when making a SR record entry.

8. DATA ANALYSIS OF SHIP OPERATIONAL PROFILES

CHAPTER INTRODUCTION

The aim of this chapter is to present the analysis of operational profiles for the case study ships, and identify how each profile impacts on energy efficiency performance. Results are presented by ship type (Tanker, Bulk carrier, and Container) and size classification (Handysize, Aframax, Suezmax): providing average operating trends over the years. Specific ship profiles are also considered in this chapter.

8.1 Analysis Introduction

The 21 case study ships listed previously in Table 10 in Section 7.1, were used to analyse the average operational profiles. Table 17 presents the number of ships with datasets available for analysis of different sizes and years. Some data variables (such as average draft at midship) were only recorded after a certain year, but were available for the same number of ships identified.

Table 17: Number of ship datasets used for the analysis of each average operating profiles

		Years									
Ship Type	**Size Classification**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
Tanker	Handysize								1	1	
	Aframax			4	4	4	4	4	4	4	4
	Suezmax			3	3	3	3	5	5	5	5
Container	Post Panamax				4	4	4	4	4	4	4
	Post Panamax Plus	2	2	2	2	2	2	2	2	2	2
Bulk Carrier	Capesize							5	5	5	5

The following comments regarding the analysis can be made:

- The operating profiles are given as a percentage of the total time duration of all reports in the specified period and operational mode.
- It was assumed that the SR records removed during data filtering (see Sub-section a)) will have a proportional impact on the results, hence the profiles remain representative.
- Where a time period has been specified, all SR records belonging to voyages that started in that period were analysed; regardless of whether the voyage finished in the time period.
- A voyage was defined from arrival at one port to arrival at the next. It therefore includes the port time prior to the sailing days.

8.2 Passage Type Profile

8.2.1 Average Profiles

The objective is to maximise the transport work of a ship: i.e. maximise laden operation and minimise ballast operation and time spent in port. This relationship is reflected in the energy efficiency performance of the ship (see the discussion on the EEOI, Sub-section 2.2.3). Furthermore, time spent in port affects the amount of fouling accumulation on the hull and propeller (see Sub-section 2.4.3): where fouling accumulates at a faster rate when the ship is stationary, increasing resistance and hence fuel consumption. Thus knowing the amount of time spent in each operational mode (laden, ballast, port) is important to identify (i.e. performance monitoring and feedback), and then consider for improvement.

Figure 19, Figure 20 and Figure 21 demonstrate the percentage of time spent in each operational mode each year. The figures demonstrate that there does not appear to be a strong increasing or decreasing trend over the years for the time spent in each operational mode.

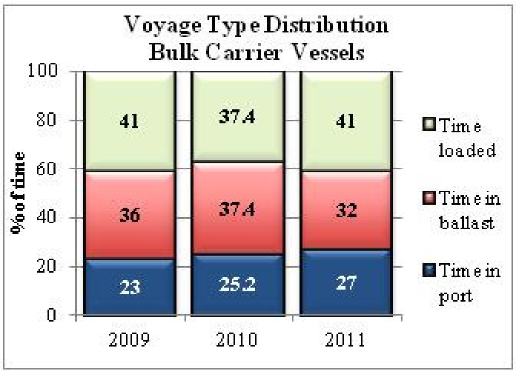

Figure 19: Passage type profile, CS bulk carrier ships

Figure 19 presents the voyage type distribution for the case study bulk carriers. It demonstrates that the bulk carriers typically spend around a quarter of their time in port per year. Whilst the percentage of time increases from 2009 to 2011, the increase is not significant enough to make a conclusive statement about a trend: particularly as only three years have been captured. The bulk carriers spend approximately 40% of their time completing laden voyages and approximate 35% in ballast.

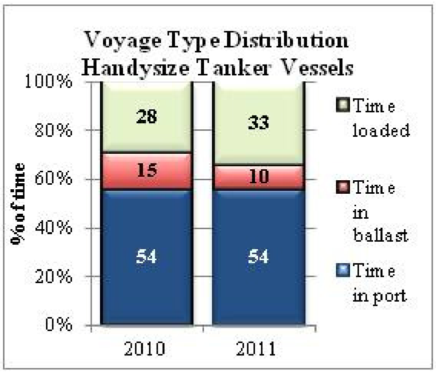

Figure 20: Passage type profile, CS tanker ships: Part A, Handy Size

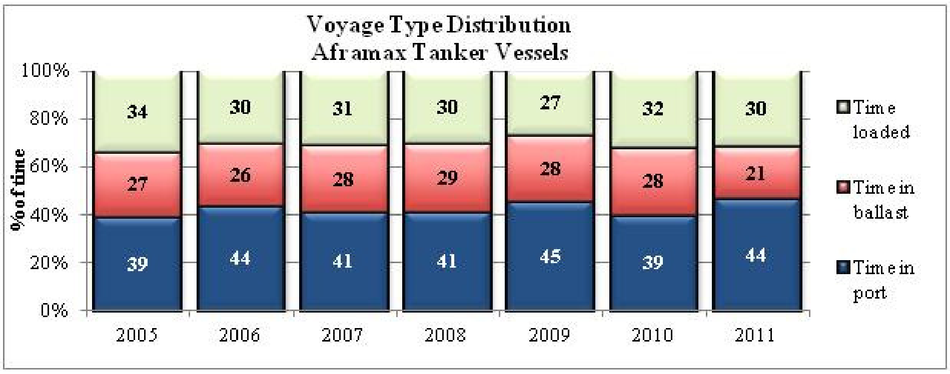

Figure 20: Passage type profile, CS tanker ships: Part B, Aframax

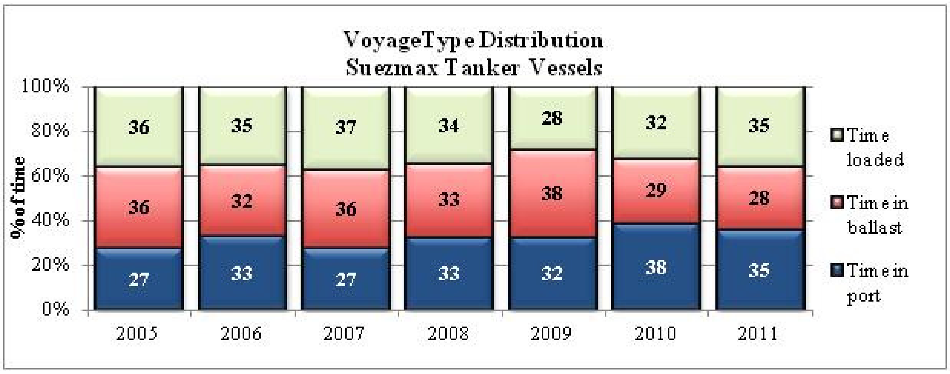

Figure 20: Passage type profile, CS tanker ships: Part C, Suezmax

Figure 20 presents the voyage type profile for the case study Handysize (smallest), Aframax, and Suezmax (largest) tankers. It is shown that the larger the tanker, the smaller proportion of time is spent in port per year: approximately 54% for the Handysize, 42% for the Aframax, and 32% for Suezmax tankers, as an average of all years. The proportion of time spent laden increases with ship size: approximately 30.5% for Handysize, 30.6% for the Aframax, and 33.8% for the Suezmax tankers. However, the Handysize tanker demonstrates the least average time spent in ballast (12.5%), followed by the Aframax (26.7%) and Suezmax (33%) tankers. The trends described are considered to be expected, when taking into account the routes and operations typical to each ship size classification. For example, Handysize tankers tend to offer a service transporting refined products on shorter, more coastal routes. Dependent on the geographical location of the ports and the availability of products to transport, it is likely that the scheduling of the Handy size tankers can be arranged to minimise ballast voyages. Nevertheless, as the Handysize tankers typically make more port stops than Aframax and Suezmax tankers in a year (due to their voyage durations being shorter) their proportion of time spent in port is higher. On the contrary, the Aframax tankers made longer voyages, and the Suezmax tankers even longer. This is typical for larger tankers as they tend to transport larger quantities of cargo between locations with high oil production and no oil production, with no cargo to transport back. This is because economies of scale provide cost savings: hence also energy efficiency and CO_2 emission savings. As a results, compared to the Handysize tankers, the Aframax and Suezmax tankers spend a smaller proportion of time in port, but their time in ballast increase as the ships have to travel further to collect the next available cargo.

Figure 21 presents the average voyage type profiles for the case study container ships. The first difference that can be noted compared to the tanker and the bulk carrier ships is that they do not operate with a ballast leg. The only exception is the Post Panamax container ships where a very small proportion of the time is spent sailing in ballast in 2004 and 2012. After reviewing the SR records corresponding to the ballast operation, it was identified that they belonged to two voyages by two ships. One of these voyages was also identified to correspond to a dry dock. Operation in ballast was therefore concluded to not be part of the typical voyage type profile for container ships. As with the tanker ships, the larger container ships (i.e. Post Panamax Plus) demonstrated less time spent in port and longer sailing times.

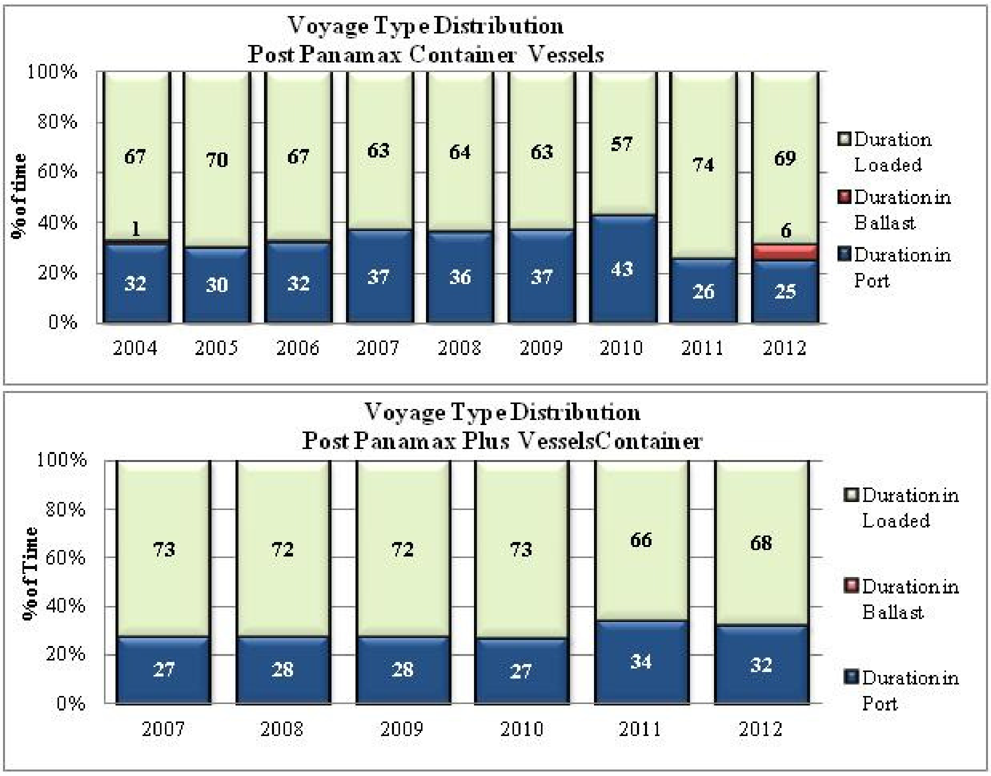

Figure 21: Passage type profile, CS container ships

8.2.2 Ship Specific Profiles

An example voyage profile for a specific ship is demonstrated in Figure 22 for the years 2006 and 2007. The case study ship used is the tanker Ship T1 (see Table 10 in Section 7.1). The duration of time spent in each mode of operation is given in days.

Figure 22 demonstrates the sailing and port time identified for each voyage: given an ID in the form T1_VXX. In some cases the passage type details recorded in the SR indicated a voyage with no sailing time: perhaps the arrival-departure-arrival sequence of SR record entries could be indicative of manoeuvring in port, between docks or anchorage. In these instances it was considered that these voyages could be combined. It is shown that typically a laden voyage is followed by a ballast voyage. However some consecutive voyages of the same operational mode (ballast, laden) can be observed. In these cases the scheduling of the ship may have been optimised to avoid a ballast leg, or not for two ballast legs, or it could be indicative of port stops or operations where no cargo was loaded or unloaded. There is the possibility that for the case of three consecutive voyages where the operational mode is the same, that the middle report entry was not made correctly. However, comparing the recorded average draft at midship value, this was not considered to be the case. Ship T1 predominantly spends between 1 and 10 days in port, with a few longer stays. This is a considerable variation.

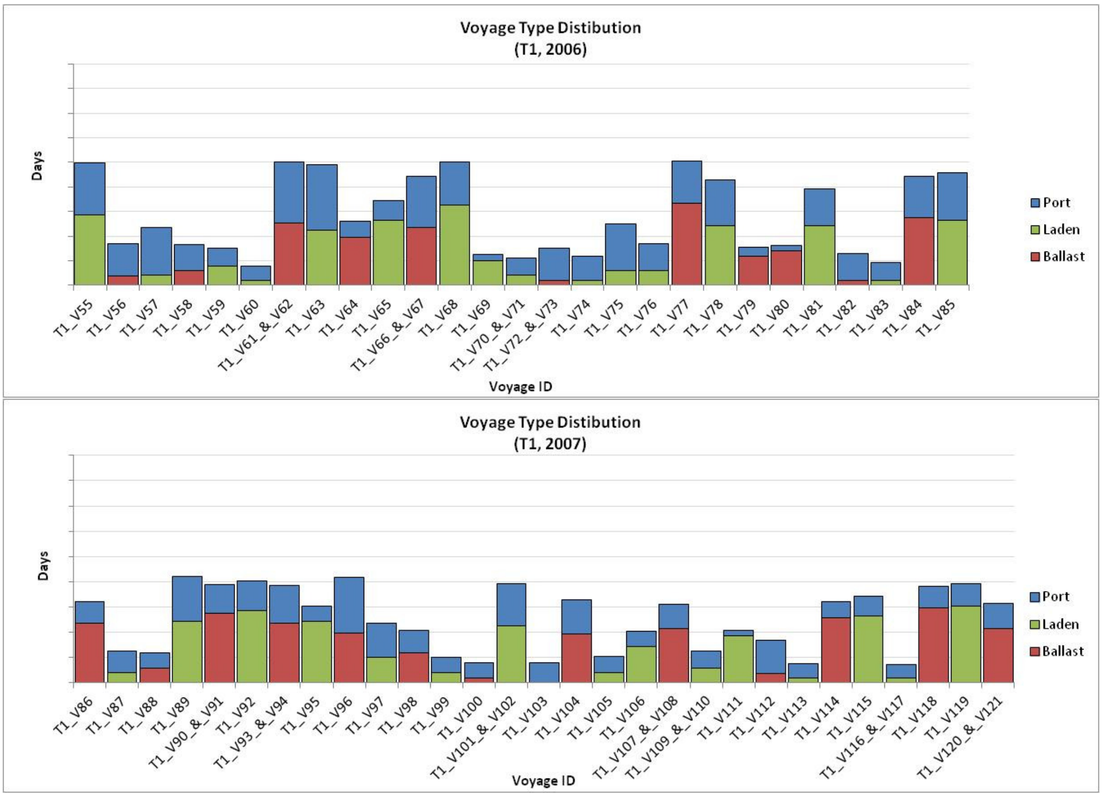

Figure 22: Passage type profile for each voyage, Ship T1

8.3 Speed Profile

The speed that a ship travels impacts on ship performance in the following ways:

- The brake power (and hence the fuel consumption and carbon emission emit) increase approximately to the cube of the speed
- The propulsion efficiency and main engine performance efficiency vary with ship and RPM (where ship speed depends on the RPM and slip factors: discussed in Sub-section 2.4.4)
- Operating speed effects the effectiveness of some types of antifouling paint systems (discussed in Sub-section 2.4.3)

For these reasons it is important to understand the speed profile of a ship. It is also important to understand how the speed profile has changed over the years and since the design of the ship, so that appropriate improvement measures for energy efficient operation can be considered. Speed profiles for individual voyages are also important for considering best fuel and energy efficient voyage practice; including speed optimisation and route planning. Examples of individual profiles are therefore also discussed in this section.

8.3.1 Average Profiles

Figure 23, Figure 24 and Figure 25 present the distribution of the average speed recorded in each SR record as a percentage of the total time spent sailing in ballast or laden, each year. A binning interval of 0.5 knots was used. It should be noted that the effects of weather and sea conditions (which directly influence speed) have not been isolated in this analysis.

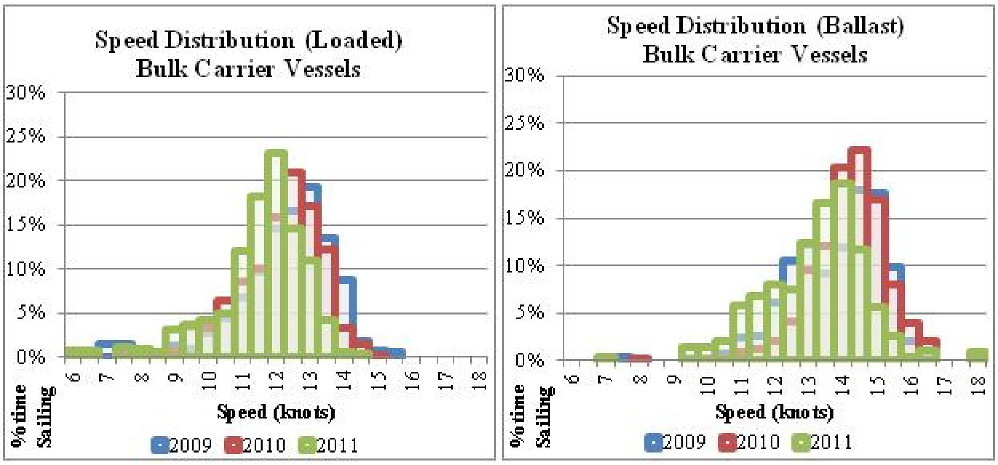

Figure 23: Speed profile, CS bulk carrier ships

Figure 23 demonstrates that the case study bulk carriers operate at faster speeds when sailing in ballast than when sailing in laden. Between 2009 and 2010 there is a decrease in the percentage of time spent at higher speeds and a greater distribution of speeds towards the lower speeds.

The case study Suezmax tanker ships operated at higher speeds than the Aframax and Handysize tankers (Figure 24). In all graphs for the case study tankers, the operational speeds have become more widely distributed, and skewed towards lower speeds over the years. The trend in decreasing speed is expected as it is known that rise in fuel costs over the years has increasingly incentivised a reduction in ship speed to conserve fuel. Whilst the distribution of speeds in laden tend to have a more predominant peak, a comparison between ballast and laden speeds show that they are in a similar range and with similar average value.

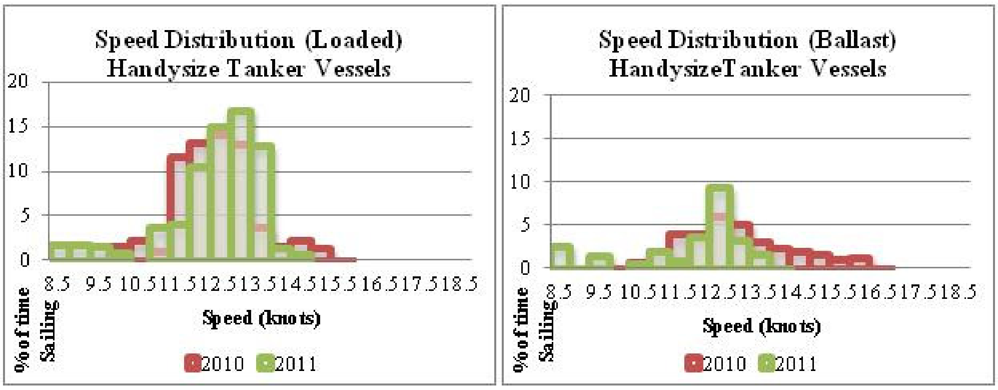

Figure 24: Speed profile, CS tanker ships: Part A, Handy Size

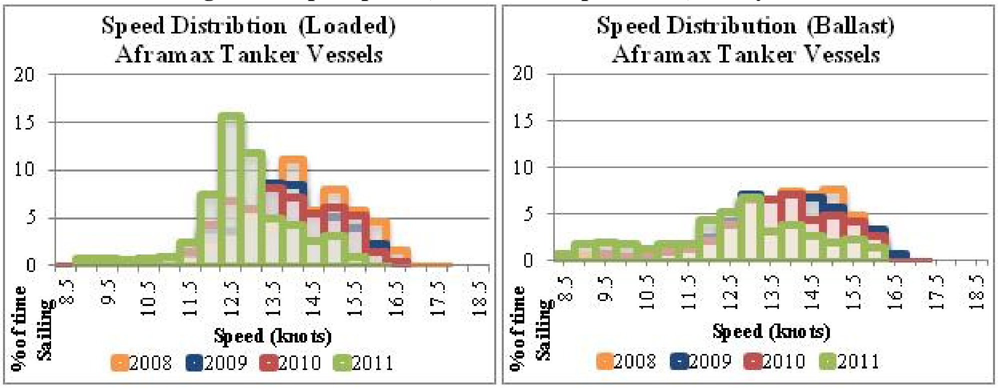

Figure 24: Speed profile, CS tanker ships: Part B, Aframax

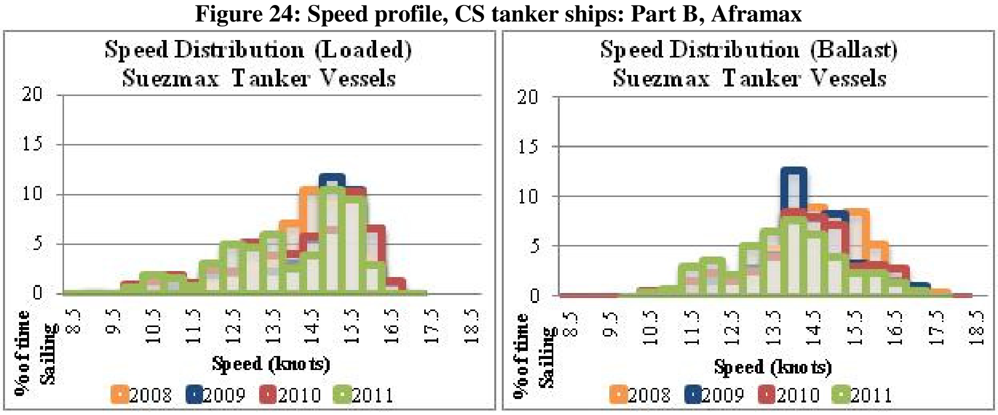

Figure 24: Speed profile, CS tanker ships: Part C, Suezmax

The speed profiles for the case study container ships (Figure 25) only include the laden condition as they do not typically operate in ballast. The profiles have been separated on two graphs: the first showing years 2006 to 2008 and the second for years 2009 to 2012. Between 2006 and 2008 the case study container ships are shown to have predominantly operated in a speed range of 20 to 25 knots. This is the same speed range also presented by (Pedersen & Larsen 2013) who analysed the speed through water recorded in SR datasets over 10 years for 5 sister container ships. (de Kat et al. 2010) also present similar figures for a Post Panamax container ship. It is clear from Figure 25 that in 2009 the proportion of time spent at 20 and 25 knots speed started to decrease and the average voyage speeds became increasingly lower. The decrease in speed in 2009 fits logically with the global economic downturn around 2007, which subsequently impacted on the shipping industry in parallel with rising fuel prices; incentivising slow steaming. The low speed for the Post Panamax ships in 2012 cannot be concluded without further investigation as it corresponds to a year with low port duration and the data sample reduced to 1 ship.

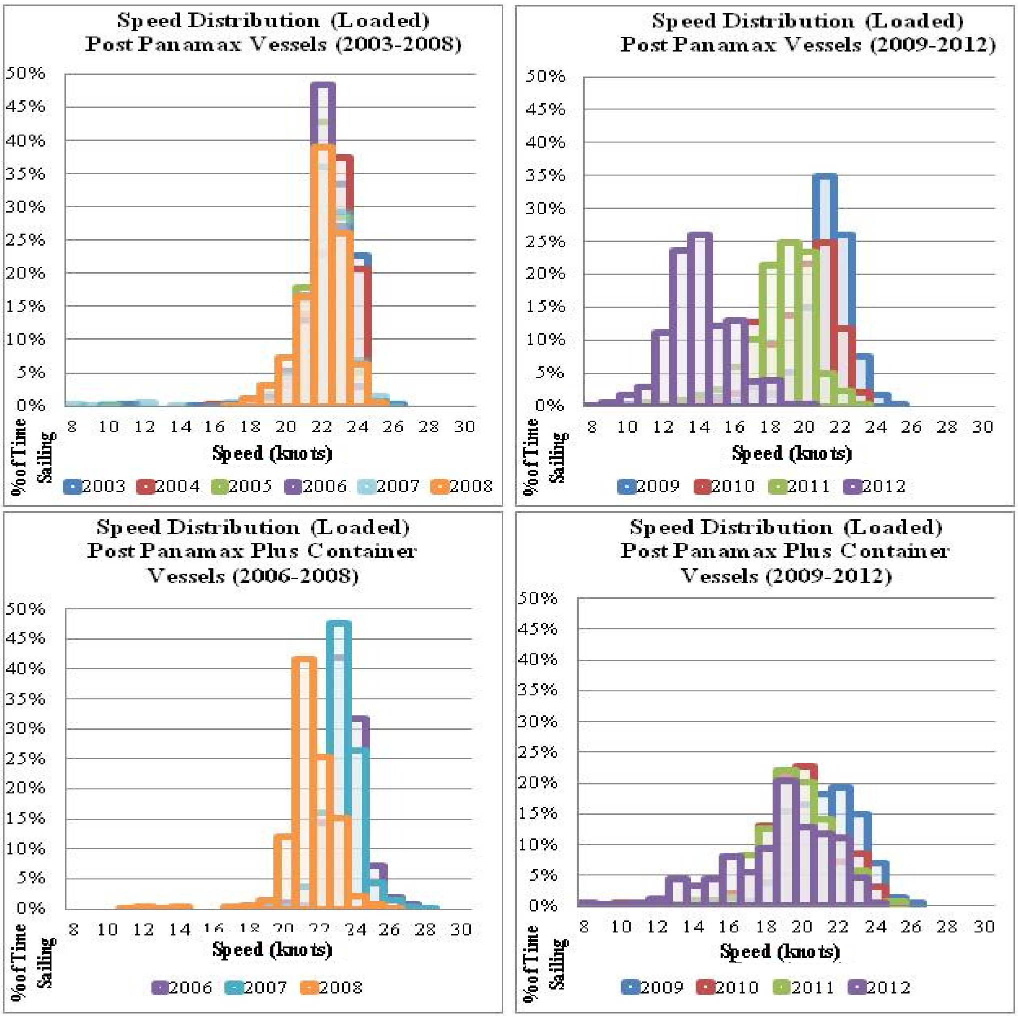

Figure 25: Speed profile, CS container ships

8.3.2 Ship Specific Profiles

Individual voyage speed profiles are presented in Figure 26 and Figure 27: again using case study Ship T1 for the example. The ID of each voyage is included in the title of each graph for discussion reference. It should be noted that the individual profiles and discussed conclusions cannot be considered typical of Ship T1's average operation, nor other tanker ships: they are only given as specific selected examples.

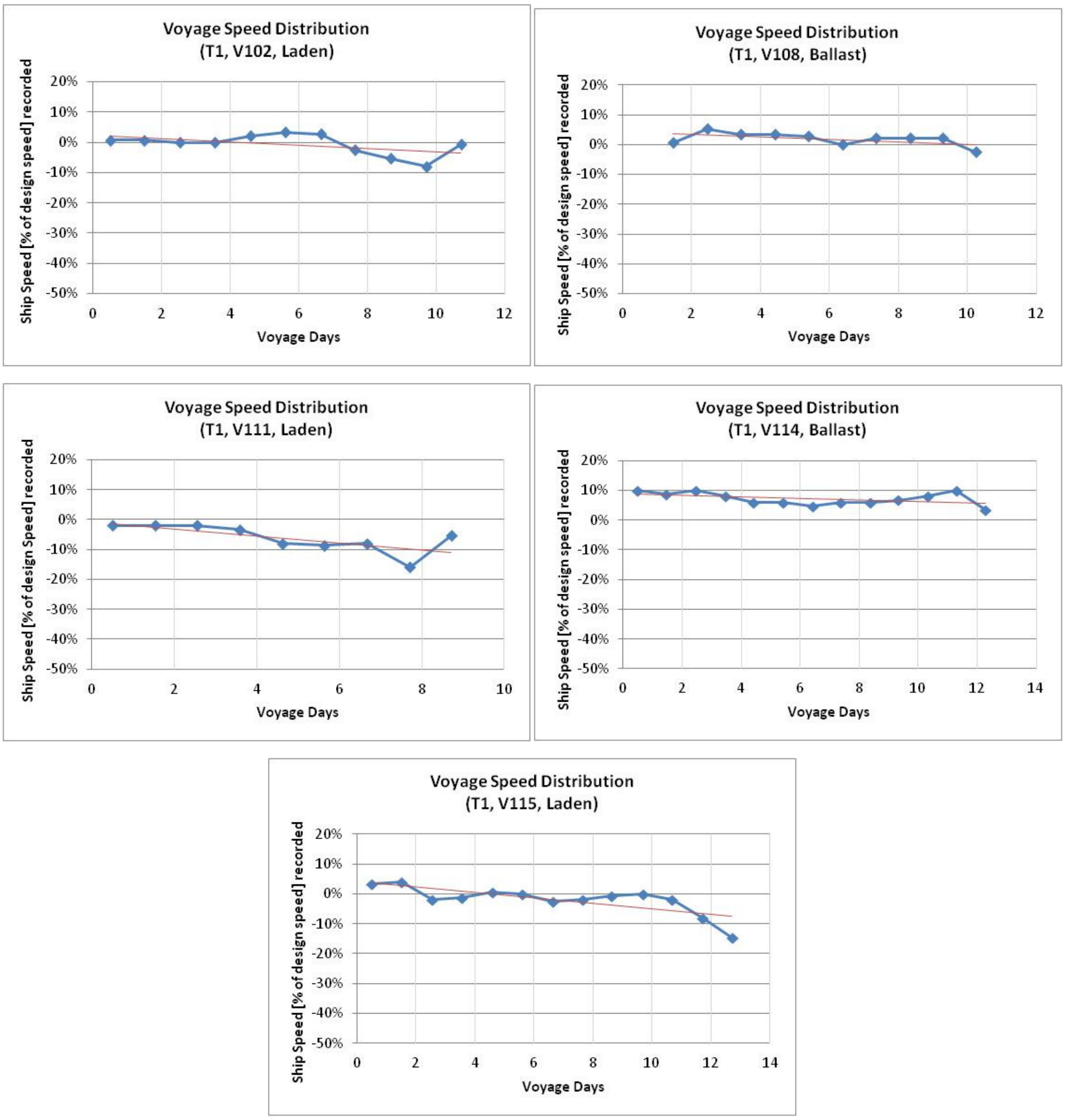

Figure 26: Voyage Speed profiles, Ship T1

Figure 26 demonstrates 5 voyage profiles. The comments provided in the SR records (i.e. the comment data variable) did not contain any information, so it is not known if there were any reasons for the deviations in the profiles, other than those speculated, as discussed. In Figure 26 the trend lines of the average speed decreases over time. This is more evident for the laden condition. This trend could be indicative of *sprint and loiter* type operation where the ship is operated at a faster speed at the start of the voyage to ensure that it will arrive at the destination port on time and not incur any charges. To avoid loitering, the operational speed can be reduced to conserve fuel and arrive in time once the ship has made the required progress and the risk of being late is reduced. Just-in-time arrival in the event of a reported port delay, speed optimisation and or weather routing, are all operational measures to consider for improving speed profiles for energy efficiency. Performance prediction and monitoring in combination with weather routing can help to understand the risks of late arrival.

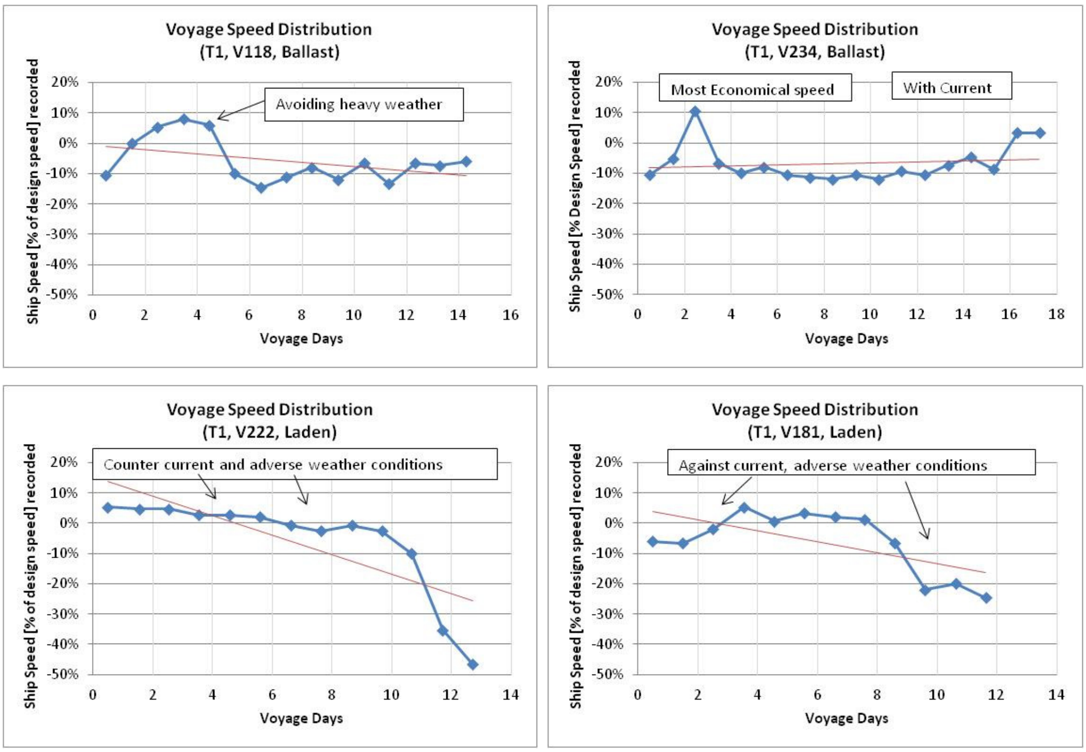

Figure 27: Voyage Speed profiles, Ship T1

Figure 27 demonstrates voyages where the comments recorded in the SR records provided information about the weather and currents experienced over the reporting time duration. It can be seen from voyages V181 and V222 that an against current does not necessarily decrease the speed of the ship. This could be because operation in currents does not pose a safety risk and therefore increasing the power to achieve the same or a higher speed over the ground, can be done. If this is the case the impact of the against current will be evident in a higher recorded Fuel Flow Rate (FFR): i.e. fuel consumption. On the other hand, the benefit of a current in the direction of the ships' travel may be utilised for an increase in ship (as seen for voyage V234) and or a reduction in FFR. The decision to utilise the speed or fuel consumption gain will depend on the commercial requirements for the voyage but should be actively considered as part of energy efficiency voyage planning practices, both onboard and onshore.

On the other hand, it is known that as weather and sea conditions worsen (i.e. the Beaufort Number increases) a ship experiences increased motions (discussed in Sub-section 2.4.3) that can become unsafe at higher operational speeds. It is for this reason that the ship speed may be reduced in adverse weather conditions: i.e. indicated for voyages V181 and V222. On the contrary, for voyage V118 the ship's average speed was increased. However this was identified to have been to avoid worse weather. Whilst the safety related benefit from avoiding the bad weather may be evident, the fuel consumption saving is not immediately identifiable. To quantify the fuel saving (or loss) comparison could be made between the recorded fuel consumption and a predicted fuel consumption for the voyage if the deviation was not made (i.e. using a SOPP model). This again emphasises the need to develop a SOPP model as part of the Framework, as addressed in Chapter 9.

8.4 Cargo Load and Trim Profile

The draft and trim of ship (corresponding deadweight and hence cargo loaded) impacts on ship performance in the following ways:

- The draft of the ship compared to its design draft in laden is more or less representative of how well the ship is being utilised for cargo transport: noting that different cargos have different densities which will cause variations. The energy efficiency objective is to maximise transport work efficiency, i.e. fuel consumed per tonne of cargo transported.
- At different draft and trim, the underwater surface area and displacement of the ship changes, therefore so too does the resistance and hence the required power and fuel consumption. The resistance will also change with appendages and the ship's form (including a bulbous bow) at different waterlines.
- If the aft draft is too shallow then propeller emergence may occur, reducing propeller efficiency greatly.

The above points demonstrate the important of understanding a ship's load and trim profiles. The cargo load profiles have been represented by considering the average draft at midship recorded in the SR records as a percentage of the design loaded draft for the ship. The first sub-section presents the average profiles and the second then looks at trim distribution profiled based on the proportion of SR records with fore and aft trim variables recorded.

8.4.1 Average Profiles – Cargo Load Profile

An analysis of how the draft distributions changed between each year was carried out but was found not to have changed greatly. Figure 28 demonstrates the profile for the case study Aframax and Suezmax tankers. It is apparent that whilst the ships operated predominantly at one draft in ballast, there is a much greater range of drafts utilised when operating in laden. The minimum percentage load (at around 40% load for both the Aframax and Suezmax case study ships) will be representative of the limiting draft to avoid propeller emergence and maintain displacement requirements. The loaded drafts are distributed from fully loaded, 100%, to around 70% and 77% for the Aframax and Suezmax tanker ships respectively. The most predominant loaded draft range appears to be between 70% and 90% load in the laden condition. (Armstrong 2013) also reports that the ship analysed operates 'loaded to approximately 80% cargo capacity as per commercial requirements instead of 98% as per design'. Figure 28 demonstrates that the load in laden ranges to lower loads, similar to those in ballast. However these records only account for a small percentage of the sailing time in laden and therefore are not considered as standard practice. Further investigation into the comments recorded in the corresponding SR records, indicated that these light loads tend to represent time spent at anchor and/or drifting, perhaps whilst waiting for berthing availability or between loading, unloading. To draw conclusive explanations further information would be required.

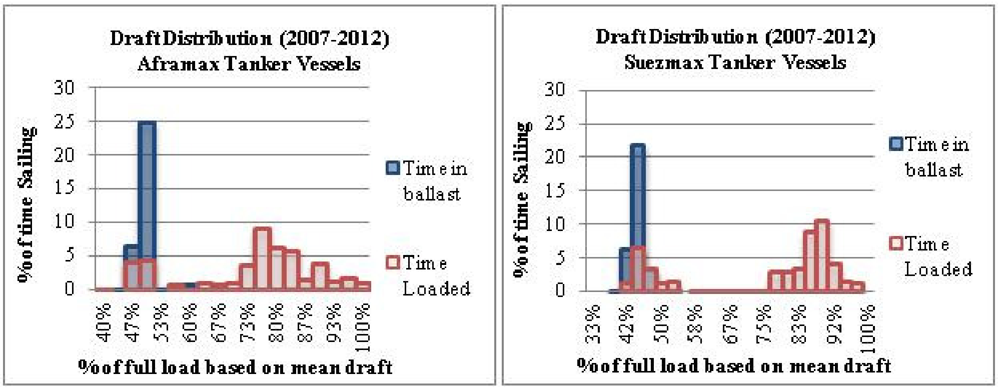

Figure 28: Cargo Load profile, CS tanker ships

Figure 29 presents the cargo loaded distribution for the Post Panamax Plus container ships in laden. Whilst there is a relatively large distribution of loads, the ships predominately operate between 60% and 75% load. The cargo loading of container ships depends on the operational route and the amount of cargo loaded at each port. (de Kat et al. 2010) present a similar profile for a Post Panamax container ship.

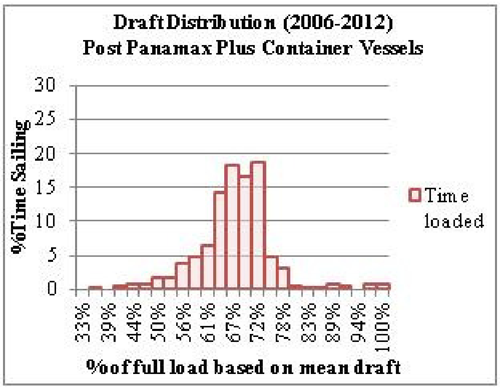

Figure 29: Cargo Load profile, CS contaier ships

8.4.2 Ship Specific Profiles – Trim Profile

It was not possible to analyse the trim distribution for all case study ships as there was only a small proportion of SR records that contained recorded fore and aft draft values (refer to Table 12 in Chapter 7). Figure 30 provides an example of the trim profile used for case study Ship T1. It is demonstrated that the trim used most of the time in ballast was 3 to 4 meters by the aft: predominantly 3 meters. This is the trim that corresponds to maintaining propeller immersion. When sailing in laden, most of the time Ship T1 operated between 0 and 1 meters trim by the aft; predominantly 0 meters trim, i.e. at even keel. After further discussion with the industry contact, it was confirmed that both trim profiles represent typical practice for the case study Ship T1.

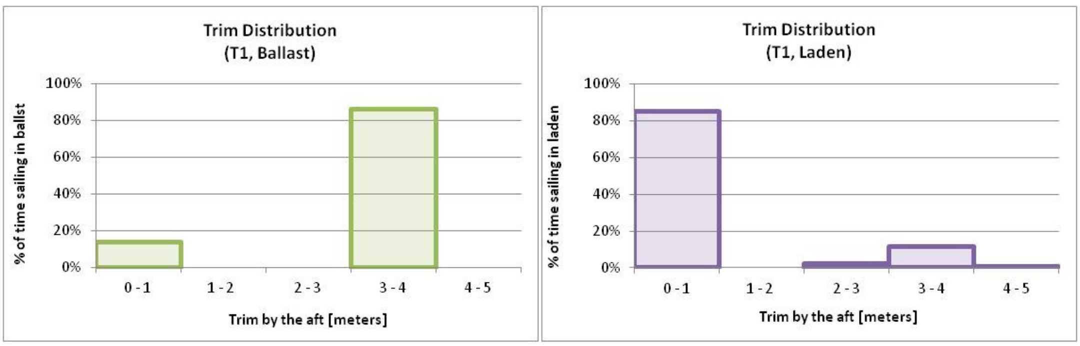

Figure 30: Trim profile, Ship T1

8.5 Dry Docking and Hull and Propeller Maintenance Patterns

The amount of fouling that accumulates on a ship's underwater surfaces affects the ship's resistance and hence power requirements and fuel consumption: previously discussed in Sub-section 2.4.3. It was also discussed that hull and propeller maintenance is typically carried out during dry docks in line with class survey requirements. Therefore, as hull and propeller maintenance impacts the ship performance, the frequency of maintenance operations are important to consider.

To identify typical trends in ship dry docking and hull and propeller maintenance strategies, the additional information provided about the case study ships was used for this analysis (see Table 10 in Chapter 7 for details for the information).

It was first concluded that the average age of the case study tanker ships was 7.5 years, 10.1 years for the container ships and 19 years bulk carriers. For the bulk carrier case study ships, dates of the dry docks were not available, however dates for when hull and propeller maintenance was carried out, were provided: including distinguishing between flat bottom hull, vertical sides hull and propeller cleaning maintenance types. The average dry docking period for the case study tanker ships was 4.7 years, and 4.8 years for the containers ships. These dry dock periods are typical of coordinating hull and propeller maintenance with the 5 year dry dock survey requirements: discussed in Sub-section 2.4.3. One of the case study tanker ships was identified to have dry docked 2.1 years after the first dry dock, although the reasons for this were not identified. During each dry docking it was noted that hull cleaning and propeller polishing (and/or coating where applicable) were carried out. For several of the case study tanker ships a date corresponding to propeller polishing or an unknown event, was recorded; typically 1.2 years after build and ranging between 0.6 and 1.6 years.

For further discussions on the analysis of operating profiles refer to (Banks et al. 2013).

CHAPTER SUMMARY

This chapter has presented an analysis of the SR operational datasets for the case study ships, to determine average and ship specific operating profiles. The impact of each profile on energy efficiency performance is identified. The following is a list of the key conclusions from each profile type:

- *Passage type distributions have not changed significantly over the years: i.e. the amount of time spent in port, sailing in laden and sailing in ballast.*
- *Larger tanker and container ship's tended to make longer voyages, spend less time in port and a greater proportion of time sailing in ballast.*
- *The average speed recorded for the case study containerships continued to notably reduce after 2008, and the range of speeds increased. The difference before and after 2008 could not be determined for the case study tanker and bulk carrier ships as the datasets were limited. A wider range of speeds with a lower average were observed for the bulk carrier case study ships and the tanker ships after 2008.*
- *Speed profiles for individual voyages demonstrated: a decreasing voyage speed; a reduction in speed in due to adverse weather; either a reduction in fuel consumption or gain in speed was utilised with following current, and the opposite with an against current. However the observations are only specific examples and cannot be considered as representative of the ship or other ships operation.*
- *There was little variation in the loaded draft profile for the bulk carrier and tanker ships whilst sailing in ballast; this was considered to be due to maintaining propeller immersion.*
- *The case study container ships were shown not to operate in ballast under typical operating conditions.*
- *Whilst sailing in laden the tanker ships operated at a draft between 70% and 90% of the design draft The container ships operated between 60 and 75% of design draft.*

- *The case study tanker ship predominantly operated at an even keel (no trim) when sailing laden, and with relatively constant trim at 3 meters by the aft in ballast to maintain propeller immersion.*
- *The case study tanker and container ships dry docked at average of 4.7 and 4.8 year intervals, retrospectively. During the dry dock hull cleaning and propeller polishing and /or coating where carried out.*
- *Prior to dry dock the case study tanker ships were identified to have undergone a propeller polishing or an unknown event at an average of 1.2 years after build, ranging between 0.6 and 1.6 years*

Note: the above conclusions are specific to the case study ships and cannot be generalised for the operation of all ship. Nevertheless, the above conclusions are important to identify, recognise and consider when deciding the best operational energy efficiency measures to implement for specific ships or fleets of ships.

9. THE SHIP OPERATIONAL PERFORMANCE PREDICTION MODEL

CHAPTER INTRODUCTION

The aim of this chapter is to present the development, results and validation of the Ship Operational Performance Prediction (SOPM) model. The model was constructed using five analysis steps including: 1) a Data Elaboration, 2) Resistance Regression Analysis, 3) Speed Regression Analysis, 4) Resistance Normalisation, and 5) a Time Dependent Performance Analysis. The case study Ship T1's data, as described in Chapter 7, is used to demonstrate the development of the SOPM model. This chapter has seven sections:

Section

9.1: Modelling Introduction

9.2: Step 1: Data Elaboration

9.3: Step 2: Resistance Regression Analysis

9.4: Step 3: Speed Regression Analysis

9.5: Step 4: Resistance Normalisation

9.6: Step 5: Time Dependent Performance Analysis

9.7: SOPP Model Results and Validation

Chapter Summary

9.1 Modelling Introduction

Literature discussed in Section 2.4 identified that the accuracy of SOPP using operational datasets, such as Report's (SR), was limited. This conclusion was further demonstrated by using the collected data for case study Ship T1 to perform the following analysis methods:

- *Filtering*
- *Filtering and performance relationships*
- *Fuel Flow Rate (FFR) multi-linear regression analysis*

The analyses and results for each of the above listed methods are presented in Appendix D – Investigation of Ship Operational Performance Monitoring.

The conclusion from the filtering analyses was that trends cannot be identified accurately using SR datasets. This is because the filtering process reduced the number of data points considerably but still demonstrates scatter; not allowing for trends to be observed in a reasonable time frame for practical SOPM. The conclusion from the multi-linear regression analysis[23] was that the FFR could be predicted with an average of 6% and 10% absolute error for ballast and laden retrospectively. This was considered a large error for SOPP; particularly when translated to the potential error in fuel cost calculations. Therefore a different method was considered necessary to meet the specification of a SOPP model (given in Sub-section 5.4.6) to support SOPM. The identified method and development of the SOPP model is presented in this chapter, addressing the following five development steps:

a) Step 1: Data Elaboration (Section 9.2)
b) Step 2: Resistance Regression analysis (Section 9.3)
c) Step 3: Speed Regression analysis (Section 9.4)

---

[23] *The Fuel Flow Rate (FFR) Regression analysis was carried out using the following generic form:* $FFR_{Pred.} = (a \times V^3)(b \times T)(c \times BN)(d \times WD) + e$

d) Step 4: Data Normalisation (Section 9.5)

e) Step 5: Time Dependent Performance Analysis (Section 9.6)

9.1.1 Case Study Ship Used For Modelling

Ship T1 was selected as the case study ship to demonstrate the development of the SOPP model for the following reasons:

- The availability of additional collected documents that could be utilised in the SOPP model development, including: the Sea Trial Document; Trim and Stability Booklet; ship, main engine and propeller particulars; main engine operational datasets.
- A proportion of the Ship Report (SR) records in Ship T1's dataset included recorded RPM and brake power[24]. These values could be used for validation.
- Dry dock dates were known.

In addition to Table 10 previously presented in Chapter 7, the data and information utilised for Ship T1 is summarised in Table 18.

Table 18: Information details for case study Ship T1

Case Study Ship Reference	T1	
Number of sister ships	2 others	
Ship Type	Tanker	
Size classification	Suezmax	
Particulars and details	Ship, Main engine, Propeller	
Documents	Sea Trial Document, Trim & Stability Booklet	
Number of records ...	**Ballast**	**Laden**
In the processed database (See Section 7.3 for details on data processing)	456 54 months of data	403 56 months of data

[24] *The variable recorded in the SR data set was labelled Brake Power. However, it is known that the power was measured by a shaft torque meter (providing a measurement of shaft power). It is not known if the shaft power measurement had or had not been corrected by the gearbox efficiency to brake power before being recorded in the SR record. This is a demonstrated uncertainty in SR datasets. Due to this unknown it was assumed that the recorded power is brake power, although it is considered that this might not be the case.*

Containing RPM recorded	219 30 months of data	212 27 months of data
Containing Brake power recorded	205 30 months of data	202 27 months of data
Range of SR data available	41 to 97 months after build	
Data variables in all records of the processed SR dataset	Date/time, Duration, Average ship speed, Draft at midship, Beaufort Number, Wind direction, Slip, Fuel Consumption	
Maintenance dates	Propeller Polish: 14 months after build Dry Dock: 58 months after build	
Paint type	Biocidal Anti Fouling System	

When presenting the modelling results for Ship T1, the following Maintenance Part (MP) definitions have been used:

- **MP1:** the period of time between build and the first hull or propeller maintenance event i.e. the propeller polish. No SR records recorded during this period were collected.
- **MP2:** The period between the propeller polish and the first dry dock. Only the very last part of this period was represented by records in the collected SR dataset.
- **MP3:** After the first dry dock, before the second. Most of this period was represented by records in the collected SR dataset. Although there was no date or SR records up until the next dry dock, it was expected that it would be approximately 5 years after the first dry dock.

9.1.2 Modelling Inputs and Outputs

Step 1, the Data Elaboration Process, was carried out prior to the model development and is required to calculate the resistance used in the SOPP model. Table 19 lists the input, intermediate, output and validation variables used in the Data Elaboration Processes. The sources of the recorded data variables are identified and equation reference is provided for the calculated variables. The equation formulae can be found in Appendix A.

Table 19: Input, Intermediate and Output variables for the data elaboration process

Inputs Variables	Intermediate Calculated Variables	Equation, found in Appendix A	Calculated Output Variables	Equation, found in Appendix A	Validation Variables
Ship Speed [recorded in the SR record]	**RPM** [calculated]	**E.5**	**Brake Power** [calculated]	**E.2**	**Fuel Flow Rate** [recorded]
Slip Factor [recorded]	**Wake Fraction** [calculated]	**E.17**	**Fuel Flow Rate** [calculated]	**E.4**	**Brake Power** [recorded in the SR record]
Propeller Pitch [Ship Information]	**Thrust Deduction Factor** [calculated]	**E.19**	**Carbon emissions** [calculated]	**E.23**	
Average Draft at Midship [recorded in the SR record]	**Propeller Relative Rotative efficiency** [calculated]	**E.21**			
Beaufort Number [recorded in the SR record]	**Apparent Speed** [calculated]	**E.6**			
Wind Direction [recorded in the SR record]	**Advance Coefficient** [calculated]	**E.9**			
Draft-Displacement curve [Trim and stability Document]	**Thrust Coefficient** [calculated] **Torque Coefficient** [calculated]	**E.12, E.13, E.14, E.15 E.16**			
Draft-Volume displacement curve [Trim and stability Document]	**Thrust** [calculated]	**E.10**			
Load-Specific Fuel Oil curve [Main engine documents]	**Torque** [calculated]	**E.11**			
Draft-Longitudinal centre of buoyancy curve [Trim and stability Document]	**Resistance** [calculated]	**E.18**			
Draft-Longitudinal centre of flotation curve [Trim and stability Document]	**Effective Power** [calculated]	**E.2**			
Draft-Waterline length curve [Trim and stability Document]	**Propeller open water efficiency** [calculated]	**E.8**			
Draft-Block coefficient curve [Trim and stability Document]	**Hull efficiency** [calculated]	**E.20**			
Draft-Prismatic coefficient curve [Trim and stability Document]	**Shaft efficiency** [calculated]	**E.22**			
Draft-Waterline coefficient curve [Trim and stability Document]	**Total Propulsion Efficiency** [calculated]	**E.3**			
Draft-Midship coefficient curve [Trim and stability Document]					
Power-Speed curve [recorded power and speed – calm water sample only]					

The input, intermediate, output and validation variables used to develop Steps 2, 3, 4 and 5 of the SOPP model are shown in Table 20.

Table 20: Input, Intermediate and Output variables for developing the SOPP model

<table>
<tr><th>Used in:</th><th>Inputs Variables</th><th>Intermediate Calculated Variables</th><th>Model Output Variables</th><th>Equation, found in Appendix A</th><th>Validation Variables</th></tr>
<tr><td>Steps 2 and 4</td><td>Resistance [calculated]
RPM [calculated]
Average Draft at Midship [recorded in the SR record]
Beaufort Number [recorded in the SR record]
Wind Direction [recorded in the SR record]</td><td>Resistance [predicted]
Normalised Resistance [calculated]</td><td rowspan="4">Brake Power [calculated]

Fuel Flow Rate [calculated]

Carbon emissions [calculated]</td><td rowspan="4">E.2

E.4

E.23</td><td rowspan="4">Fuel Flow Rate [recorded in the SR record]

Brake Power [recorded in the SR record]</td></tr>
<tr><td>Steps 3</td><td>Speed [recorded in the SR record]
RPM [calculated]
Average Draft at Mid Ship [recorded in the SR record]
Beaufort Number [recorded in the SR record]
Wind Direction [recorded in the SR record]</td><td>Speed [predicted]</td></tr>
<tr><td>Step 4</td><td>Date/time [recorded]
Build Date [Ship information]
Dry Dock , hull and propeller maintenance Dates [Ship information]
Normalised Resistance [calculated]</td><td>Resistance due to time dependent performance changes [calculated]
Saving due to maintenance during dry dock [calculated]
Maximum additional Resistance due to time dependent performance changes [calculated]</td></tr>
<tr><td>Other</td><td>Load-Specific Fuel Oil curve [Main engine documents]</td><td></td></tr>
</table>

After the SOPP model had been developed for the specific ship (i.e. having completed Steps 1 to 5), the inputs and intermediate, model and extended output are shown in Table 21.

Table 21: Input, Output variables for the SOPP model

Inputs Variables	**Intermediate Calculated Variables**	**Model Output Variables**	**Extended Output Variables**
RPM [calculated] **Average Draft at Midship** [recorded in the SR record] **Beaufort Number [**recorded in the SR record] **Wind Direction** [recorded in the SR record] **Date/time** [recorded] **Build Date** [Ship information] **Dry Dock , hull and propeller maintenance Dates** [Ship information] **Saving due to maintenance during dry dock** [calculated] **Maximum additional Resistance due to time dependent performance changes** [calculated]	**Resistance** [calculated] **Normalised Resistance** [calculated] **Resistance due to time dependent performance changes** [calculated]	**Ship Speed** [calculated] **Brake Power** [calculated] **Fuel Flow Rate** [calculated] **Carbon emissions** [calculated]	**Speed Loss** **Power Increase** **Added resistance due to the following , above the specified baseline values:** **RPM** **Draft at midship** **Beaufort Number** **Wind Direction** **Time dependent performance changes (such as hull and propeller degradation and fouling)**

9.2 Step 1: Data Elaboration

9.2.1 Method

The Data Elaboration Process was used to calculate additional variables (e.g. resistance) using the variables recorded in the SR dataset and the information collected for the case study ship T1. This information should be available to shipping companies for all their ships. The calculation steps of the Data Elaboration Process are given in the method flow diagram in Figure 31. The referenced equations can be found in Appendix A and the description of each step can be found in the referenced sub-sections.

A validation of the Data Elaboration Process is presented in Sub-section 9.2.9 and observation trends using the Elaborated SR dataset in Sub-section 9.2.10.

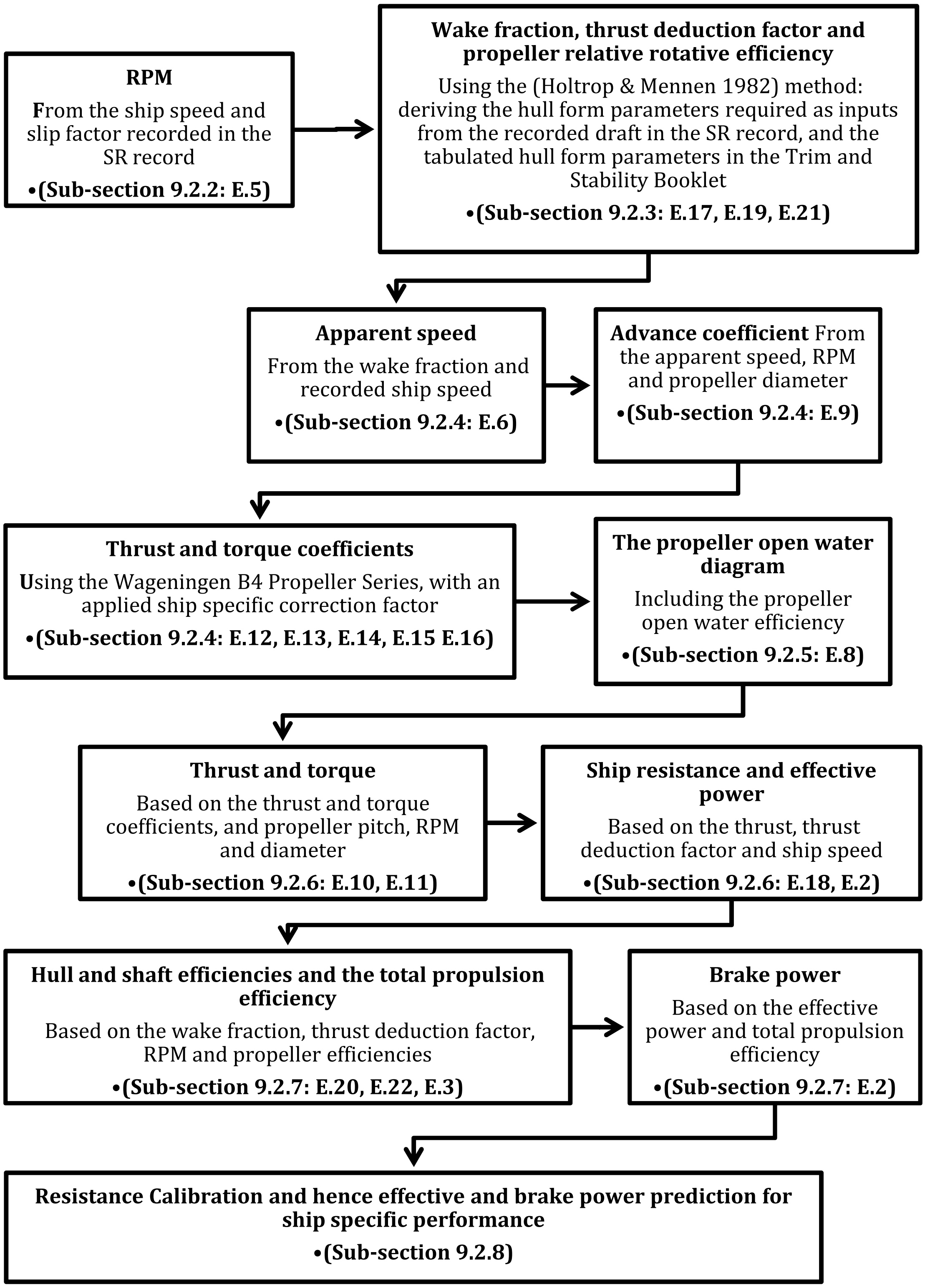

Figure 31: SOPP model, Step 1: Data Elaboration Process Method Flow

9.2.2 RPM

For case study Ship T1 an RPM value was recorded in approximately the last $^1/_3{}^{rd}$ of the SR dataset. Therefore using the recorded RPM would limit the size of the data sample considerably. However, the slip factor was a recorded variable in nearly all SR records. The apparent slip cannot be directly measured and it must be calculated from the ship speed and RPM (E.5: Appendix A). Therefore it was considered that the recorded apparent slip could be used to derive the RPM for each SR record.

Figure 32 demonstrates the error between the calculated (using the recorded slip and ship speed) and the recorded (in the $^1/_3{}^{rd}$ of the SR dataset) RPM values. The difference was found to be very small: an absolute average error of 0.19% for ballast and 0.26% for the laden condition. No systematic variation in the residuals was identified: indicating only random error, most likely due to value rounding.

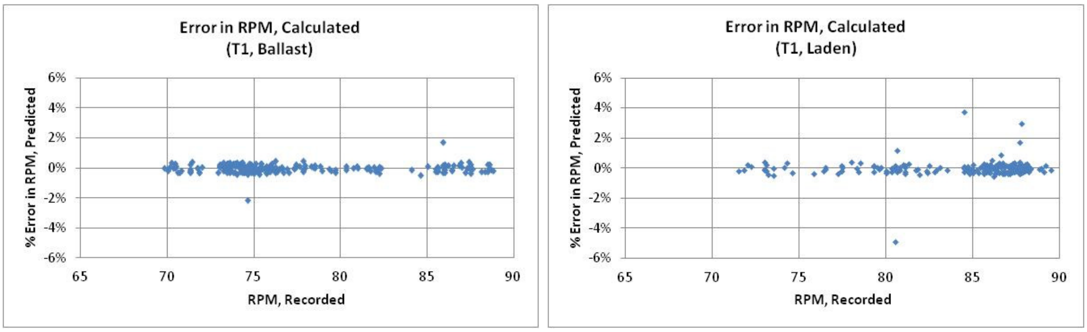

Figure 32: Calculated RPM Residual, Ship T1

The calculated RPM was used in the Data Elaboration Process for case study Ship T1 as it was considered representative of what the recorded RPM value would have been if it was included in the full SR dataset.

9.2.3 Wake fraction, thrust deduction factor & propeller relative rotative efficiency

The (Holtrop & Mennen 1982) was used to calculate the wake fraction (ω) and the thrust deduction factor (τ) required for the calculation of the propulsion coefficients, and the propeller relative rotative efficiency (η_R). The equations to calculate these values, (E.17, E.19 and E.21) are given in Appendix A and discussions on the methods were presented in Sub-section 2.4.3.

- **Form Parameter Inputs**

The (Holtrop & Mennen 1982) method requires the following input data:

L_{WL}: Ship Length (waterline)	*C_p: Prismatic Coefficient*
LCB: Longitudinal centre of buoyancy	*C_W: Waterplane Coefficient*
B: : Ship breadth	*C_M: Midship Coefficient*
V: : Ship Speed	*S: Ship underwater surface area*
Δ : Displacement	*S_{app}: Appendage underwater surface area*
T_A: Draft (aft)	*p: Propeller pitch*
T_F: Draft (fore)	*D: Propeller diameter*
C_B: Block Coefficient	*A_E/A_O: Propeller blade area ratio*

Ship form parameters L_{wL}, LCB, C_B, C_p, C_w, C_M and Δ are not recorded in the SR dataset. However, the Trim and Stability Booklet was available for Ship T1, providing tabulated values for each of these form parameters at different average drafts values and trim for specific loading conditions.

The following calculation process was used:

a) Input the tabulated data at 0.5m draft intervals

b) Plot each form parameter against average draft at midship

c) Add a trend line to each plot (Figure 33) and identify the line equation

d) Predict each form parameter for the given SR record given the recorded draft, using the line equations

The plots for each form parameter are shown in Figure 33.

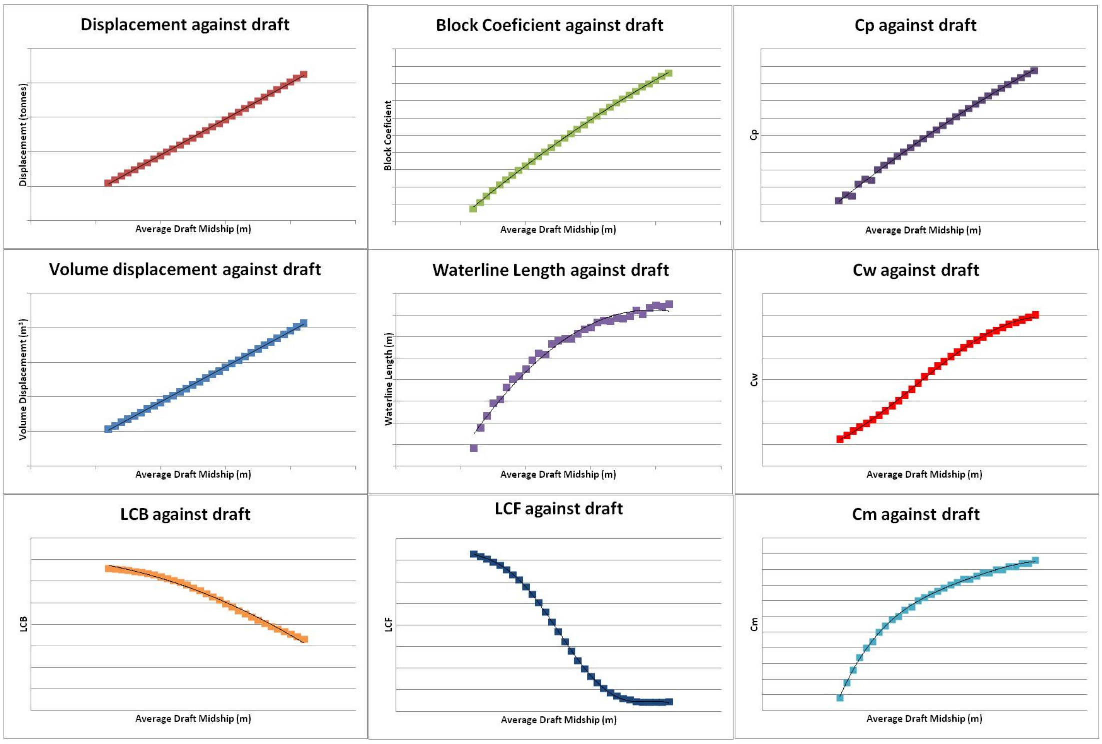

Figure 33: Ship form parameters, Ship T1

It was considered that using data from the Trim and Stability Booklet would not invalidate the SOPP model specification requirement, to be widely applicable to all companies, as its production is a requirement for class approval. Furthermore, similar information is available from Loading Computer Systems, commonly used onboard.

The input of the Trim and Stability Booklet data only needs to be carried out during development set up of the SOPP model. Therefore the model run time would not be increased.

Use of the data from the Trim and Stability booklet as described, was considered to be the best option available for predicting the form parameters for each SR record as it captures changes in the hull form with draft. However, prediction uncertainty will depend on measurement of the average draft at midship, and how well the tabulated form parameters fit the true form of the ship.

▪ **Fore and Aft Draft Inputs**

An input to the (Holtrop & Mennen 1982) method is the fore and aft draft. These values were only recorded for approximately $^{1}/_{3}$rd of Ship T1's SR dataset. However, the analysis of the trim operating profile for case study Ship T1, presented in Sub-section 8.4.2, demonstrated that Ship T1 predominantly operates with the following:

- A trim of 3m by the aft in ballast condition
- At even keel in laden condition (0m trim)

The fore and aft draft for each SR record was therefore determined by taking the recorded average draft at midship and adjusting the fore and aft draft for a 3m trim for only the ballast records.

▪ **Other Inputs**

The appendage and propeller details required as inputs were found between the Sea Trial Document and the particulars and details for the ship, main engine and propeller for Ship T1. However, the following parameters were still required:

h_B : position of the centre of the transverse area A_{BT}
A_{BT} : transverse sectional area of the bulb at the position where the still-water surface intersects the stem
C_{stern} : Coefficient representing the aft body form

h_b and A_{BT} were not known for the case study Ship T1 and therefore they were estimated from a similar ship. Whilst this will have introduced inaccuracy into the prediction results, it is noted that h_b and A_{BT} are only used in the calculation of the wake fraction and therefore do not affect the prediction of thrust deduction factor and propeller relative rotative efficiency. Furthermore, the error in the calculated wake fraction due to the estimation of h_b and A_{BT} is expected be small as the sensitivity to fine bulbous bow form differences compared to the impact of all other terms in the calculation, or exclusion of the bulbous bow completely, is expected to be low. An uncertainty and sensitivity analysis would be required to quantify this assumption.

The value of C_{stern} was selected corresponding to a normal section shape; rather than a V-shaped section or U-shaped with a Hogner stern.

The density of sea water was assumed to be constant at 1025 kgm^3 and kinematic viscosity at $1.19E^{-6}$ m^2s. During ship operation these values will vary dependent on the operational area (e.g. due to temperature, salinity, humidity). If information related to the air and sea temperature and density were recorded in the SR's dataset, variations due to these factors could be reflected in the calculation of the wake fraction thrust deduction factor and propeller relative rotative efficiency.

- **Calculation**

In addition to the Holtrop & Mennen method, the methods listed below (discussed in chapter Sub-section 2.4.3) were also used to calculate the wake fraction. These methods were implemented as they are less extensive than the Holtrop & Mennen and require less input parameters; which could have been an advantage for SOPP modelling. The average results for all methods are given in Table 22.

Table 22: Average wake fraction calculated using different methods, Ship T1

Method	Average Wake Fraction for T1 (Ballast)	Average Wake Fraction for T1 (Laden)	Applicable	Reference
Holtrop & Mennen	0.399	0.406	Yes	(Holtrop & Mennen 1982)
BSRA	0.479	0.458	Yes/No C_B in some SR records was too large.	(Molland et al. 2011)
Harvald	0.480	0.559	No C_B too large	(Molland et al. 2011)
D.W Taylor's	0.335	0.356	Yes	(W. Muckle 1975)
Schiffbaukalender	0.369	0.338	Yes	Poradnik Okretowca, 1960 referenced in (Moody 1996)

The BSRA and Harvald methods provided high estimates, whilst the D.W Taylor's and the Schiffbaukalender methods provided low estimates of the wake fraction. This could be due to model scale extrapolation errors previously discussed as a source of common error in Sub-section 2.4.3 and hence were cautioned. (MAN Diesel & Turbo 2011) identify that the wake fraction should be between 0.20 and 0.45 for ships with one propeller: where ships with a larger block coefficient have a larger wake fraction. The Holtrop & Mennen was thus considered to provide the best estimate and was considered necessary to calculate within the Data Elaboration Process.

The BSRA method was also used to calculate the thrust deduction factor along with the Holtrop & Mennen method: Table 23. The BSRA provided a somewhat surprising result that the ballast value was larger than the laden value. The Holtrop & Mennen method was again selected as it provided a value within the reasonable range for the thrust deduction factor: between 0.12 and 0.30 for ships with one propeller, being larger for ships with a larger block coefficient (MAN Diesel & Turbo 2011).

Table 23: Average thrust deduction fraction calculated using different methods, Ship T1

Method	Average Thrust deduction Fraction for T1 (Ballast)	Average Thrust deduction Fraction for T1 (Laden)	Applicable	Reference
Holtrop & Mennen	0.194	0.221	Yes	(Holtrop & Mennen 1982)
BSRA	0.205	0.203	Yes/No C_B in some SR records was too large.	(Molland et al. 2011)

The average values for the calculated propeller relative rotative efficiency using the Holtrop and Mennen methods were 1.01 for ballast and 1.02 for laden. Again this is within the range given by (MAN Diesel & Turbo 2011); between 1.0 and 1.07.

- **Verification and validation of the wake fraction, thrust deduction factor & propeller relative rotative efficiency**

To verify that the Holtrop & Mennen formulations had been implemented correctly, they were cross checked with the input values and results given as an example in the (Holtrop & Mennen 1982) paper. The implemented formulations provided the same results as the example and thus were considered correct.

There was no direct way to validate the calculated wake fraction, thrust deduction and propeller relative rotative efficiency. Therefore it was considered that comparison of the speed-resistance and speed brake-power curves using three methods labelled *Holtrop & Mennen*, *Sea Trails* and *Hullspeed (Holtrop)*, would be the best indication of whether the (Holtrop & Mennen 1982) provides representative results for the specific case study Ship T1. The calculation of each curve is given below:

- **Holtrop & Mennen**
    - **a)** Implement the full (Holtrop & Mennen 1982) method to calculate resistance.
    - **b)** Convert the resistance to brake power using the Determined Total Propulsion Efficiency Relationships (Appendix E) and ship speed: E.2 given in Appendix A.
- **Sea Trials**
    - **a)** Select the power-speed curve found in the Sea Trial document .
    - **b)** Convert the power-speed curve to resistance-speed using the Determined Total Propulsion Efficiency Relationships (Appendix E) and ship speed: E.2 given in Appendix A.
    - **c)** Determine the line equations for the power-speed and resistance-speed curves, for the ballast and laden condition.
    - **d)** Use the line equations to calculate the power and resistance for each SR record based on the speed recorded in the SR record.

- **Hullspeed (Holtrop)**
    - **a)** Select a similar geometry ship and scale it to the case study ship's form parameters in MaxSurf Pro[25].
    - **b)** Determine the power-speed and resistance-speed curves for the similar, scaled ship in Hullspeed[25], selecting the (Holtrop 1984) analysis method. [a constant total ship propulsion system efficiency of 0.75 was used, and the analysis was carried out for the ballast and laden draft]
    - **c)** Export the curve data to the spread sheet and plot each curve.
    - **d)** Determine the line equations for each curve.
    - **e)** Use the line equations to calculate the power and resistance for each SR record based on the speed recorded in the SR record.

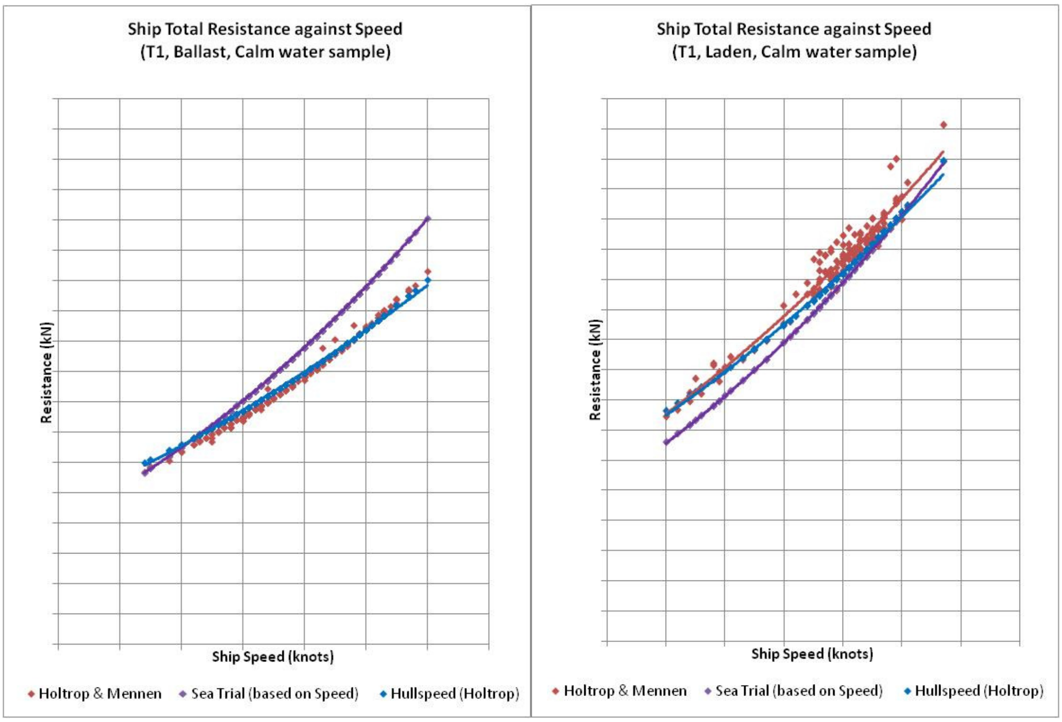

Figure 34: Ship resistance against speed, validation of the Holtrop and Mennen application, Ship T1

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[25] *Hullspeed and Maxsurf Pro are computer software program within the Maxsurf 15.1 suite, dedicated to ship design process functions (Bentley 2009)*

The sample of SR records used for the comparison correspond to calm water conditions, and hence sea trial conditions.

Figure 34 demonstrates the resistance-speed comparison curves for case study Ship T1. The following conclusions were made:

- The Holtrop & Mennen and Hullspeed curves are very similar indicating a correctly implemented Holtrop & Mennen method.
- The sea trial curve is similar to the Holtrop & Mennen and Hullspeed curves, indicating the applicability of Holtrop & Mennen and Hullspeed for predicting Ship T1's performance.
- Expanding on the conclusion above: at higher speeds the Holtrop & Mennen and Hullspeed curves under predict the ship resistance in Ballast, and over predict at lower speeds in laden. This could be due to: the determined total propulsion efficiency (discussed further with the following figure): an incorrect estimate generated by the theoretical methods; discrepancies due to the sea trials not being carried out in calm water conditions. The error in the theoretical estimate is likely to be due to the generalisation of the formulae to best predict for many ships, rather than for a specific ship.
- Scatter is seen with the Holtrop & Mennen method but not with the other two methods. This is due to the captured change in draft within the implemented Holtrop & Mennen method. The greater scatter in laden than in ballast is explained by greater variation in draft observed in laden than in ballast (demonstrated in Sub-section 8.4.1).

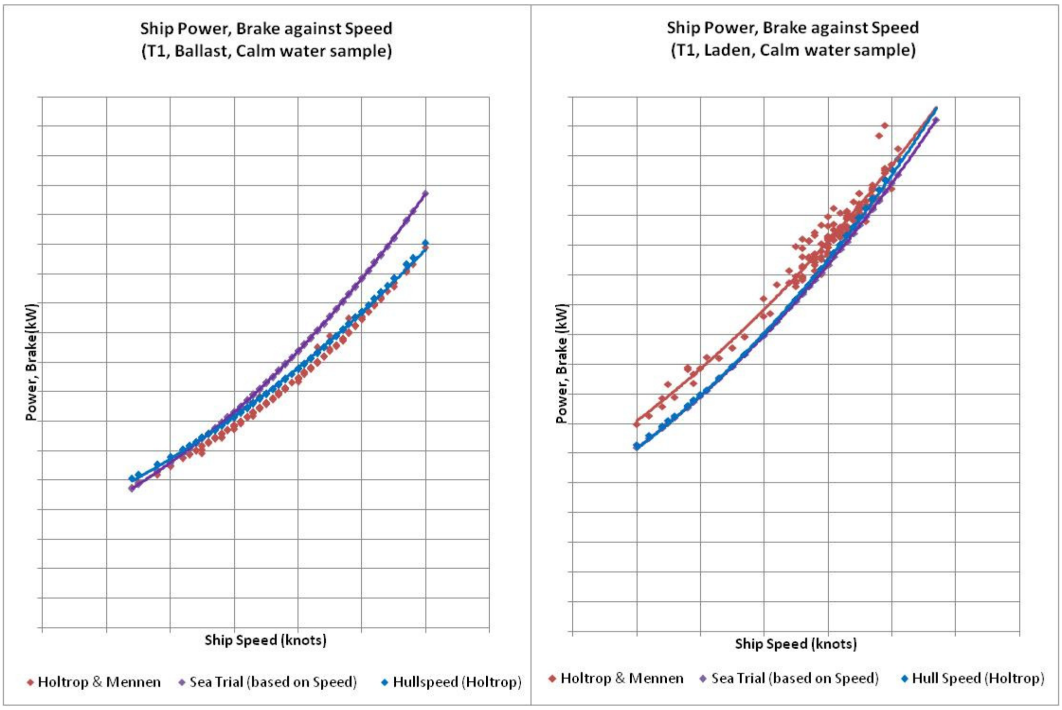


Figure 35: Brake power against speed, validation of the Holtrop and Mennen application, Ship T1

Figure 35 presents the power-speed curve comparison. This comparison removes the need to multiply the brake power by the Determined Total Propulsion Efficiency (Appendix E) in the Sea Trial method. However the Holtrop & Mennen requires the resistance to be divided by the Determined Total Propulsion Efficiency. The conclusions made from the comparison were as follows:

- The Holtrop & Mennen and Hullspeed methods still under predict ship performance in ballast at higher speeds; indicating that it is not an error with the determined total propulsion efficiency prediction.
- However, whilst the Hullspeed method better matches the results of the sea trial in laden, the implemented Holtrop & Mennen still overestimates the power slightly, particularly at lower speeds.

Table 24 presents a perhaps more interesting result from Figure 34 and Figure 35; which is the exponent value for each curve. The exponent is important as, during relatively simple SOPP modelling, the ship power is often estimated by the theoretical assumption that power varies with cube of the ship speed, and hence the resistance by the square. (MAN Diesel & Turbo 2011) indicates that the exponent of power could be around 3.2 for tankers and 3.5 for medium speed ships.

Table 24: Power-Speed and Resistance-Speed relationship exponents, Ship T1

Resistance against Speed (Figure 34)	**Ballast**	**Laden**
Holtrop and Mennen	2.43	2.32
Sea trial (based on speed)	2.87	2.19
Hullspeed	2.20	2.66
Brake power against Speed (Figure 35)	**Ballast**	**Laden**
Holtrop and Mennen	3.17	2.76
Sea trial (based on speed)	3.61	3.18
Hullspeed	3.00	3.18

The sea trial exponents in Table 24 are of most interest for the subsequent SOPP modelling as they are representative of case study Ship T1's actual performance. The exponents are in the range of 3.2 to 3.6 for power and 2.2 to 2.9 for resistance: neither of which appear unreasonable.

9.2.4 Thrust and Torque Coefficients

- **Inputs and Calculation**

The calculation process for the thrust and torque coefficients for each SR record is as follows, the equations are found in Appendix A:

- **a)** Calculate the apparent speed from the ship speed and calculated wake fraction (E.7)**.**
- **b)** Calculate the advance coefficient using the apparent speed, RPM and propeller diameter (E.9).
- **c)** Use the Wageningen B4-screw propeller series to calculate the thrust and torque coefficients**:** E.12**,** E.13**,** E.14**,** E.15 and E.16.

The Wageningen B4-series was selected for this calculation as the thrust and torque coefficients for varying operating conditions were not known for Ship T1's propeller, but it was known to have four blades. The input data required for the calculation was found in the collected information for the ship containing the particulars and details of the propeller.

- **Correction Factors for Ship T1**

The thrust and torque coefficients for one operating condition were given for a test recorded in the collected information for the propeller. The test operating condition corresponded to the MCR point and included the following recorded values: brake power, ship speed, draft, RPM, thrust coefficient ($K_{T,rec,MCR}$) and torque coefficients ($K_{Q,recMCR}$). It was considered that Correction Factors for the generic Wageningen B4-screw series prediction could therefore be obtained, specific to Ship T1.

The Correction Factor was determined by comparing the Wageningen B4-screw Series predicted values for the same MCR condition ($K_{T,Wag,MCR}$ and $K_{Q,Wag,MCR}$), with the recorded values in the propeller document, as follows:

$$K_{T,Cor} = \frac{K_{T,rec,MCR}}{K_{T,Wag,MCR}}$$

$$K_{Q,Cor} = \frac{K_{Q,rec,MCR}}{K_{Q,Wag,MCR}}$$

The Correction Factors calculated were 1.063 for K_T and 0.955 for K_Q. It was considered that as they are not too different from 1 then the Wageningen B4-screw Series calculation provides a good first approximation.

The Correction Factors were assumed to be constant for all SR records and thus were multiplied to the K_T and K_Q values calculated using the Wageningen B4-screw series for each SR record.

- **Thrust and Torque Coefficients Results**

A validation of the thrust and torque coefficients values calculated for each SR record was made after the Data Elaboration Process had been implemented. The results are presented at this intermediate stage, although the calculation steps will be described in following subsections.

a) The calculated torque and thrust coefficients were used to calculate brake power for each SR record (as will be described in subsequent sub-sections).

b) The brake power values recorded in approximate $^{1}/_{3}{}^{rd}$ of the SR dataset for Ship T1 were compared to calculated brake power for the corresponding records.

Table 25 presents the results of the comparison made before and after the thrust and torque coefficient Correction Factors for Ship T1 were applied.

It is evident that the application of the thrust and torque coefficient Correction Factors for Ship T1 reduces the absolute average error in brake power prediction by at least 3.5%. The correction factors were therefore maintained in the data elaboration process.

Table 25: Brake power prediction error with and without applying K_T and K_Q correction factors, Ship T1

K_T correction factor	K_Q Correction Factor	Average absolute error of brake power calculation (Ballast)	Average absolute error of brake power calculation (Laden)	Type of Correction
1	1	8.43%	13.61%	No correction applied
1.063	0.955	4.45%	8.64%	Correction factors found for T1 calculated using the data from T1's Propeller Document.

9.2.5 Propeller Open Water Characteristics

For each SR record:

a) Calculate the propeller open water efficiency: E.8 given in Appendix A.

Figure 36 demonstrates the propeller open water characteristics calculated for Ship T1. The average value of the propeller open water efficiency for all SR records was 0.59 and 0.55 in ballast and laden. These values are within the typical range of 0.35 to 0.75 given by (MAN Diesel & Turbo 2011).

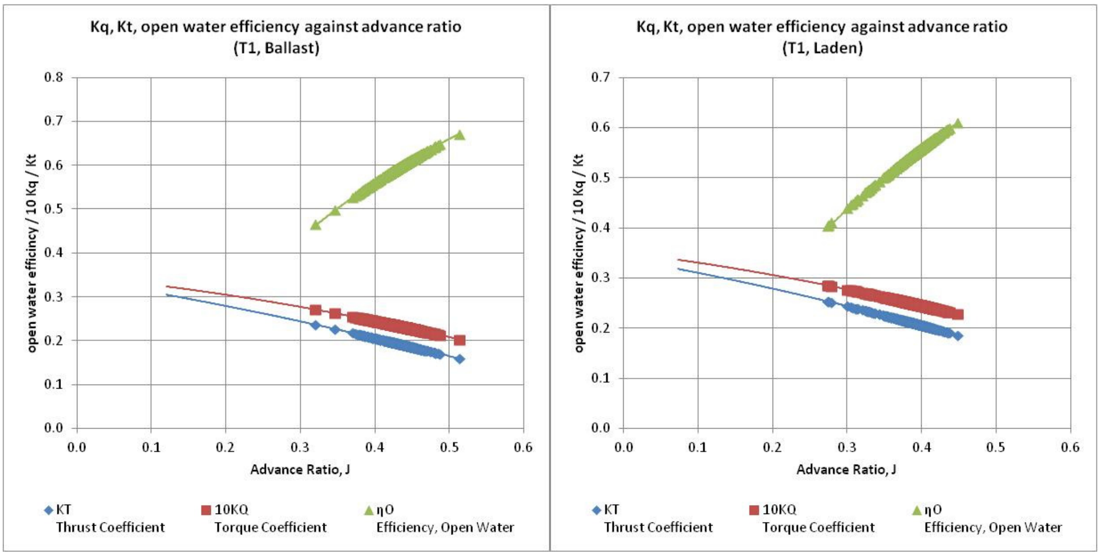


Figure 36: Calculated K_T and K_Q and η_o, Ship T1

9.2.6 Thrust, Torque, Resistance and Effective Power

For each SR record (equations given in Appendix A):

a) Calculate the thrust from the thrust coefficient: E.10.

b) Calculate the torque from the torque coefficient: E.11.

c) Calculate the ship resistance: E.2.

d) Calculate the effective power from the resistance and ship speed: E.2.

9.2.7 Total Ship Propulsion System Efficiency

For each SR record (equations and figure given in Appendix A):

a) Calculate the hull efficiency from the wake fraction and thrust deduction factor (E.20).

b) Select the propeller relative rotative efficiency calculated using the Holtrop and Mennen method (E.21).

c) Select the propeller open water efficiency calculated for the propeller open water characteristics E.8.

d) Calculate the shaft efficiency: (Figure 74 and E.22).

e) Calculate the total propulsion efficiency based on the above propulsion system efficiencies: (E.3).

The method used to calculate the shaft efficiency (SNAME 1990) is based on engine load (see Figure 74 and E.22 in Appendix A). However, as the engine load was not known from the SR data (power was not recorded in all SR records) the load was estimated using the recorded RPM value as a percentage of the MCR RPM, as shown in the relationship below:

$$\%\ \text{Load} = \left(\frac{\text{RPM}_{rec}}{\text{RPM}_{MCR}}\right)^3$$

Note here that a cubic relationship has been assumed to calculate the load % . However it is acknowledge that the exponent will change from 3 dependent on the ship type and how heavily the propeller is loaded due to weather conditions and hull and propeller fouling and surface degradation.

The average shaft efficiency determined for the SR records for Ship T1 in laden was 0.988, ranging from 0.98 to 0.99. In ballast it was 0.984, ranging from 0.978 to 0.990. These values fit within the typical range of 0.96 and 0.995 given in (MAN Diesel & Turbo 2011).

The average hull efficiency calculated for Ship T1 was found to be 1.34 in ballast and 1.31 in laden. Again this fit within the typical range of hull efficiencies identified by (MAN Diesel & Turbo 2011): between 1.1 and 1.4, with higher hull efficiency for ships with a higher block coefficient.

9.2.8 Data Elaboration Calibration

▪ **Calculation**

For the SR records with brake power values recorded (approximately $^{1}/_{3}{}^{rd}$ of the SR dataset for Ship T1) the following were calculated:

- **Recorded**
  - **a)** Calculate resistance from the recorded brake power values recorded in the SR dataset for Ship T1: using the Derived Total Propulsion Efficiency (see Appendix E).
- **Calculated**
  - **a)** The resistance calculated by the data elaboration process (Implementation of Sub-sections 9.2.2 to 9.2.7).

Figure 37 presents a comparison of the recorded and calculated resistance. It demonstrates that for ballast the trend lines are very similar in gradient, although the calculated values over predict the recorded values slightly. Looking at the data points themselves, the calculated values appear to follow a very similar variation pattern to the recorded values, only slightly higher (a systematic error). The same is evident for laden.

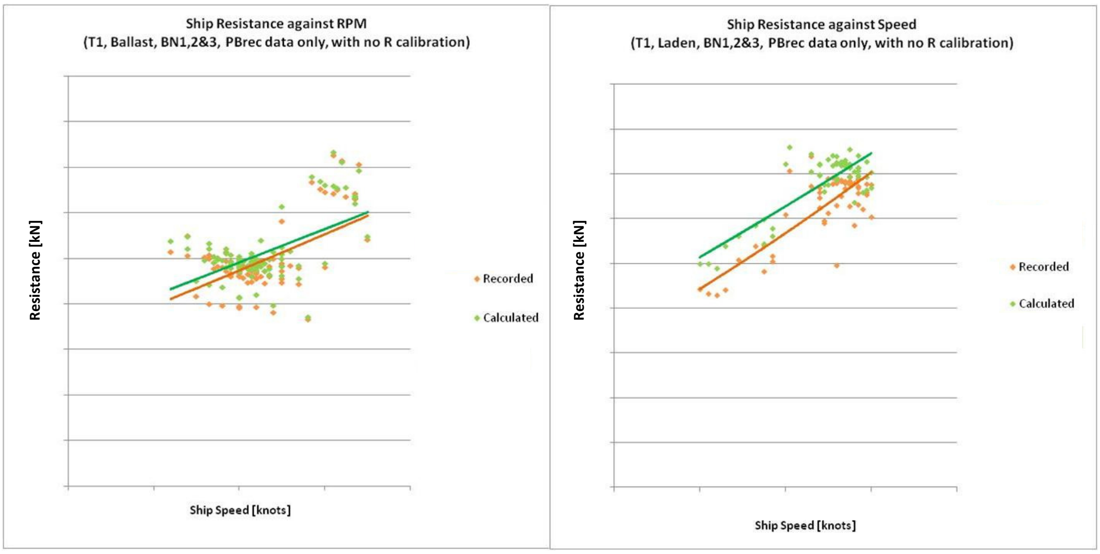


Figure 37: Uncalibrated total ship resistance against ship speed, Ship T1

Due to the strong similarity in data point variation it was considered that the systematic error could be removed by applying a calibration between the two trend lines, using the relationship shown below:

$$R_{cal,cali.} = R_{cal,no\ cali.} - \left[\left(a_{\cdot cal} \times {V_{rec}}^{b_{cal}}\right) - \left(c_{\cdot rec} \times {V_{rec}}^{d_{rec}}\right)\right]$$

Where a and c are the coefficients of the linear line equations, and b and d are the exponents.

Figure 38 presents the comparison between recorded and calculated resistance after the calibration was applied. The remaining error is reduced and appears to be random.

[Note: the liner trend for the recorded resistance-speed curve, derived from the recorded brake power, has been used as an input to the data elaboration process. However, the recorded values have not been used directly, only the trend. As the recorded values are not a direct input to the Data Elaboration Process they are still considered valuable for model validation.]

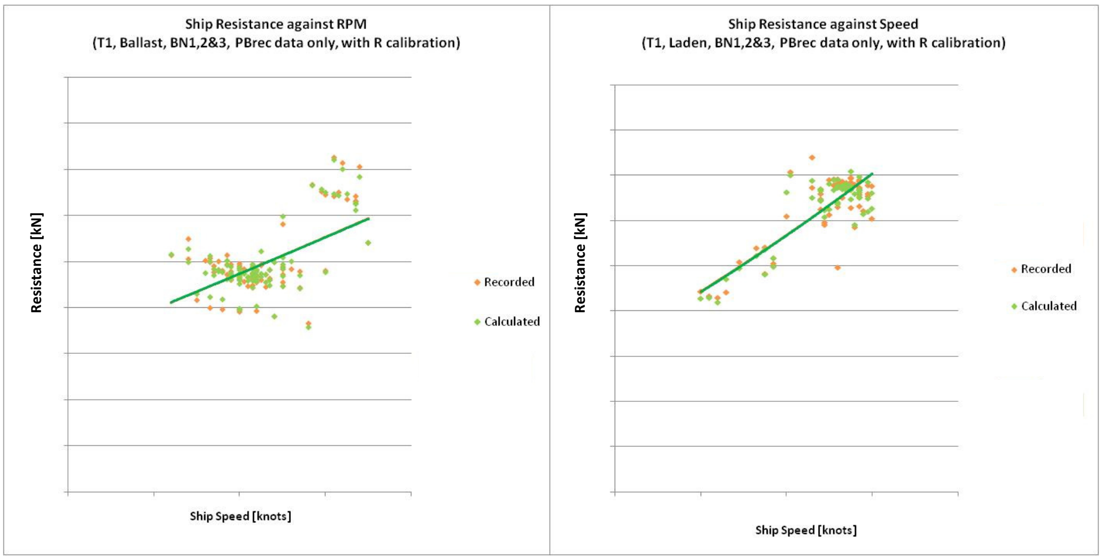


Figure 38: Calibrated total ship resistance against ship speed, Ship T1

- **Calibration Results**

To produce the calibrated Data Elaboration results:

a) Apply the fixed calibration relationships (one for ballast and one for laden) to all SR records (not just those with brake power recorded).

b) Calculate brake power from the calculated resistance using the total propulsion system efficiency calculated for each SR record.

Considering only the SR records with brake power values recorded, Table 26 presents the absolute average error between the predicted and recorded brake power. The absolute average prediction error reduced by approximately 1% after the calibration was applied. The use of the calibration was therefore considered beneficial to include within the Data Elaboration Process.

As the calibration was the last step in the Data Elaboration Process it can be concluded that the Data Elaboration Process can be used to predict the brake power for the case study Ship T1 with an average absolute error of 3.38% in ballast and 3.59% in laden, and with coefficients of determination (R^2) of 96.5% and 90.1% retrospectively.

Table 26: The average absolute error in predicted brake power before and after the calibration processes, Ship T1

	Sample number	Average Absolute Error	Coefficient of Determination, R^2
	Ballast		
Before calibration	204	5.41%	96.55%
After calibration	204	3.38%	96.5%
	Laden		
Before calibration	202	5.15%	90.05%
After calibration	202	3.59%	90.05%

9.2.9 Validation of the Data Elaboration Process

To validate the ship resistance calculated using the Data Elaboration Process, a comparison of results was made with a Sea Trial dataset sample a sample based on the recorded brake power in the SR records. The samples corresponded to sea trial conditions (i.e. only using records with a Beaufort Number recorded as 1, 2 or 3). The calculation steps to obtain the dataset samples are given below:

- **Calculated**
  - **a)** Calculate via the Data Elaboration Process for all SR records in the selected sample, i.e. corresponding to calm water conditions.
- **Recorded**
  - **a)** Select only the SR records in the dataset with brake power values recorded (resulting in a smaller data sample than for the other two comparison dataset samples)
  - **b)** Calculate the resistance from the recorded brake power using the Determined Total Propulsion Efficiency Relationships (Appendix E), and the recorded ship speed.
- **Sea trials (based on speed)**
  - **a)** Select the brake power-speed curves (one for laden and the other for ballast) given in the Sea Trial document.
  - **b)** Calculate the resistance-speed curves using the Determined Total Propulsion Efficiency Relationships (Appendix E).
  - **c)** Generate the line equation for each resistance-speed curve
  - **d)** Determine the resistance for each SR record in the sample, based on the recorded speed and the line equations.

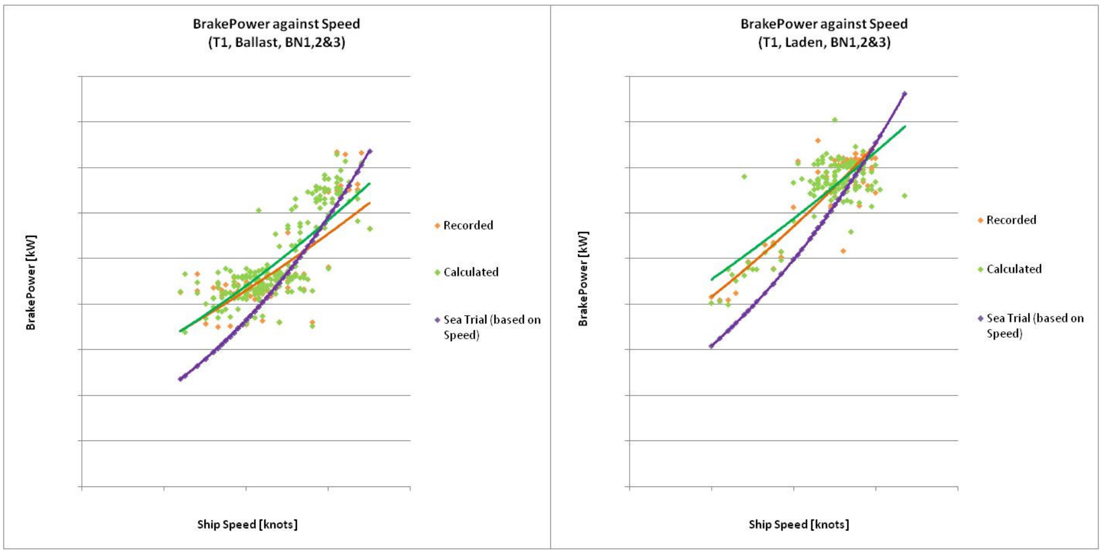


Figure 39: Brake power against speed, comparison of calculated results with other sources, Ship T1

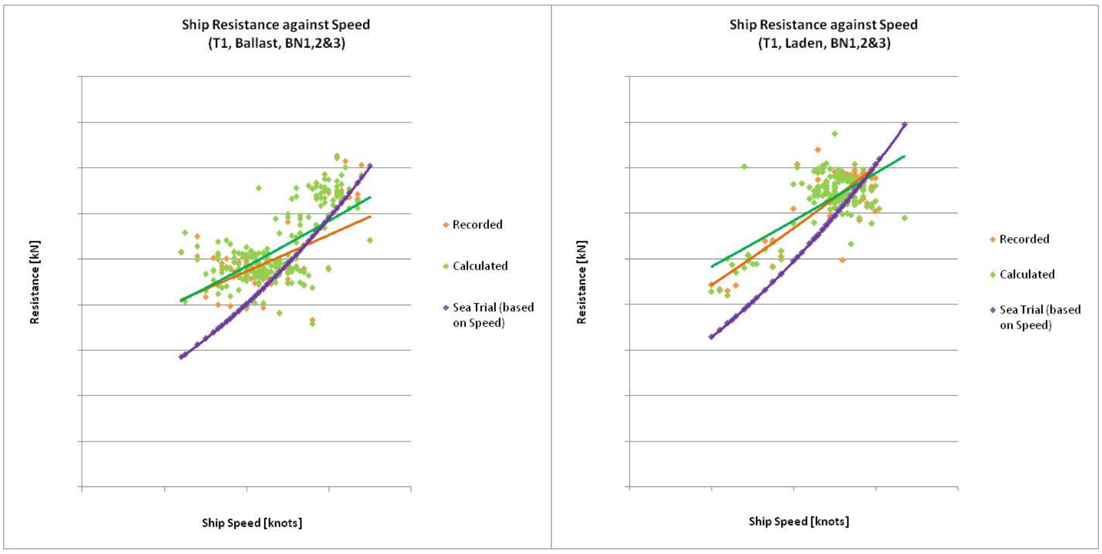


Figure 40: Resistance against speed, comparison of calculated results with other sources, Ship T1

Figure 39 and Figure 40 demonstrates the comparison for the brake power-speed curves and resistance-speed curves retrospectively. The following conclusions were made:

- The recorded and calculated data points above the sea trial data points are expected due to but not limited to operation: at a larger draft; with increased hull and propeller surface degradation and fouling; travelling against a current: i.e. heavier loading on the propeller.

- The recorded and calculated data points below the sea trial data points could be due to operation: at a lower draft; in favouring wind and sea directions and at lower Beaufort Numbers, or in favouring currents: i.e. lighter loading on the propeller.

- The recorded and calculated data points demonstrate reasonable agreement with each other. The trend lines differ slightly (unlike the calibrated results, Figure 38) but this is due the larger sample of data points for the calculated dataset, and the filtering of all datasets for Beaufort Numbers 1, 2 or 3.

- Each trend line was plot with a power curve. However, the recorded and calculated trends appear linear: not in line with the expected near cubic relationship, like the sea trial curve. Nevertheless, as the recorded and calculated data samples represent performance in varying operational conditions (i.e. Beaufort Numbers, wind directions, drafts), they can only be compared with each other. It is therefore the positioning of the data points relative to the sea trial curve that is of more interest than the trend lines.

- The recorded and calculated trend lines demonstrate clustering of data and thus the trend lines may be more influenced by the densely clustered data points. The clustering is considered more likely to be due to the operational points of the ship, rather than induced error in the Data Elaboration Process.

- The maintained similarity between the recorded and calculated trend lines and the data point variation, despite differences in the data sample size, increases confidence regarding the generalised application of the Data Elaboration Process for Ship T1.

- In laden, one of the data points for the calculated dataset sample can be seen to be much higher than the sea trial data. A corresponding recorded value was not available for this data point. Therefore it could be considered as an extreme value, or, it could be evident of error induced from the record of an incorrect input data value.

9.2.10 Performance Trend Observations

Before moving on to step 2, the Elaborated SR dataset was used to observed how certain performance relationships change over time.

Figure 41 demonstrates how the calculated resistance changes over time. The following conclusions can be made:

- In both ballast and laden the resistance decreases at the time of the dry dock and then starts increasing again with time in MP3.
- The trend line in MP2 in both ballast and laden appears to remain relatively constant. This is could be due to the small time period of data available before the dry dock and a low fouling rate expected toward the end of a MP.
- The resistance graphs demonstrate a large amount of scatter due to operating in varied conditions that effect ship resistance, including but not limited to; ship speed, draft, and weather and sea conditions.
- The cluster of data points around month 96 in the laden condition demonstrate a low resistance. This was identified to correspond to a similar decrease in ship speed.
- It can be concluded that observing how resistance changes over time does not provide sufficient information about the causes of resistance increase; thus is not suitable for SOPM alone.

Each figure demonstrates operation before dry dock (blue data points – Maintenance Part (MP) 2) and after (orange data points – MP3). The dry dock is marked with the vertical green line.

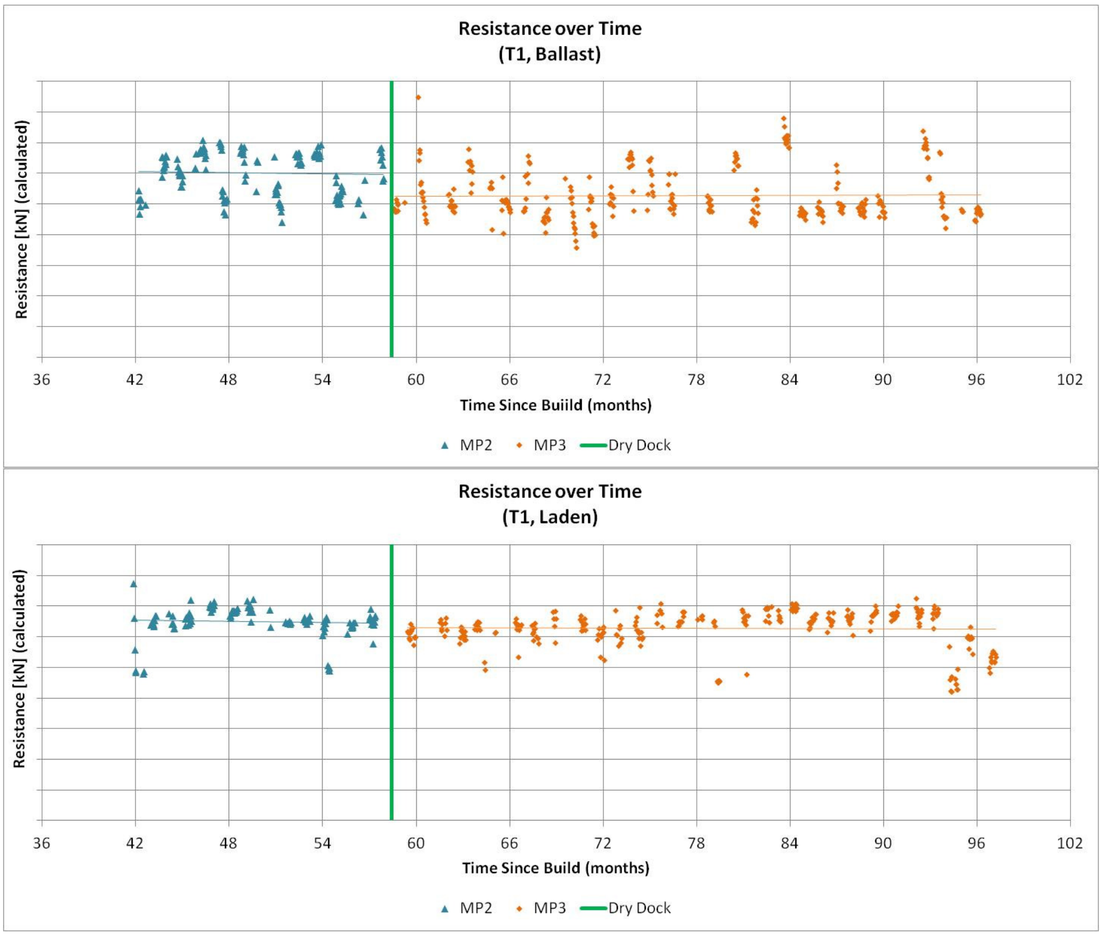


Figure 41: Calculated ship resistance over time, Ship T1

Figure 42 demonstrates the speed ratio (ship speed over RPM). This ratio relationship is also seen in the apparent slip equation: E.5 Appendix A. The following conclusions were made for how the speed ratio changes over time:

- The speed ratio decreases over time, indicating that to maintain a constant ship speed the RPM required to overcome the additional slip conditions increases (for discussion on the factors that affect slip refer to 2.4.4). As weather and sea conditions do not change systematically over time and the average draft was not shown to change significantly over the years, the time dependent decrease in the speed ratio can be considered due to hull and propeller surface degradation and fouling, which increase slip.

- After the dry dock the speed ratio increases, increasing confidence that the time dependent change is due to hull and propeller surface degradation and fouling.
- Compared to Figure 41, the decrease in data points is not observed around month 96, as the ratio captures the proportional changes in speed.
- Scatter amongst the data points can still be seen using the speed ratio. The speed ratio also can also not be used to identify the individual components of slip increases. Therefore the speed ratio alone was considered insufficient for SOPM as specified in the Sub-section 5.4.6.

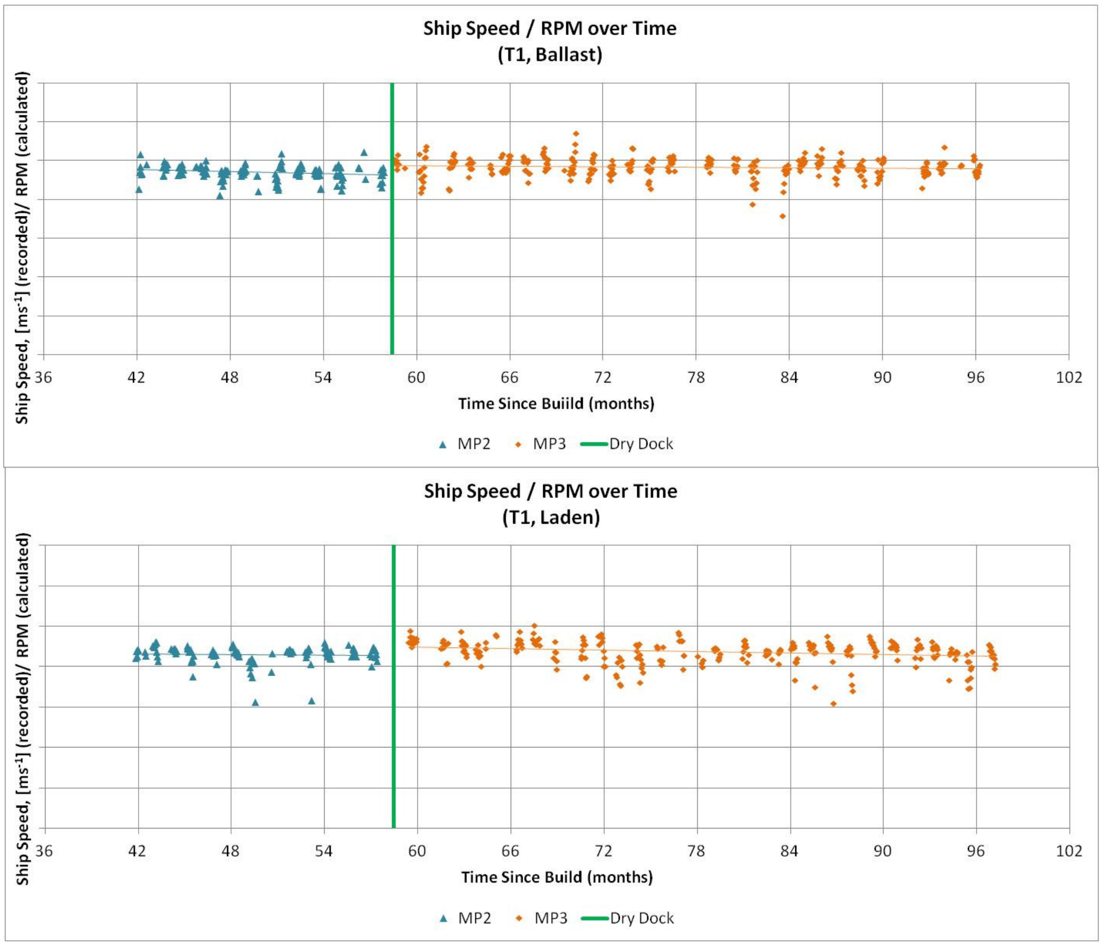


Figure 42: Speed ratio over time, Ship T1

9.3 Step 2: Resistance Regression Analysis

9.3.1 Method

With the Elaborated SR dataset available, step 2 towards the development of the SOPP model was to use the recorded and calculated variables within a multi-linear regression analysis. Multi-linear regression was selected as it is relatively simple and quick to perform and interpret, and it allows for the input and output variables to be analysed in terms of influences and statistical parameters.

The Criterion Variable (CV) selected for the regression analysis was the calculated Resistance via the Data Elaboration Process (referred to as $Resistance_{calc.}$ and shortened to *Resistance* in this chapter section).

The Predictor Variables (PV's) selected for the analysis were: RPM, Draft, Beaufort Number and Wind direction. Time since build was not included as a PV as it was assessed during the time dependent performance change analysis (Step 5, Section 9.6). It was not possible to include a PV to capture the effects of currents on ship performance as there was no suitable variable recorded in the SR datasets for use, or that could be calculated.

RPM was selected as a PV instead of ship speed as the two variables are highly correlated: inclusion of both would induce multicollinearity where an assumption of multi-linear regression analysis is that multicollinearity between PV's does not exist. Moreover, ship speed is a function of the RPM, and the slip conditions experienced (i.e. influenced by the other PV's; draft, Beaufort Number and wind direction). A further advantage of using the RPM variable in the regression analysis is that it captures the voluntary change in throttle position and hence ship speed: whereas the ship speed over ground comprises of voluntary and involuntary changes.

The steps to the regression analysis are presented in the following sub-sections:

- 9.3.2: Exploratory Analysis
- 9.3.3: Regression Analysis Results
- 9.3.4: Regression Prediction Equations
- 9.3.5: Validation

▪ Data Samples

The processed dataset of SR records for case study Ship T1 (see Section 7.3) was split into a modelling and testing sample for both ballast and laden. This was done to allow for testing that the prediction equations generated from the regression analysis are generic to Ship T1's performance, and not just specific to the data points used to carry out the regression (i.e. the modelling sample). There are many methods discussed for deciding modelling and test sample sizes in (Tabachnick & Fidell 2007), (Green 2010), (Pallant 2010). The size selection chosen was to split the ballast and laden samples 70:30 for the modelling and test samples retrospectively, and this was done by carrying out the following steps:

- **a)** Split all the processed SR records for Ship T1 into a ballast and laden sample (reasoning for this will be identified in the next sub-section)
- **b)** Assign each SR record with a random number in the ballast and laden samples, using a random number generator.
- **c)** Sort the SR records in order of ascending random number.
- **d)** Select the last 30% of the ballast or laden sample to form the test sample, leaving 70% for modelling.

The number of processed SR records in each sample are summarised in Table 27.

Table 27: Model and test sample sizes, Ship T1

Number of SR records in:	Ballast	Laden
The full data set	456	403
Modelling Sample	319	282
Testing Sample	137	84

▪ Software

The software used to perform the regression analysis was IBM SPSS V21.0 (International Business Machines Corporation n.d.): also previously known as Predictive Analytics Software, PASW.

▪ Regression Analysis Method

Stepwise statistical regression was the first choice method for the Resistance Regression analysis. This method enters the PV's with the largest impact on the R^2 value into the regression equation first, but does not include PV's with an insignificant R^2 value. The selection of which PV's to include in the analysis is therefore based on statistical reasoning, and not user defined. It is for this reason, and due to possible over fitting, that the use of stepwise statistical regression method is often cautioned in literature. As a second choice, the forward statistical regression method was used: also called the Enter method in SPSS. In this method all chosen PV's are entered in order of their impact on R^2. This method was selected when it was considered that all selected PV's should be included: based on basic principles.

▪ First Iteration of Resistance Regression Analysis

Before presenting the development of the model using final results, during first iteration of the regression analysis it was decided that the draft PV should not be included in the ballast Resistance Regression Analysis.

This was concluded as the output coefficients for the regression analysis (with the general form as shown below) using the ballast modelling sample indicated that resistance decreases with an increase in draft. This is known not to be true. It was considered that this result was most likely to have occurred due to the very small variation in drafts used when sailing in ballast, hence the impact from the varied draft was not large enough to accurately represent the correct relationship. For presentation of the prediction equations in this chapter, the draft term has still been included in the general form of the ballast equation, but the coefficient has been set to zero.

$$R_{pred.} = (\mathrm{a} \times \mathrm{RPM}) + (\mathrm{b} \times \mathrm{T}) + (\mathrm{c} \times \mathrm{BN}) + (\mathrm{d} \times \mathrm{WD}) + \mathrm{e}$$

9.3.2 Exploratory Analysis

An exploratory analysis was carried out prior to regression analysis to explore the data and identify the following: the existence of outliers; normal distribution of the PV's; multicollinearity or singularity between PV's. The objective of the exploratory analyses was to help ensure that the assumptions for multi-linear regression would be met.

There were no outliers identified in the ballast modelling sample. However, a number of outliers were identified in the laden modelling sample for which no plausible explanation could be determined from the other recorded variables in the SR records. Therefore these records were removed, reducing the modelling sample from 282 to 275 records.

A relatively normal distribution was identified for each of the PV, except for draft: where two distributions were evident: i.e. one peak for ballast operation and another for laden. It was for this reason that data samples were split between ballast and laden and a prediction equation was produced for both. One of the most informative exploratory analysis results to observe was the Correlation Matrix plots. Figure 43 and Figure 44 demonstrate the Correlation Matrix plots for ballast and laden retrospectively.

It should be noted that similar plots were produced for the Fuel Flow Rate (FFR) Regression Analysis described in Appendix D as part of the investigation. In Appendix D a similar discussion to the one that follows here is made for the FFR Correlation Matrix plots, which is arguably of more interest for practical observations than resistance: as FFR is a measurable variable whereas the resistance cannot be directly measured and must be calculated. Nevertheless, the discussion points are similar and the discussion related to the Resistance Regression Analysis was used to support and justify the development of the SOPP model.

Figure 43 demonstrates the following for the ballast condition:

- Resistance increases with both RPM and Speed as expected. The plot makes it evident that there is much less scatter for the resistance-RPM relationship than the resistance-speed relationship: highlighting the beneficial use of RPM as the PV. A linear trend fits the resistance-RPM correlation well, although a transformation of the ship speed (e.g. to the cube) may better represent the resistance-speed relationships.
- Resistance is positively correlated with draft. The small range of drafts used in ballast, shown by the vertical cluster in the centre of the plot, demonstrates the small variation.
- Resistance is positively correlated with Beaufort Number, although a significant amount of scatter is observed. Due to the scatter a correlation trend other than linear cannot be determined.
- Resistance remains relatively constant with wind direction, although a reduction in resistance would be expected with increasing wind direction at

lower Beaufort Numbers. Again the scatter is too large to determine a conclusive trend.

- Time since build was included in the Correlation Matrix exploratory analysis for observation (it was not included as a PV in the regression analysis). It can be concluded that the unfiltered resistance data decreases over time. However it can also be observed that speed decreased over time and the draft remained the same.
- Assuming that the scatter does not impact the trends identified: the RPM is positively correlated with speed, draft, Beaufort Number and wind direction, but speed is positively correlated with RPM, draft and wind direction, but not Beaufort Number. The wind direction is more positively correlated with speed than with RPM. The observation for Beaufort Number with speed could be considered due to the impact of voluntary speed (RPM) increase and or involuntary speed loss in adverse conditions: i.e. a greater RPM is required to maintain the same speed in increasing Beaufort Numbers due to increased slip, else a speed loss is observed.
- It appears that in wind directions moving towards the aft of the ship, the RPM is kept the same and therefore the benefit is gained as an increase in ship speed, with no increase in resistance.
- The inter-relationships between the PV's RPM, Beaufort Number and wind direction were not considered to induce multicollinearity to the regression analysis that may invalidate its results: rather it was considered that the interrelationships should be captured in the coefficients determined from the multi-linear regression analysis.
- Draft, Beaufort Number and wind direction demonstrate no dependency on each other.

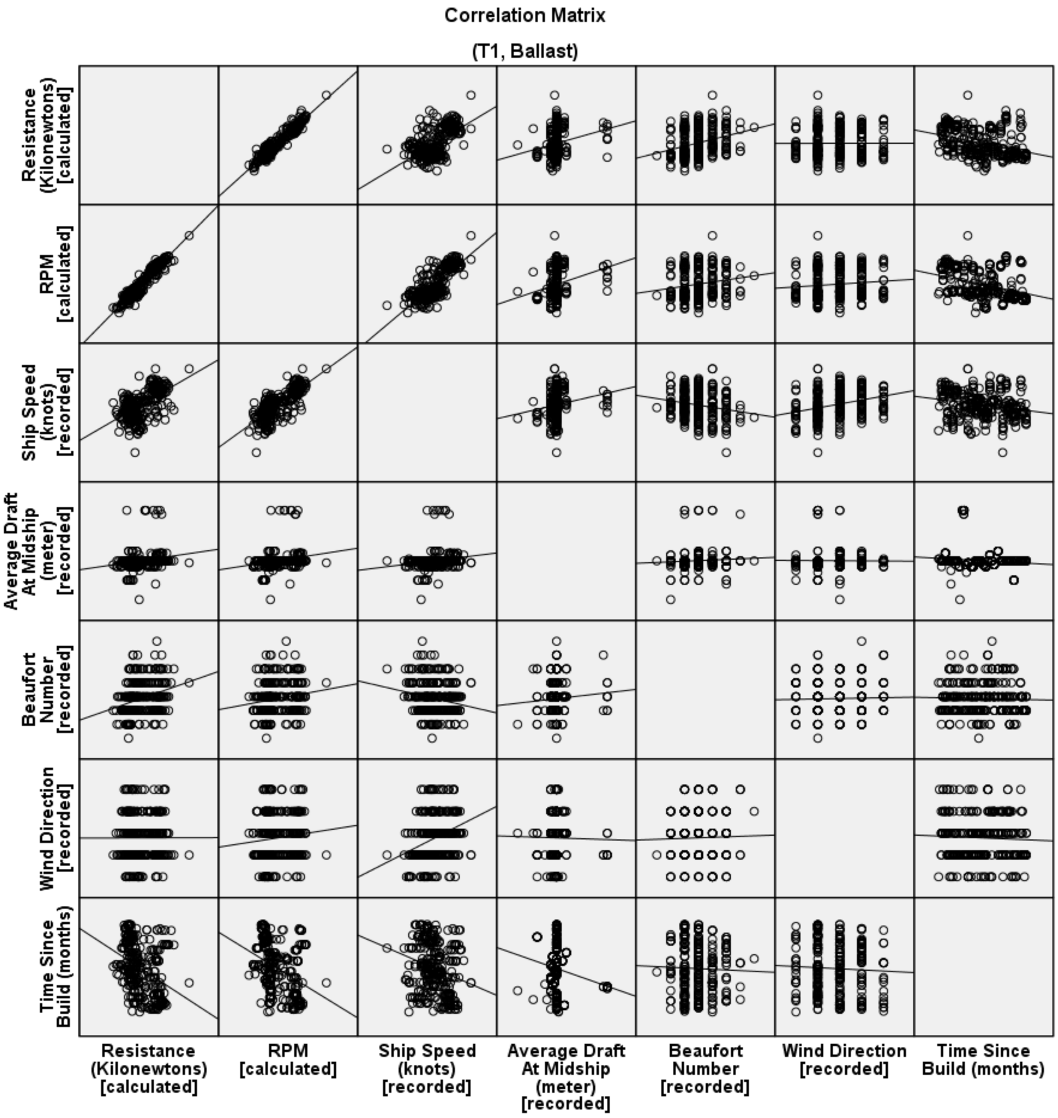


Figure 43: Correlation Matrix, Ship T1, Ballast

Figure 44 demonstrates the laden Correlation Matrix. The same observations can be made as for Figure 43 apart from the following:

- There is a thinning of data points at lower resistance. However, as the points still fall on the resistance-RPM correlation line and appear to be related to a lower ship speed, no action was taken to remove these data points.

- In the laden condition the RPM decreases as well as the speed with an increase in Beaufort Number. This is most likely explained by the voluntary reduction in RPM and hence speeds in adverse weather.
- The average draft appears to decrease over time although there is still a vast amount of scatter.

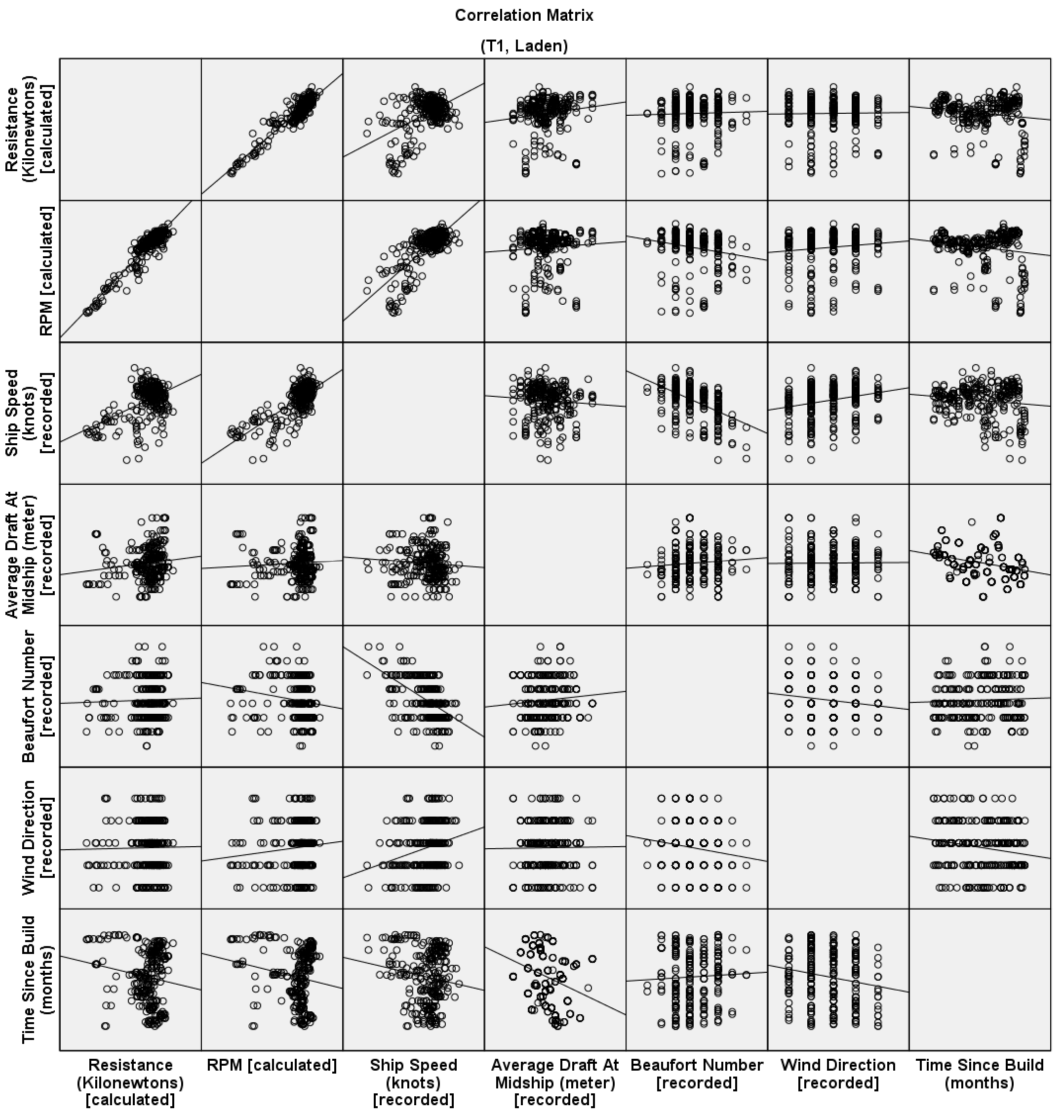


Figure 44: Correlation Matrix, Ship T1, Laden

9.3.3 Regression Analysis Results

The dataset descriptive results demonstrated that there were no missing values for any of the PV's or the CV in either the ballast or laden modelling samples: 319 and 275 records in each sample retrospectively. This was expected having applied the filters described in Sub-section 7.3.3 during the data processing. The correlation statistics results (related to the Correlation Matrix plots, Figure 43 and Figure 44) are provided in Table 28 for ballast and laden.

Table 28: Correlation Matrix Statistics, Regression Analysis, Ship T1

		Resistance (KN) [calculated]	RPM [calculated]	Average Draft At Midship (m) [recorded]	Beaufort Number [recorded]	Wind Direction [recorded]
Ballast						
Pearson Correlation	Resistance (KN) [calculated]			Draft is not included in the ballast regression analysis	.296	.002
	RPM [calculated]	.964			.167	.101
	Average Draft At Midship (m) [recorded]					
	Beaufort Number [recorded]	.296	.167			.026
	Wind Direction [recorded]	.002	.101		.026	
Sig. (1-tailed)	Resistance (KN) [calculated]		.000		.000	.486
	RPM [calculated]	.000			.001	.035
	Average Draft At Midship (m) [recorded]					
	Beaufort Number [recorded]	.000	.001			.322
	Wind Direction [recorded]	.486	.035		.322	
Laden						
Pearson Correlation	Resistance (KN) [calculated]		.941	.139	.032	.016
	RPM [calculated]	.941		.065	-.179	.107
	Average Draft At Midship (m) [recorded]	.139	.065		.093	.011
	Beaufort Number [recorded]	.032	-.179	.093		-.146
	Wind Direction [recorded]	.016	.107	.011	-.146	
Sig. (1-tailed)	Resistance (KN) [calculated]		.000	.010	.298	.393
	RPM [calculated]	.000		.140	.001	.039
	Average Draft At Midship (m) [recorded]	.010	.140		.062	.431
	Beaufort Number [recorded]	.298	.001	.062		.008
	Wind Direction [recorded]	.393	.039	.431	.008	

The following conclusions were made from Table 28:

- For the ballast condition the resistance is significantly correlated with the RPM and Beaufort Number but not wind direction. Despite the statistically low significance of the correlation between the resistance and wind direction, the wind direction was still included as a PV due to its considered practical importance.
- For the laden condition the resistance is significantly correlated with RPM and draft, but not Beaufort Number and wind direction. However, from the Correlation Matrix plots it was identified that at higher Beaufort Numbers, the resistance did not necessarily decrease, but the RPM decreased. Multi-linear regression analysis should account for this inter-correlation relationship within the output regression coefficients and thus Beaufort Number was still included as a PV.
- A significant correlation was identified between the PV's RPM and Beaufort Number, and RPM and Wind direction. However these relationships were not considered to induce multicollinearity due to practical understanding of the relationships.

The model Summary Statistics results are presented in Table 29.

Table 29: Regression Model Summary Statistics, , Regression Analysis, Ship T1

	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
Ballast	.979	.958	.958	34.750	2.018
Laden	.966	.933	.932	31.113	1.203

Table 29 demonstrate the following:

- The ballast modelling sample provided a good prediction, with an R^2 (coefficient of determination) value of 0.98; indicating that 98% of the variance in the resistance is accounted for by the selected PV's.

- For the laden modelling sample, a very good prediction is also provided, with an R^2 value of 0.96.
- The Durbin-Watson value for ballast and laden conditions is within the range of 0 and 4, reflecting no autocorrelation.

The ANOVA Statistics results presented in Table 30 demonstrate that:

- The prediction equations found by the regression analyses are considered significantly valid for predicting the resistance (according to the F-test).

Table 30: ANOVA Statistics, Regression Analysis, Ship T1

		Sum of Squares	df	Mean Square	F	Sig.
Ballast	Regression	8705395.131	3	2901798.377	2402.961	.000
	Residual	380391.733	315	1207.593		
	Total	9085786.864	318			
Laden	Regression	3659128.425	4	914782.106	945.020	.000
	Residual	261360.662	270	968.002		
	Total	3920489.086	274			

The residual scatter plot and distribution of residuals are shown in Figure 45. They demonstrate:

- For both ballast and laden the residuals can be considered normally distributed. This strengthens the prediction performance and complies with the assumptions of multi-linear regression analysis.
- The standardised residual[26] scatter plots demonstrate homoscedasticity: i.e. no distribution trends can be observed and the residuals are relatively evenly distributed around zero along the scale of predicted values.

[26] *i.e. the prediction error between the resistance calculated via the Data Elaboration Process and the resistance predicted using the regression prediction equations, in a standardised format.*

- The standardised residual scatter plots do not demonstrate any considered outliers. One residual value can be seen at a high predicted value for ballast. This is not considered to be an outlier as the point is within the residual distribution for the main cluster of data points.

- For the laden condition, a thinning of data points can be seen for the lower predicted values in the standardised residuals scatter plot. This could be due to homoscedasticity, however it is considered much more likely to be due to a reduction in the number of data points recorded in this range, particularly as they are distributed around zero and do not demonstrate a marked difference from the main cluster of points.

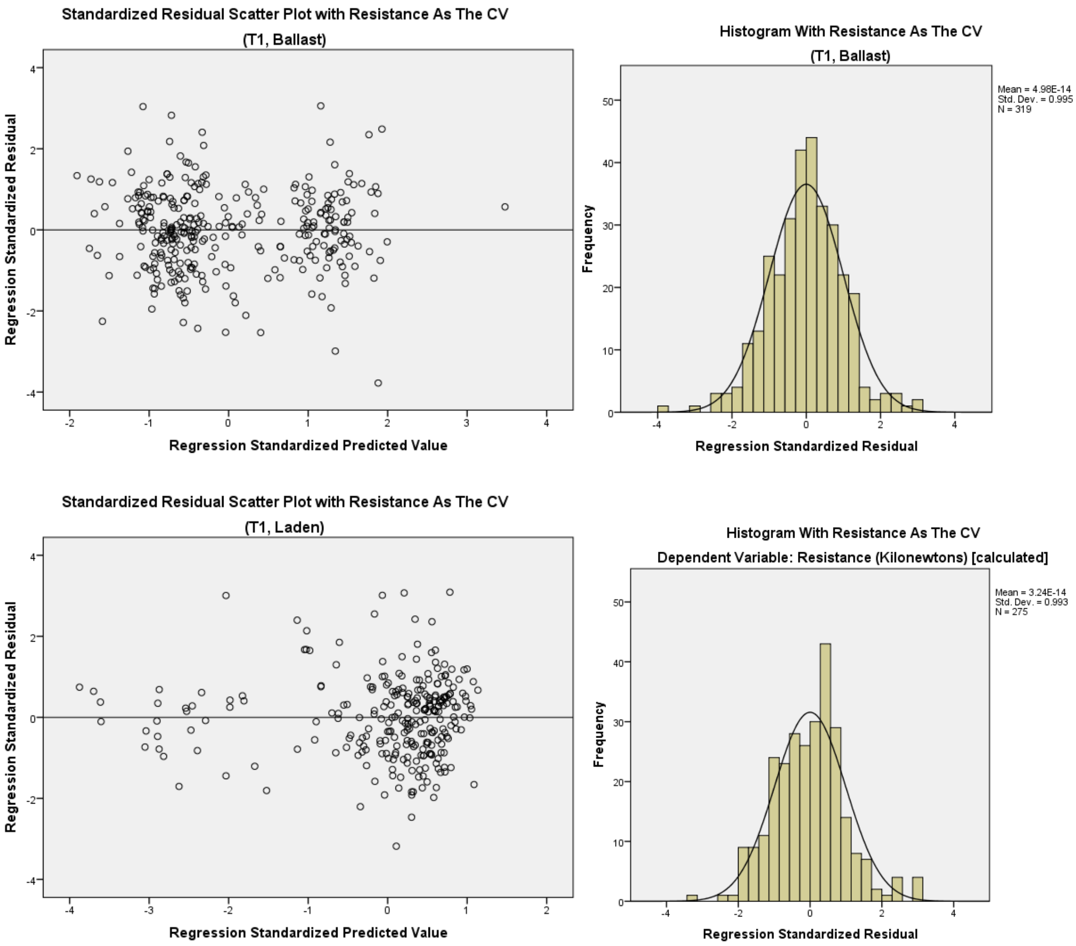


Figure 45: Residuals scatter plot and distribution, Regression Analysis, Ship T1

The Coefficient Results shown in Table 31 demonstrate the following:

- Regarding at the unstandardized coefficients, the wind direction was found to have a negative coefficient. This is in contrast to the correlation results but is inline with practical understanding of ship performance. Hence it is considered that the analysis has accounted for the inter-correlations previously discussed.
- With an increase in all other PV, the resistance is found to increase.
- Comparing the 95% confidence intervals between the ballast and laden coefficient results, they fall within the same ranges. The values for the constants are outwith the 95% confidence intervals, but this is expected as the resistance will logically be higher when sailing laden than when sailing in ballast. This result for independent samples increase confidence that the determined performance prediction equations are representative of the impacts of each PV.
- Furthermore, the above discussed result, regarding the comparison of the 95% confidence intervals, suggest that if the same is true for many ships then there may be the potential to identify a generalised prediction equation. However, the accuracy of a generalised prediction equation would be expected to be lower than for a specific ship analysis. This investigation is recommended for future work.
- The standardised coefficients indicate that the RPM has the largest influence on the ship resistance. The Beaufort Number has the next largest influence, although much less than the RPM. This is followed by the wind direction (considering the absolute value) and then the draft for the laden analysis.
- The t-statistic and the significance demonstrate that each coefficient and the constants are significant for inclusion in the prediction equation: i.e. they provide a prediction improvement by being included as a PV.

- The tolerance and Variation Inflation Factors (VIF's) demonstrate that no multicollinearity was identified between the PV's as the values are far from 0 and close to 1 retrospectively.

Table 31: Coefficients of the prediction equations, Regression Analysis, Ship T1

	Unstandardized Coefficients		Standardized Coef.	t	Sig.	95.0% Confidence Interval for B		Collinearity Statistics	
	B	Std. Error	Beta			Lower Bound	Upper Bound	Tolerance	VIF
Ballast									
(Constant)	-1365.62	29.41		-46.428	.000	-1423.49	-1307.75		
RPM [calculated]	30.716	.379	.951	80.939	.000	29.969	31.463	.963	1.039
Beaufort Number [recorded]	20.039	1.685	.139	11.889	.000	16.723	23.355	.972	1.029
Wind Direction [recorded]	-.355	.042	-.098	-8.467	.000	-.438	-.273	.990	1.010
Laden									
(Constant)	-1590.02	60.31		-26.364	.000	-1708.76	-1471.29		
RPM [calculated]	31.005	.510	.978	60.816	.000	30.001	32.008	.955	1.047
Average Draft At Midship (m) [recorded]	10.560	2.876	.058	3.671	.000	4.897	16.223	.984	1.016
Beaufort Number [recorded]	16.752	1.408	.193	11.898	.000	13.980	19.524	.941	1.063
Wind Direction [recorded]	-.147	.039	-.060	-3.790	.000	-.223	-.071	.972	1.029

9.3.4 Regression Prediction Equations

The following equations (E9.1 and E9.2) summarise the final prediction equations generated by the Resistance Regression Analysis, used in the SOPP model:

$$R_{T,Pred.Bal} = (30.716 \times \mathrm{RPM}_{rec}) + (0 \times \mathrm{T}_{rec}) + (20.039 \times \mathrm{BN}_{rec}) + (-0.355 \times \mathrm{WD}_{rec}) - 1365.62$$

E9.1

$$R_{T,Pred.Lad} = (31.005 \times \mathrm{RPM}_{rec}) + (10.560 \times \mathrm{T}_{rec}) + (16.752 \times \mathrm{BN}_{rec}) + (-0.147 \times \mathrm{WD}_{rec}) - 1590.02$$

E9.2

Table 32 presents the input value limits for the use of the ballast and laden prediction equations. Input data outwith these limits should not be used with the developed SOPP model for case study Ship T1 to avoid extrapolation of the results.

Table 32: Input limits to the prediction equations, Regression Analysis, Ship T1

		Minimum	**Maximum**
Ballast	RPM [calculated]	68.5	96.3
	Average Draft At Midship (m) [recorded]	7	9.3
	Beaufort Number [recorded]	1	8
	Wind Direction [recorded]	0	180
Laden	RPM [calculated]	71.6	89.6
	Average Draft At Midship (m) [recorded]	14.3	17.5
	Beaufort Number [recorded]	1	8
	Wind Direction [recorded]	0	180

9.3.5 Validation

Validation of the Resistance Regression Analysis was carried out by comparing the R^2 values of the modelling and test samples, and the modelling statistics.

One ballast data record was removed from the ballast test sample as it was found to contain an input value outwith the limits identified for the application of the prediction equation.

The validation comparison is shown in Figure 46 and Table 33 for the ballast condition, and Figure 47 and Table 34 for laden condition.

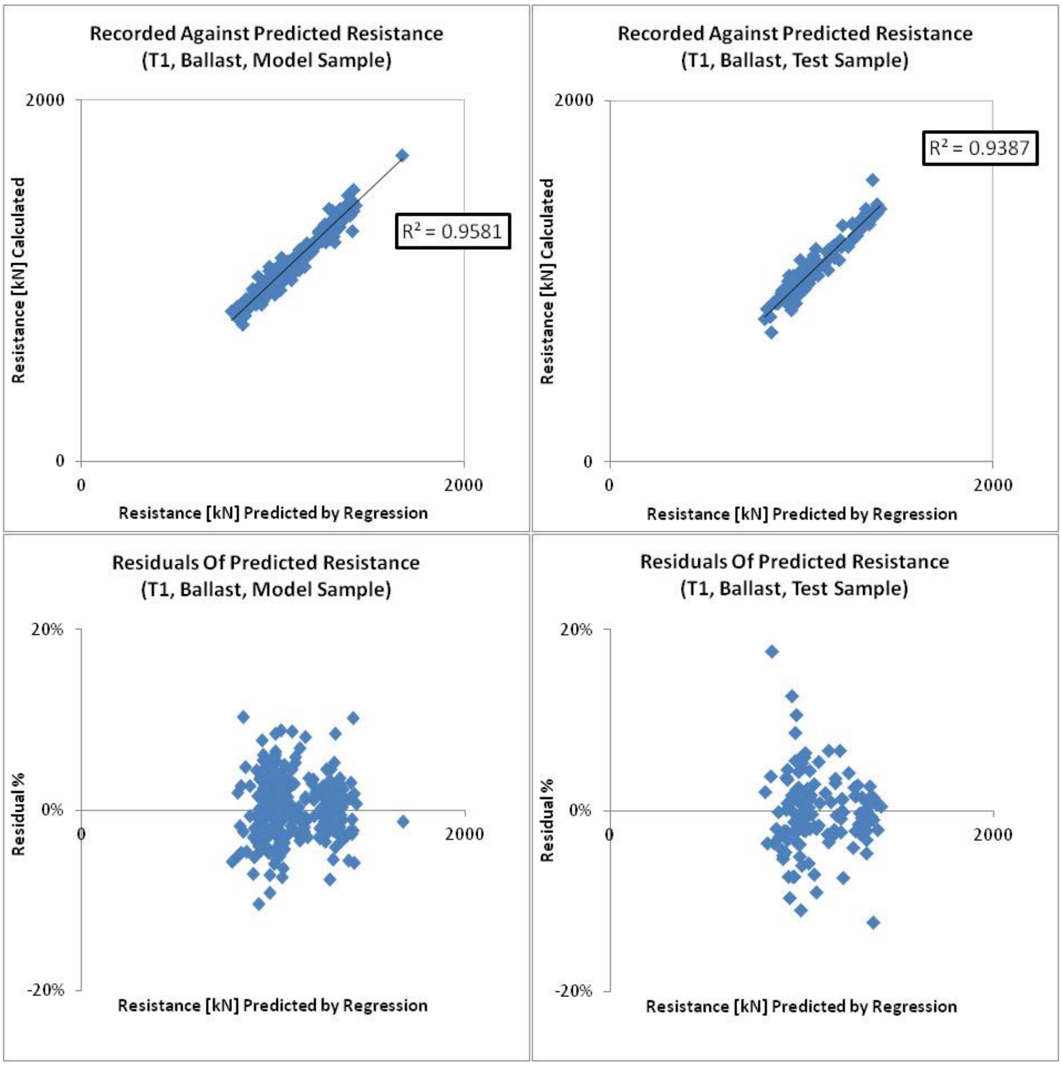


Figure 46: Correlation and residual scatter plots, comparison between modelling and test samples, Ship T1, Ballast

Table 33: Comparison of modelling and test sample statistics, Ship T1, Ballast

	Model Sample	Test Sample
Sample size	319	136
Sum of Residuals	0.00	-0.16
Average ABS % Error	2.48%	3.01%
Max ABS % Error	10.31%	18%
Standard Error %	3.15%	3.95%

Figure 46 and Table 33 demonstrate:

- The R^2 value for the test sample is very high and close to that of the model sample.
- The residuals of the test sample are in a similar range and pattern to those of the model sample.
- The absolute average error and standard error is not much greater for the test sample than the model sample (it is not expected to be smaller).
- The above conclusions indicate that the ballast prediction equation can be considered suitably generalised for the prediction of resistance for the case study Ship T1.
- The absolute error in the prediction is in the range of 2.4% to 3.0%, with a standard error between 3.2% and 4.0%, for case study Ship T1.

Figure 47 and Table 34 provide results supporting similar conclusions for the laden condition as discussed for ballast. The following additional conclusions were made:

- The absolute error in the laden condition is less than for ballast, and is around 1.9% for both, with a standard error between 2.4% and 2.5%.
- Whilst the sum of residuals is zero for the model sample, a larger under prediction (but still relatively small compared to the magnitude of resistance values) is observed for the test sample.

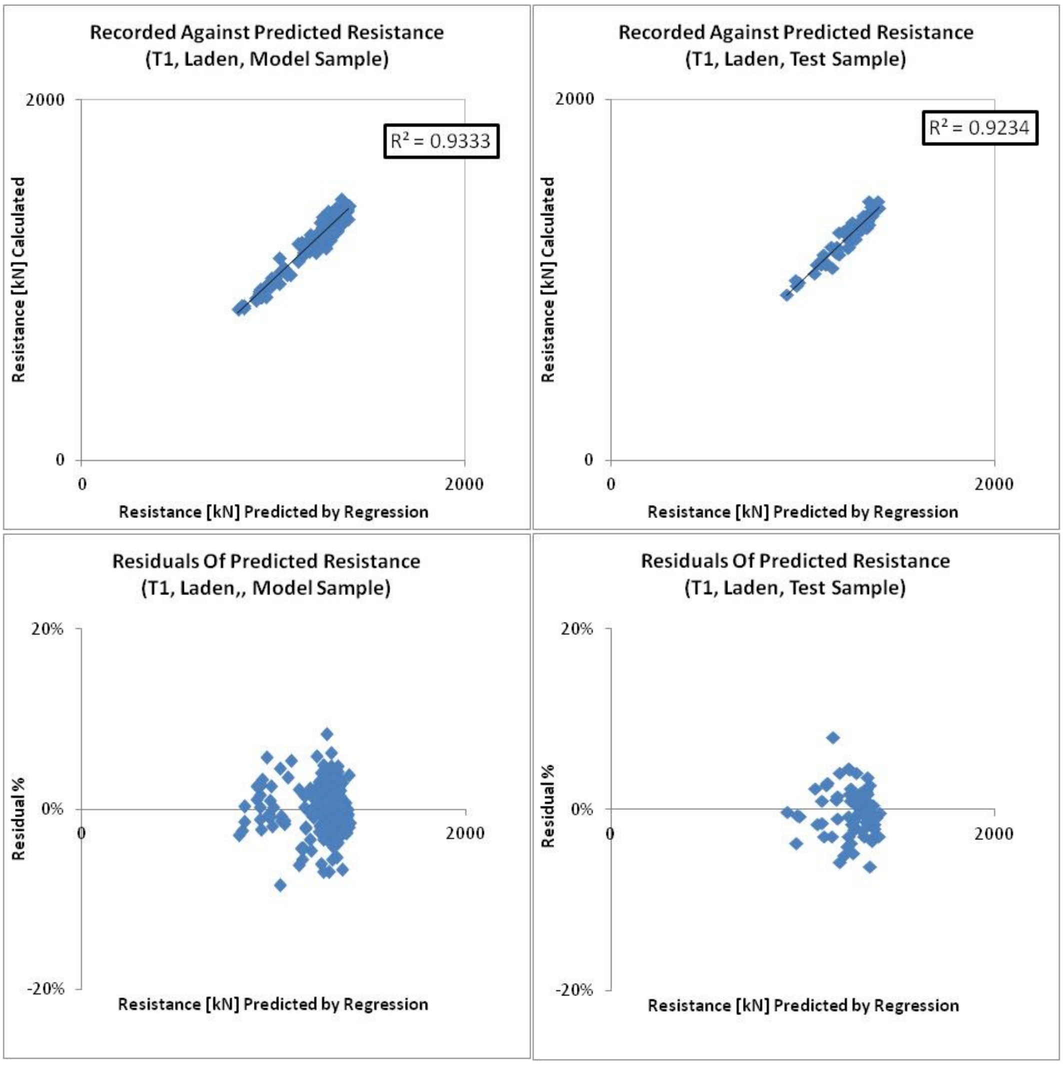


Figure 47: Correlation and residual scatter plots, comparison between modelling and test samples, Ship T1, Laden

Table 34: Comparison of modelling and test sample statistics, Ship T1, Laden

	Model Sample	Test Sample
Sample size	275	84
Sum of Residuals	0.00	-267
Average ABS % Error	1.92%	1.88%
Max ABS % Error	8.40%	8.08%
Standard Error %	2.45%	2.42%

The model and test samples were then combined for ballast and laden.

Table 35 presents the results for the combined samples: with an R^2 value of 0.95 and 0.91, an average absolute error of 2.6% and 2.1% and standard error of 3.4% and 2.8%, for the ballast and laden samples retrospectively.

Table 35: Combined sample statistics using the regression analysis prediction equation, Ship T1

	Ballast	Laden
Coefficient of determination	0.95	0.91
Sample size	455	402
Sum of Residuals	-486	-1362
Average ABS % Error	2.64%	2.08%
Max ABS % Error	17.68%	11.79%
Standard Error %	3.40%	2.84%

As a final note for the Resistance Regression Analysis, it is expected that the above prediction results could be improved if additional PV were included in the analysis; such as for currents, and hull and propeller degradation and fouling. However, no variables were available in the SR datasets to represent the current and the time since the last maintenance activity was not selected as a PV purposefully, as it will be addressed in Step 5 of the SOPP model development.

9.4 Step 3: Speed Regression Analysis

In Section 9.1 it was highlighted that ship speed is a function of the RPM and the slip conditions experienced (i.e. influenced by but not limited to the PV's used in the Resistance Regression Analysis). The ship speed was also not selected as a PV within the Resistance Regression Analysis to avoid multicollineraity. However, for the SOPP development in Steps 4 and 5, the ship speed is required as an input. It was therefore considered that the same multi-linear regression analysis method, as described in the previous Section 9.3, could be used to predict the Ship Speed (i.e. the CV) based on the following PV's: RPM, average draft at midship, Beaufort Number and wind direction. These PV's are the same as for the Resistance Regression Analysis and therefore no additional input data would be required.

9.4.1 Regression Analysis results

The prediction equations shown in E9.3 below were found to be significant and sufficiently generalised to predict the speed of Ship T1 given the PV input values. Interpretation of the analysis results was carried out as described in Section 9.3.

$$V_{Pred.Bal.} = (0.172 \times \mathrm{RPM}_{rec.}) + (0.048 \times \mathrm{T}_{rec.}) + (-0.316 \times \mathrm{BN}_{rec.}) + (0.005 \times \mathrm{WD}_{rec.}) + 1.463$$

$$V_{Pred.Lad.} = (0.209 \times \mathrm{RPM}_{rec.}) + (-0.153 \times \mathrm{T}_{rec.}) + (-0.320 \times \mathrm{BN}_{rec.}) + (0.003 \times \mathrm{WD}_{rec.}) + 0.226$$

E9.3

Table 36 summarises the statistic results for the Speed Regression Analysis for the combined modelling and test samples. The absolute prediction error was within 3.5% for the case study Ship T1 example. A small over prediction is observed and the standard error is around 4% to 4.5%. The R^2 value was 0.72 for both laden and ballast. It is considered that the prediction of ship speed could be improved if speed through water was used along with additional PV's as inputs to capture the remaining impacts of slip: such as currents or hull and propeller surface degradation and fouling.

Table 36: Statistics for the prediction for ship speed, Regression Analyses, Ship T1

	Ballast	Laden
Sample size	455	402
Coefficient of determination	0.72	0.72
Sum of Residuals	7.31	26.02
Average ABS % Error	3.00%	3.44%
Max ABS % Error	23.09%	28.57%
Standard Error %	3.92%	4.48%

9.5 Step 4: Resistance Normalisation

9.5.1 Method

The aim of carrying out the Resistance Normalisation was to isolate the components of additional resistance due to operation at different RPM and drafts, in different Beaufort Numbers and wind directions and with different hull and propeller surface degradation and fouling conditions. This aim was identified as a requirement of the SOPP model specified in Sub-section 5.4.6. A normalisation process was also selected to avoid excessive filtering of the dataset. Similarly approaches to data normalisation were discussed in Sub-section 2.4.5.

To determine the normalised resistance in step 4, the method shown in Figure 48 was used:

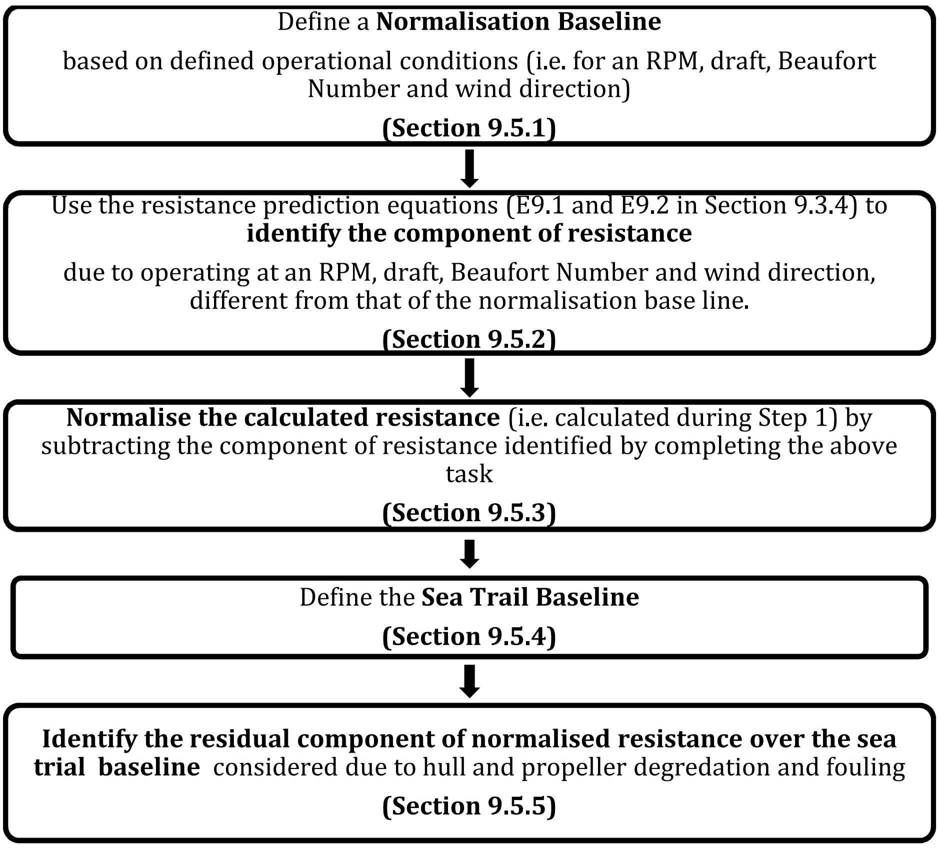


Figure 48: SOPP model, Step 4: Regression Normalisation Method Flow

The residual component of normalised resistance over the Sea Trial Baseline was considered due to hull and propeller degradation and fouling. How this component was analysed and modelled as a function of the SOPP is presented in the next development step, Step 5: Time Dependent Performance Analysis.

The combined samples for ballast and laden were used to perform the Resistance Normalisation.

9.5.2 Normalisation baseline

The input variables for the normalisation baseline are presented in Table 37 below.

Table 37: Normalisation Baseline, model input variables, Ship T1

	Ballast	**Laden**
RPM	85	86
Average draft at midship	8 m	16 m
Beaufort Number	1	2
Wind Direction	0 degrees (Head seas)	0 degrees (Head seas)
$Speed_{pred}$ (predicted using the above inputs to the Speed prediction equations (E9.3: Section 9.4.1)	16 knots	15 knots

The input values for the Normalisation Baseline are based on Ship T1's laden and ballast design drafts, the weather conditions recorded for the Sea Trial, and the RPM corresponding to one load condition. Approximate values for the Normalisation Baseline for Ship T1 are given in Table 37 (precise values were used for the model development).

The ship speeds for the normalisation baseline (Table 37) were determined using the speed prediction equations (E9.3: Section 9.4.1) are also shown below in Table 37.

9.5.3 Components of Additional Resistance

The calculations in E9.4 were carried out for each SR record in the ballast and laden samples using the resistance prediction equations ($_{pred}$). This was to identify the components of ship resistance that can be apportioned to operating at an RPM, draft (T), Beaufort Number (BN) or wind direction (WD) recorded in the SR record ($_{rec}$), which are different to those specified for the Normalisation Baseline ($_{Nbase}$)

$$\Delta R_{Pred.rec.RPM} = (a \times RPM_{rec.}) + (b \times T_{NBase}) + (c \times BN_{NBase}) + (d \times WD_{NBase}) + e$$

$$\Delta R_{Pred.rec.T} = (a \times RPM_{NBase}) + (b \times T_{rec}) + (c \times BN_{NBase}) + (d \times WD_{NBase}) + e$$

$$\Delta R_{Pred.rec.BN} = (a \times RPM_{baseline}) + (b \times T_{NBase}) + (c \times BN_{rec}) + (d \times WD_{NBase}) + e$$

$$\Delta R_{Pred.rec.WD} = (a \times RPM_{NBase}) + (b \times T_{NBase}) + (c \times BN_{NBase}) + (d \times WD_{rec}) + e$$

E9.4

Where $_{pred.rec.X}$ notes predicted for the recorded value of variable X

9.5.4 Normalisation

The calculated resistance ($_{Cal.}$) determined during the Data Elaboration Process was then normalised using E9.5:

$$R_{Norm} = R_{Cal.} - (\Delta R_{Pred.rec.RPM} + \Delta R_{Pred.rec.T} + \Delta R_{Pred.rec.BN} + \Delta R_{Pred.rec.WD})$$

E9.5

The normalised resistance is therefore expected to incorporate: the baseline resistance; plus any additional resistance not accounted for by the PV’s in the regression analysis (e.g. due to currents or hull and propeller degradation and fouling); plus half the prediction error incorporated from using the method of least squares in the regression analysis.

9.5.5 Sea Trial Baseline

As the Normalisation Baseline was considered to also incorporate half the prediction error incorporated in the resistance prediction equations a Sea Trial Baseline was used to benchmark the ship performance against its performance when it first entered into service.

The Sea Trial Baseline was calculated as follows:

a) Plot the Sea Trial brake power-speed curve for ballast and laden

b) Convert the brake power-speed curve to resistance-speed using the Determined Total Propulsion Efficiency Relationships (Appendix E), and E.2 (given in Appendix A)

c) Determine the line equations for the resistance-speed curves

d) Calculate the resistance for the identified speed using the resistance-speed line equation

Using the same speed predicted for the Normalisation baseline (approximately 16 knots for ballast and 15 knots for laden) the Sea Trial Resistance Baseline was identified.

9.5.6 Residual component of normalised resistance over the sea trial baseline

Figure 49 shows the following plot over time:

- The **Normalised resistance** for each SR record in Ship T1’s dataset
- The **Sea Trial Baseline** corresponding to the speed of the normalisation baseline
- The **first dry dock** date for Ship T1

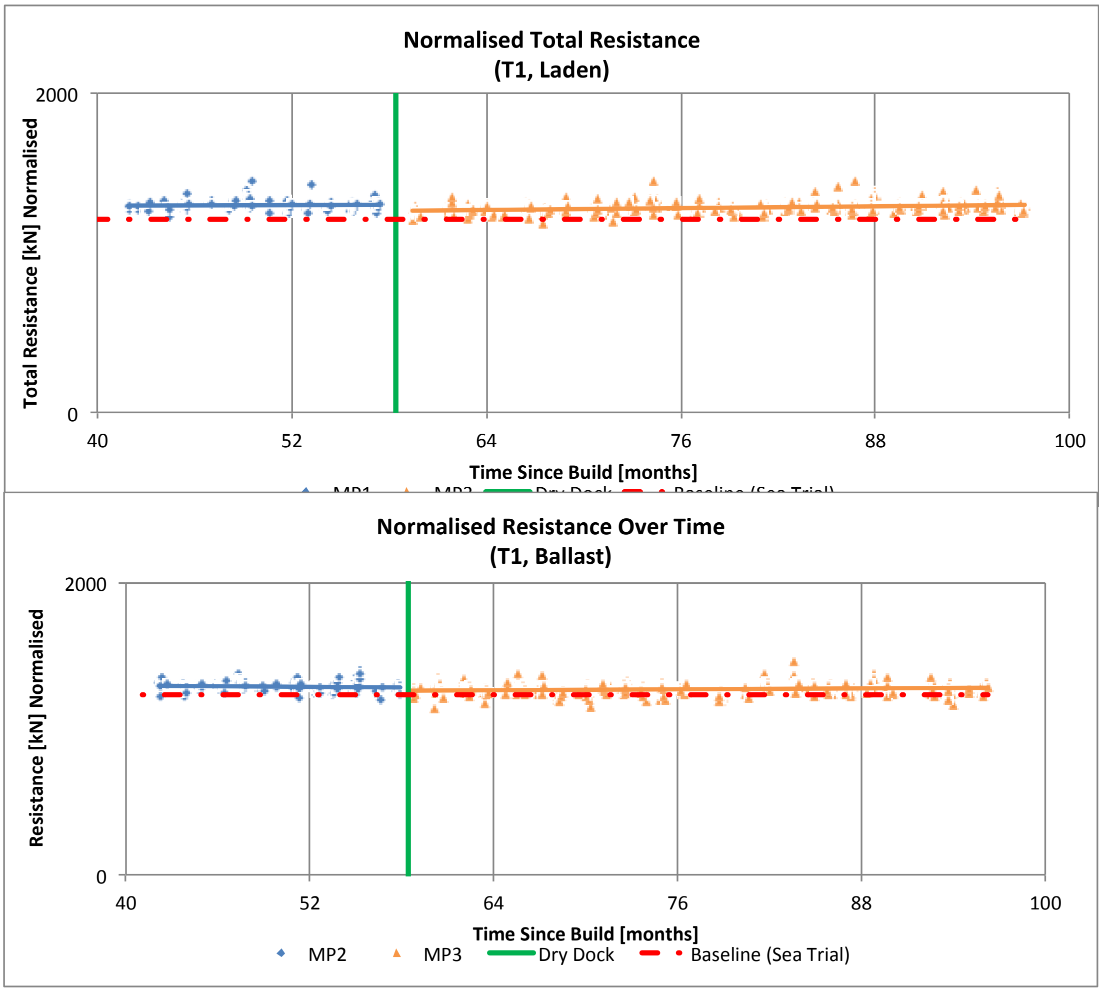


Figure 49: Normalised resistance over time, Ship T1

Figure 49 demonstrates the following:

- The data points in Maintenance Part (MP) 3 in ballast, and MP2 and MP3 in laden, show an increase in normalised resistance over time. This is expected as it is assumed that the normalised resistance value should include a time dependent increasing component of resistance due to hull and propeller surface degradation and fouling: not accounted for by the PV corrections.
- The increasing trend is not considered to include engine performance degradation as the calculated resistance (determined during the data elaboration process) was calculated from the RPM and speed and considering

only hydrodynamic and propulsion system performance: not main engine efficiency.

- The trend for MP2 in ballast slightly decreases which is contradictory to what would be expected. However, this did not raise too much of a concern as the decrease is only slight and could be due to only having a small proportion of data points before the dry dock available for analysis. Furthermore, the rate of fouling increase after four years of operation is expected to be less than the increase just after build or maintenance.
- Between MP2 and MP3 (i.e. after dry dock maintenance) the resistance is shown to reduce for both ballast and laden.

Figure 50 demonstrates the increases in normalised resistance as a percentage above the Sea Trial Baseline (defined in Section 9.5.5). The following points were concluded:

- At the end of MP2 the normalised resistance is shown to be in the range of 2.5% to 7.5% above the sea trial baseline in ballast, and 5% to 10% in the laden condition
- The percentage of normalised resistance falls at the start of MP3, after the dry dock, in both ballast and laden, by about 2.5%.
- At the start of MP3 the normalised resistance starts increasing again to a similar levels compared to the end of MP2 by month 94. Data was not available up to the second dry dock and thus the total resistance increase MP3 could not be analysed.

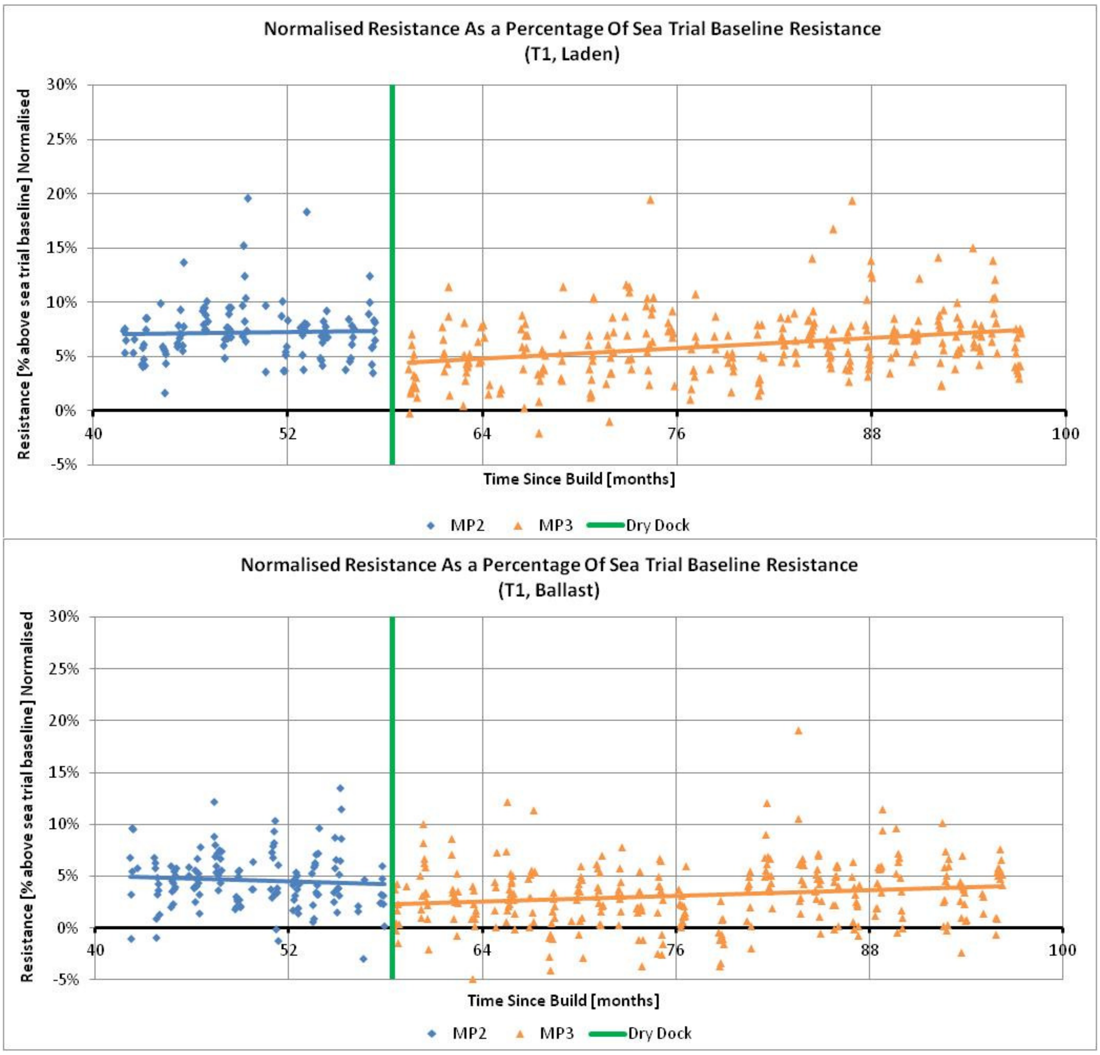


Figure 50: Normalised resistance over time as a percentage of the baseline, Ship T1

9.6 Step 5: Time Dependent Performance Analysis

9.6.1 Method

Step 5 was carried out using the normalised resistance, to quantify and model the time dependent change considered due to hull and propeller surface degradation and fouling.

In Section 9.5.6, a linear trend line was used to demonstrate the time dependent increase in normalised resistance. However, assuming the increase is due to hull and propeller surface degradation and fouling, it is known that the fouling rate does not increase linearly. A logarithmic trend line was used to try and capture the change, but this too was not considered representative. It was therefore decided that the cumulative distribution function of a Weibull distribution could be used to model the change. The generic form of the function can be seen below where two coefficients need to be defined: *f* the scale parameter, *g* the shape parameter and where γ is the location parameter.

$$f(T) = \left[\mathbf{1} - \left(\boldsymbol{e}^{-\left(\frac{\boldsymbol{T}-\boldsymbol{\gamma}}{f,}\right)^{\boldsymbol{g}+\mathbf{1}}}\right)\right]$$

For the time dependent performance change analysis, the location parameter is the time since build (t) less the time since last maintenance (t_{MP}) as a proportion of the total maintenance period (t_{int}). Thus the function can be written as follows:

$$f(T) = \left[\mathbf{1} - \left(\boldsymbol{e}^{-\boldsymbol{f}\left(\frac{\boldsymbol{t}-\boldsymbol{t_{MP}}}{\boldsymbol{t_{int}}}\right)^{\boldsymbol{g}+\mathbf{1}}}\right)\right]$$

This function varies between 0 and 1, so to predict the resistance due to the time dependent performance changes (ΔR_{TD}) the maximum resistance attained within the maintenance part (R_{max}) is required as a multiple. The function is therefore shown below:

$$\Delta R_{TD} = R_{max}\left[1-\left(e^{-f\left(\frac{t-t_{MP}}{t_{int}}\right)^{g+1}}\right)\right]$$

E9.6

The method for completing Step 5 is shown in Figure 51.

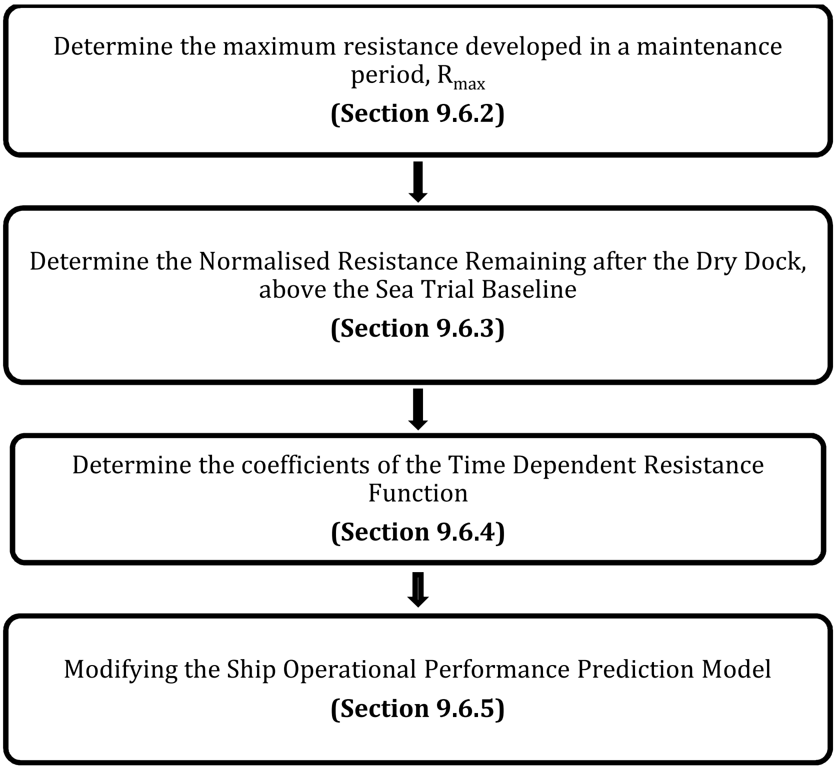


Figure 51: SOPP model, Step 5: Time Dependent Performance Change Method Flow

9.6.2 Maximum Resistance Developed in a Maintenance Period, R_{max}

To determine an initial estimate for R_{max} at the first Dry Dock, the following calculation was carried out:

a) Take an average of the Normalised Predicted Resistance data points available in MP2. (The average was used as there were few data points available for MP2).

To determine an initial estimate for R_{max} at the estimated second Dry Dock, using the data in MP3 the following was carried out:

a) Estimate the date of the second dry dock by assuming the same interval as between ship build and the first dry dock (i.e. 58 months).

b) Plot a linear trend line for the MP3 Normalised Resistance above the Sea Trial baseline data points.

c) Extrapolate the trend line to the second dry dock and determine the Normalised Resistance above the Sea Trial baseline on entry into the second dry dock.

d) Carry out steps b and c above again, but plotting a logarithmic trend line (i.e. to capture the decreasing rate of fouling increase). An example is shown in Figure 52.

e) Take an average of the R_{max} determined via the linear and logarithmic trend lines.

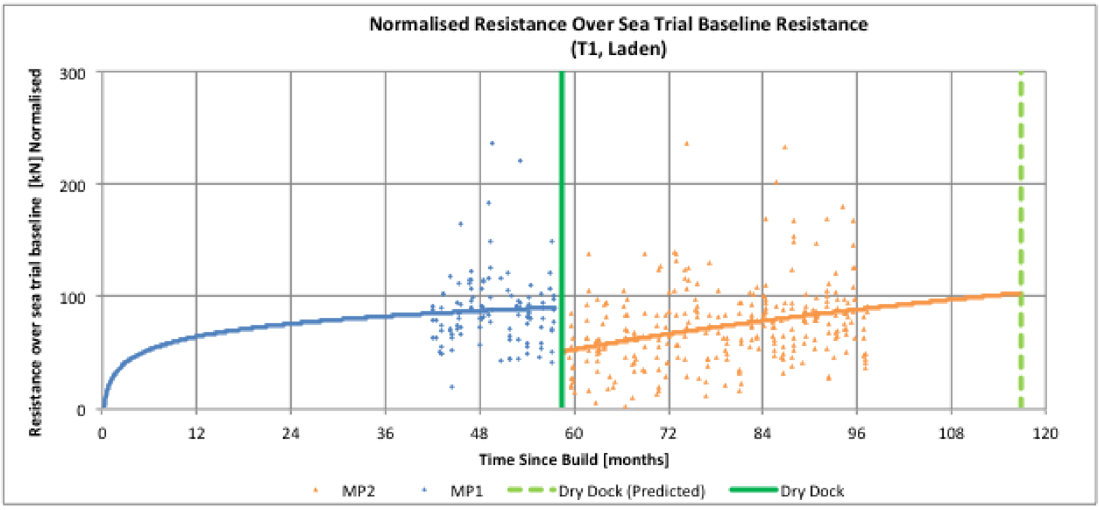


Figure 52: Logarithmic trends plot to the normalised resistance data points, Ship T1, Laden

This initial estimate was updated as described in the following Section 9.6.4, using an optimisation solver. The final values for the determined R_{max} are shown in Table 38.

9.6.3 Normalised Resistance Out of Dry Dock

It was assumed that the Normalised Resistance above the Sea Trial Baseline at Time Since Build equal to zero would be zero, as this was the date when the sea trial was carried out.

The Normalised Resistance above the Sea Trial Baseline remaining after the ship came out of the first dry dock was identified as follows:

- **a)** Identify the line equation of the linear trend line plot for the Normalised Resistance over time, plot in MP3.
- **b)** Use the line equation to calculate the Normalised Resistance at the time of the dry dock (i.e. directly after exit from the dry dock). This is referred as the *Normalised Resistance after dry dock* ($\Delta R_{AD\text{-}D}$)

9.6.4 Coefficients of the Time Dependent Resistance Function

To determine the coefficients for the curve function (shown in E9.6) the following steps were taken:

- **a)** Remove the Normalised Resistance above the Sea Trial Baseline remaining after the first dry dock (calculated in Section 9.6.3) by subtracting the constant amount from each SR record in MP3. This is referred as the *Time Dependent Normalised Resistance* (ΔR_{TDcalc})
- **b)** Make an initial estimate for the coefficients within a reasonable expected range (these were selected to be 6 for f and 0.1 for g)
- **c)** Based on the initial estimates for the coefficients and R_{max}, for MP2 and MP3, predict the Time Dependent Normalised Resistance using the function (E9.6), ($\Delta R_{TD.pred}$), for each SR record
- **d)** Calculate the square of the difference between the calculated Time Dependent Normalised Resistance calculated in step c above and the that in step a for each SR record.

e) Use an optimisation solver to minimise the sum of all SR records in one MP, by changing the coefficients f and g.

The coefficient results were similar and, because there were so few data points available for MP2, the coefficients for MP2 were manually changed to those of MP3 in order to define a more generalised equation.

The R_{max} values were then also updated using the optimisation solver to select the best fit through the data points. Table 38 presents the final coefficients and R_{max} values determined for each maintenance part for the ballast and laden models.

Table 38: Time dependent curve parameters, Ship T1

Dry dock Interval	58	months
Ballast		
	MP2	**MP3**
g	0.200	0.200
f	2.5	2.5
R max	57	36
Laden		
	MP2	**MP3**
g	0.200	0.200
f	2.5	2.5
R max	90	43

The Time Dependent Resistance function is hence shown in E9.7, where the R_{max} value differs for ballast and laden maintenance parts.

$$R_{TD} = R_{max}\left[1 - \left(e^{-2.5\left(\frac{t-t_{MP}}{t_{int}}\right)^{3}}\right)\right]$$

E9.7

Figure 53 presents the normalised Time Dependent Resistance change above the Sea Trial Baseline not including the remaining resistance after dry dock. The data points from the SR records and the model prediction curves are shown. The figure demonstrates:

- The increase in resistance (in kN) is greater in laden than in ballast, as would be expected with an increased underwater surface.
- There is still a large amount of scatter around the time dependent modelled function. This scatter is not unexpected with the uncertainty expected in input data and the modelling assumptions made. Nevertheless, the scatter is relatively evenly distributed around the function curve.

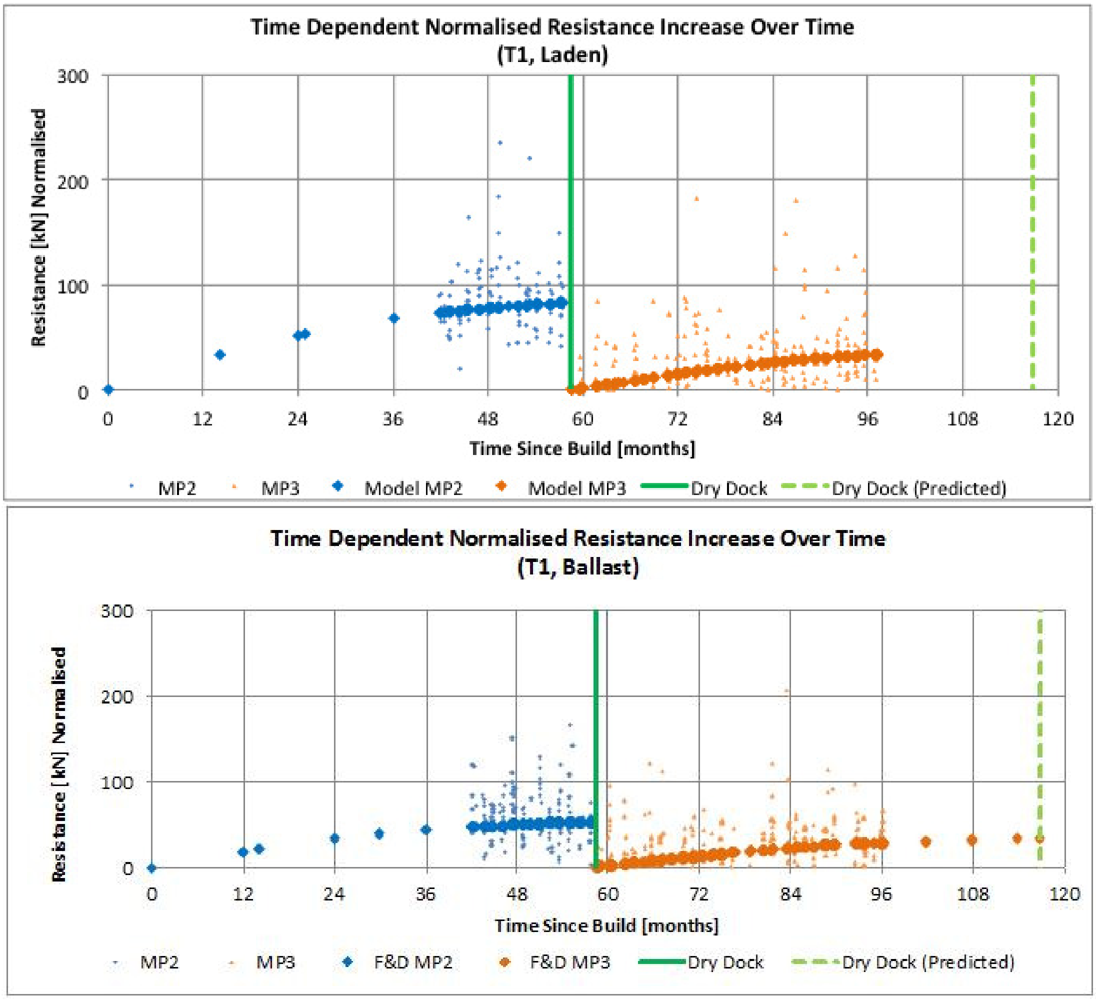


Figure 53: Additional resistance above the sea trial baseline due to hull fouling and surface degradation, Ship T1

9.6.5 Modifying the Ship Operational Performance Prediction Model

Having defined the function for the time dependent increase, the final SOPP model was constructed, comprising of:

- R_{Pred}: the resistance prediction equations (determined via the resistance regression analysis) which includes the ΔR's due to operation at the specified RPM, draft, Beaufort Number and wind direction.
- $\Delta R_{between\ baselines}$: to account for the difference between the Normalisation and Sea Trial Baseline resistance.
- $\Delta R_{AD\text{-}D}$: the resistance above the Sea Trial Baseline remaining after a dry dock (assumed to remain constant).
- ΔR_{TD} : the time dependent resistance above the Sea Trial Baseline and that remaining after dry dock.

$$R_{Pred,SOPP} = R_{Pred,} - \Delta \mathrm{R}_{between\ baselines} + \Delta R_{aAD-D} + \Delta R_{TD}$$

E9.8

Where

$$\Delta \mathbf{R}_{\boldsymbol{between\ baselines}} = R_{NBase} - R_{STBase}$$

The following assumptions for the use of this SOPP model should be noted:

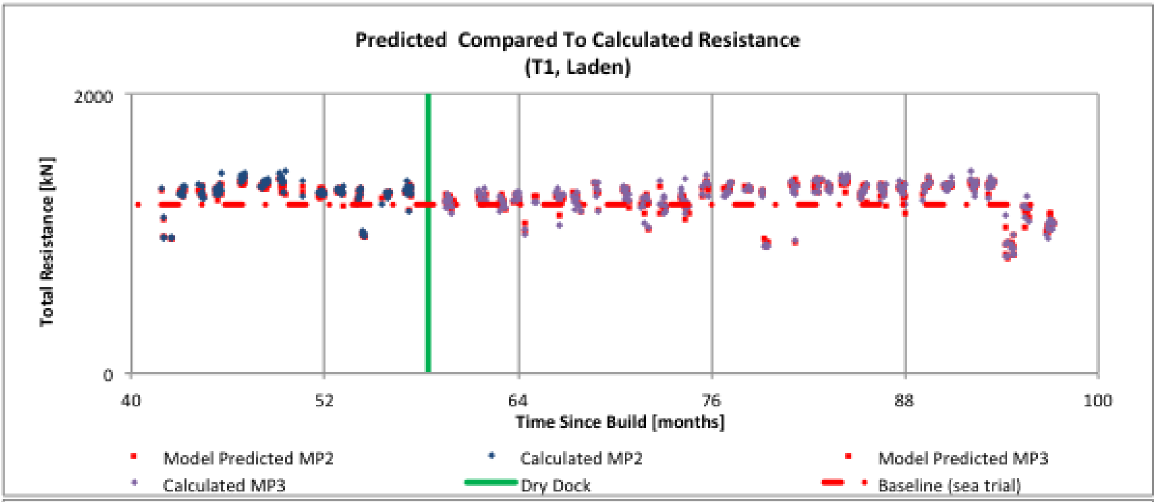
- The model assumes that the time dependent resistance and the resistance remaining after dry dock is a) independent of a change in RPM, draft, Beaufort Number and wind direction, and b) it remains constant with a change in the Normalisation Baseline. These assumptions are expected to differ and therefore future work to investigate the changes is recommended.
- The model assumes a regular dry docking interval (t_{int}). Without knowledge of when a dry dock occurs, this was assumed but could be updated if known.

- The model requires an estimate for R_{max} and the resistance saving gained from carrying out different types of hull maintenance. If the operational data is available this can be derived (as demonstrated in this Chapter); otherwise it has to be assumed. Completion of many case study applications may reveal typical trends for R_{max} or expected savings. This is therefore suggested for future work.

9.7 SOPP Model Results and Validation

9.7.1 Results

Using the SOPP model equation in E9.8. The ship resistance was predicted for each SR record. Figure 54 presents the predicted resistance by the model and the calculate resistance via the data elaboration process. It is evident that there is little difference between the two.



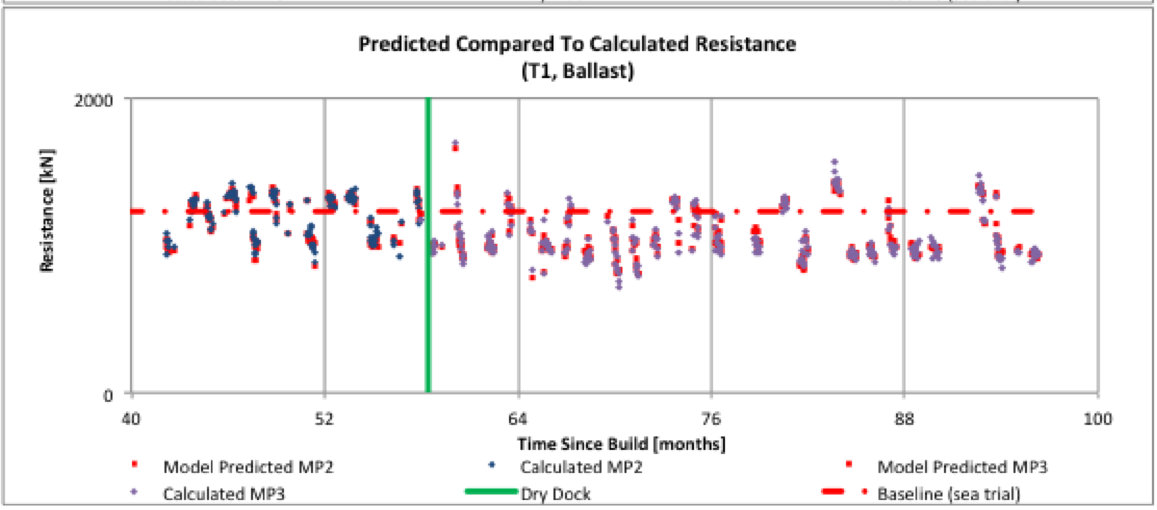


Figure 54: Comparison between recorded and predicted resistance, Ship T1

Figure 55 presents the model predicted and the calculated normalised resistance over the sea trial baseline. The model prediction demonstrates that the resistance increases by around 7% in laden and 4.6% in ballast. This percentage remains constant for an increase in power over the sea trial baseline power. Comparing this percentage increase with Figure 6 in Section 2.4.3, a power increase around 10% would correspond to hull deterioration and slime. For a ship that has been in operation for 5 year, this performance change seems a low.

Further investigation would be required in future work to assess if the contribution due to time dependent changes has been captured accurately, as no data or information related to a known quantification currently exists. Suggested investigations would therefore include investigation of the impact of using different baseline conditions and performing several case studies, preferably using case study ship for whom increased information is available regarding their hull and propeller condition and resistance quantification.

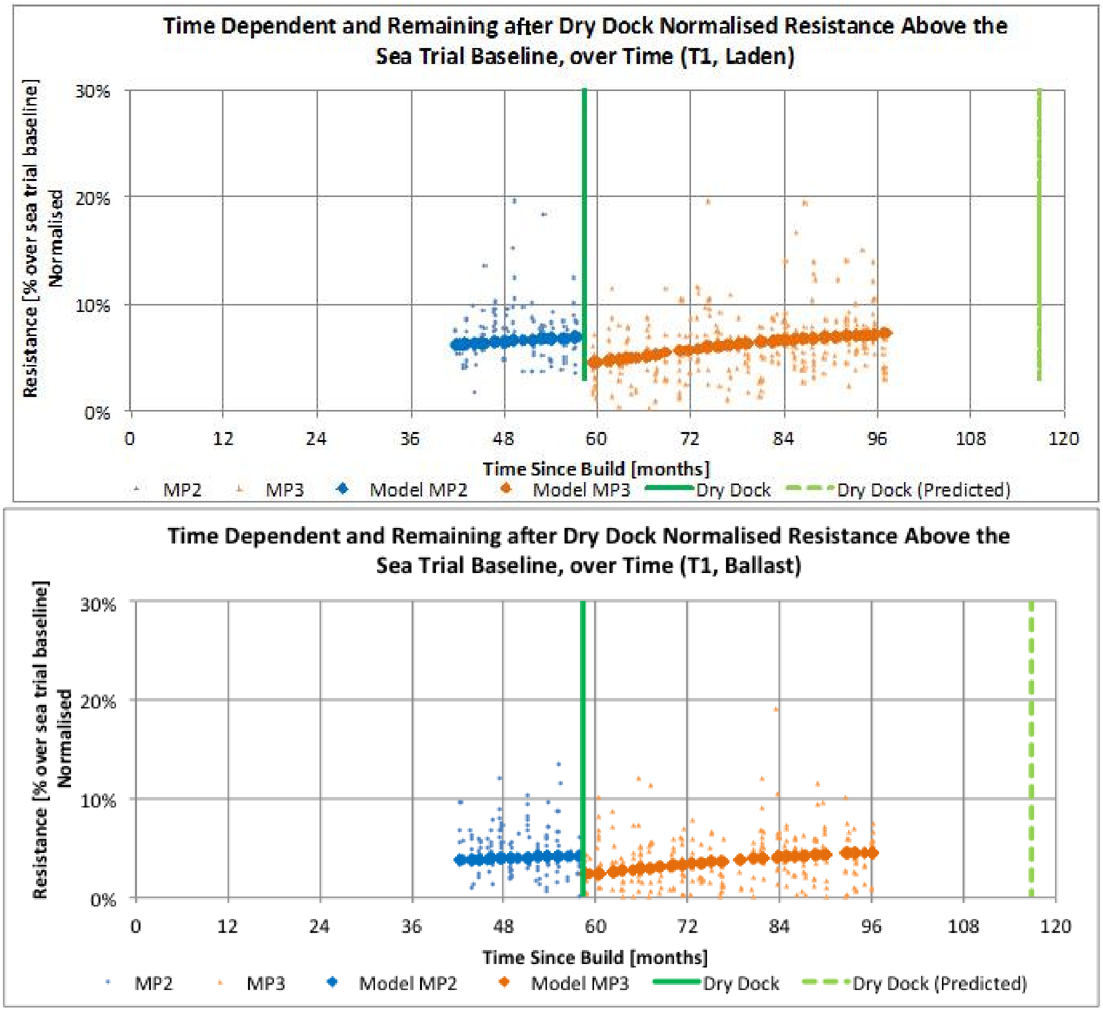


Figure 55: Modelled Normalised Resistance over the Sea Trial Baseline, Ship T1

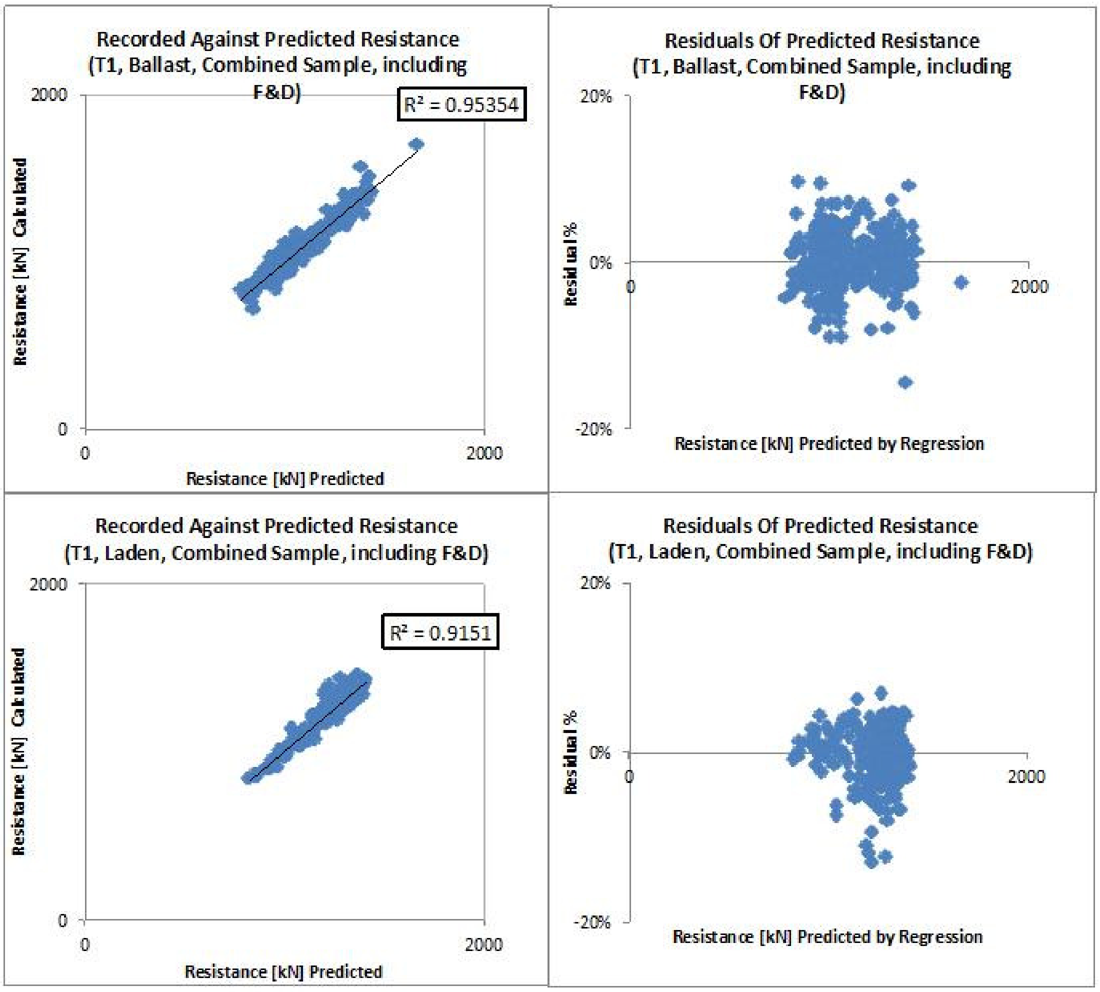


Figure 56: Correlation and residual scatter plots, including hull and propeller fouling and surface degradation, Ship T1

Table 39: Statistics for the prediction for resistance using the SOPP model, Ship T1

	Ballast	**Laden**
Sample size	402	402
Sum of Residuals	620	-890
Average ABS % Error	2.15%	1.95%
Max ABS % Error	15%	13%
Standard Error %	3.3%	2.7%

Figure 56 and Table 39 demonstrate the prediction statistics for the SOPP model, compared to the resistance calculated via the Data Elaboration Process. The following conclusions were made:

- The R^2 value for the ballast SOPP model prediction was 0.95 for the ballast condition, and 0.91 for laden.
- The residuals of the prediction are relatively evenly distributed around zero error. The increasing variation in the laden residual towards higher resistance is considered due to the increase in data points in this range.
- The absolute average error of the SOPP model prediction was within 2.2% for ballast and laden. The standard error was less than 4%. The maximum absolute errors are within the range of 10% to 13%.

9.7.2 Validation

The results presented in the previous chapter section compare the predicted resistance to the calculated resistance. Therefore to provide a validation of the SOPP model, the predicted results were compared to the following for case study Ship T1:

- The fuel consumption recorded in all the SR records
- The brake power recorded approximately $^1/_3$rd of the SR records
- The resistance derived from the brake power recorded approximately $^1/_3$rd of the SR records (not the calculated resistance via the data elaboration process). Whilst this dataset is not a true validation as it is not directly recorded, it provides an insight for the resistance values.

It should be noted that the above listed data variables were not used to construct the SOPP model, thus they can be considered as independent validation datasets.

It should also be highlighted that, if developing the SOPP model for other case study ships with no brake power record (i.e. if a torque meter is not installed), periodic measurements of brake power using indicated diagrams (discussed in 2.4.5) could be used to produce a validation dataset.

▪ **Prediction of SFOC**

To calculate predicted Fuel Flow Rate (FFR) using the SOPP model, the SFOC was required. This was calculated from the Main Engine Operational dataset collected for case study Ship T1. The average SFOC trend produced from the dataset is presented in Figure 57. If similar operational datasets are not available to all companies, the SFOC-load curve could be derived from; the main engine shop trial, the project guide (although this could include a 5% error), or via another sources. Hence the requirement for wide applicability of the SOPP model is not invalidated.

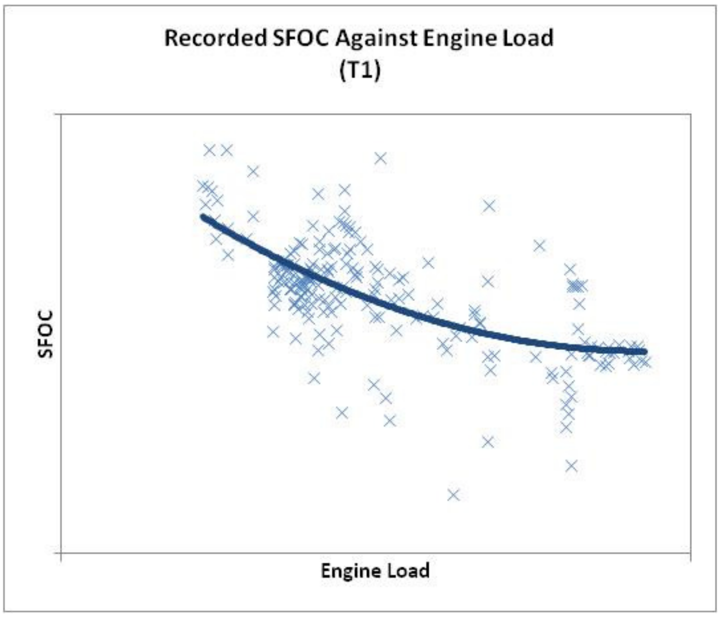


Figure 57: SFOC against engine load, Ship T1

▪ **Validation results**

Table 40 presents the results from the validation comparison. The following statements can be concluded:

- The fuel consumption is predicted with surprising[27] accuracy for the case study Ship T1: with an absolute average error of 3.5% for ballast and 2.7% in laden, and standard error of 4.6% and 4.0% respectively.
- The above stated absolute average error in fuel consumption prediction is considerably less than the 9.9% and 8.3% absolute average error determined using the same dataset and performing a FFR regression analysis. These results are presented in Appendix D.
- The absolute average error in the SOPP model's prediction of brake power was 2.7% and 3.0% for ballast and laden, and 3.6% and 5.2% standard error respectively.
- Whilst the quantification of impacts due to time dependent performance changes appears to be low, the overall SOPP model provides a method with considered accuracy for predicting brake power and fuel consumption.

Table 40: Validation statistics using the SOPP model, Ship T1

	Resistance (kN)	**Power, Break (kW)**	**Fuel Consumption (t/day)**
	Ballast		
Number in Sample	205	205	455
Sum of residuals	3	1	-6
Standard Error %	0.0%	3.6%	4.6%
Max Error	20%	13.1%	24.3%
Average Absolute Error	3.7%	2.7%	3.5%
	Laden		
Number in Sample	202	202	403
Sum of residuals	-3	-3	-4
Standard Error %	0.0%	5.2%	4%
Max Error	26.8%	27.8%	17%
Average Absolute Error	3.8%	3.0%	2.7%

[27] *When considering the expected uncertainty in the input data and the assumptions made during model development. An uncertainty analysis is suggested for future work.*

CHAPTER SUMMARY

A Data Elaboration Process was described that allows for the calculation of brake power and resistance, using only data recorded in Ship Report (SR) operational data sets and data and information typically available for all ships. The Data Elaboration Process was shown to predict brake power for the case study ship with an average absolute error of 3.38% in ballast and 3.59% in laden.

A Resistance Regression Analysis was described presenting two output prediction equations for ship resistance (for ballast and laden), based on input values for RPM, draft, Beaufort Number and wind direction. The output prediction equations predict ship resistance with an average absolute error of 2.6% and 2.1%, standard error of 3.4% and 2.8%, and an R^2 value of 0.95 and 0.91 for the ballast and laden respectively: this is compared to the resistance calculated during the data elaboration process.

A Speed Regression Analysis was described presenting two output prediction equations for ship speed, again based on input values for RPM, draft, Beaufort Number and wind direction. The output prediction equations predict ship speed with an average absolute error within 3.5%, standard error within 4.5% and an R^2 value of 0.72: this is compared to ship speed recorded in each SR report.

A data normalisation process was described to identify the resistance components associated with the baseline resistance and operation away from the baseline conditions for RPM, draft, Beaufort Number and wind direction. The component of the normalised resistance that systematically increases over time were considered due to hull and propeller surface degradation and fouling.

A time dependent analysis was described to model the time dependent resistance change, assumed due to hull and propeller surface degradation and fouling. Including this modelled function in the SOPP model, it provided a prediction of fuel *consumption with an absolute average error of 3.5% for ballast and 2.7% for laden, and standard error of 4.6% and 4.0% respectively, for the case study ship. The absolute average error for the prediction of brake power was 2.7% and 3 % for ballast and laden, retrospectively, and standard error of 3.6% and 5.2%.*

The performance penalty due to hull and propeller degradation and fouling for the case study ship, was shown to be in the range of a 7% resistance, brake power and fuel consumption increase, compared to the sea trial performance.

Whilst further investigation is required to determine if the above prediction is a low estimate, the SOPP model provides a method for predicting total fuel consumption, brake power and resistance with considered. It also provides a method to identify performance contributions due to different operational conditions. Furthermore it is a solution that only requires input data and information that should be widely available for all ships.

The SOPP model is valuable for providing an insight into the operational performance of a ship and it should be possible to develop for most ships the world fleet. However, care should be taken when applying and interpreting the SOPP model results as the input data is expected to contain uncertainty and is representative of input data averaged over the period between data records used to construct the model (i.e. 24 hours). Thus it is applicability to SOPM at an instantaneous point in time or at a frequency lower than the collection of input data should be cautioned.

10. CASE STUDIES

CHAPTER INTRODUCTION

This chapter demonstrates how the analysis of Operating Profiles and the Ship Operational Performance Prediction (SOPP model) can be utilised to address the research aims, within the identified Operational Framework to improve ship energy efficiency. The utilisation demonstrations (case studies) are discussed in five chapter sections as follows:

10.1 Mapping of Ship Performance Parameters

10.1.1 Introduction

The case study examples presented in this section demonstrate how the developed SOPP model (Chapter 9) can be used for mapping different ship performance parameters. It should be emphasised that the developed SOPP model provides a method for ship performance mapping with the following attributes:

- Fast
- Simple
- Flexible

The developed SOPP model is fast, as once it has been developed, the prediction of performance parameters can be calculated instantaneously with a change in input values: the data elaboration, resistance regression analysis, normalisation and time dependent analysis only need to be carried out to update the model coefficients, not to utilise it. As only the input variables need to be changed, the prediction process is simple to use and results easy to interpret. Both these attributes are demonstrated in the case study presented in Section 10.3.

The SOPP model is flexible as it predicts the intermediate, model and extended outputs (given in Table 21 previously presented in Chapter 9 but shown again below) with a change in any or all input variables; within the limitation ranges of the model. It is noted that further flexibility is provided as a model output can be defined an input, and then the corresponding listed input(s) can be predicted: e.g. given a defined constant brake power, the RPM and hence speed in specified operating conditions can be predicted. Calculated examples will be shown in rest of this section. Another flexibility advantage of the SOPP model is that the prediction results (or a series of results with varying input conditions) can be provided in at least three formats, including:

- Graphically (as shown in the following sub-section examples)
- Tabulated
- Polynomials

The best format for a specific application can hence be selected.

Table 21: Input, Output variables for the SOPP model

Inputs Variables	**Intermediate Calculated Variables**	**Model Output Variables**	**Extended Output Variables**
RPM [calculated] **Average Draft at Mid Ship** [recorded in the SR record] **Beaufort Number** [recorded in the SR record] **Wind Direction** [recorded in the SR record] **Date/time** [recorded] **Build Date** [Ship information] **Dry Dock , hull and propeller maintenance Dates** [Ship information] **Load-Specific Fuel Oil curve** [Main engine documents]	**Resistance** [calculated] **Normalised Resistance** [calculated] **Resistance due to time dependent performance changes** [calculated]	**Ship Speed** [calculated] **Brake Power** [calculated] **Fuel Flow Rate** [calculated] **Carbon emissions** [calculated]	**Speed Loss** [calculated] **Power Increase** [calculated] **Added resistance due to the following , above the set baseline** [calculated]**:** **RPM** **Draft at midship** **Beaufort Number** **Wind Direction** **Time dependent performance changes (such as hull and propeller degradation and fouling)**

A limitation of the SOPP model for mapping applications, is the uncertainty in the performance prediction; thus it should not be used in an applications where the required level of accuracy is higher than expected from the SOPP model prediction (given in Sub-Section 9.7). An uncertainty and sensitivity analysis is recommended for future work to clarify model limitations. Nevertheless, if the uncertainty is acknowledged when interpreting results and considered acceptable, performance predictions and trends can be produced by the model, which, in the right presentation format, can be valuable for increasing awareness and knowledge about performance trends related to observational inputs (e.g. Beaufort Number). This provides an enabler towards increasing ship operational performance awareness and knowledge, hence addressing the aims of the Operational Framework presented in Chapter 5.

An additional limitation is that the input data used to construct the model is representative of averaged data typically over a 24 hour period. It may even be a mix of averaged and instantaneous data. Therefore it should be cautioned when using the model to predict ship performance at an instantaneous point in time or for a frequency less than that of the recorded input data.

The following sub-sections provide examples of mapping applications. The examples were selected so that the developed SOPP model can be compared with published performance trends.

10.1.2 Generalised Power Diagram Example

The generalised power diagram (GPD) was a focus of the work presented by (Telfer 1926) and (Hasselaar 2010); discussed in chapter Sub-section 2.4.5. The highlighted advantages of a GPD are that, if any two values out of ship speed, RPM and power are known, the other can be predicted. The advantages of using a GPD therefore extend to:

- If no torque meter is installed the recorded ship speed and RPM can be used to predict the power
- If a torque meter is installed, the measurements of RPM and power (with low uncertainty) can be used to predict a more accurate value for the ship speed.

However, these advantages can only be realised if the GPD is periodically calibrated for changes in wake fraction, and this is the limitation of the method.

The developed SOPP model provides a prediction of resistance and hence power and ship speed given an input RPM and slip conditions (i.e. due to draft, Beaufort Number and wind direction). Time is also included as an input variable, thus the prediction of ship performance at a time since build accounts for the changes in ship performance due to hull fouling (i.e. inclusive of the changes in wake fraction).

The GPD presented in Figure 58 was constructed by varying the RPM and Beaufort Number, and keeping the draft, wind direction and time constant. The ship speed, resistance and then brake power predictions were calculated as intermediate and model outputs to plot the figure.

The variables modelled in the SOPP model that affect slip, given the speed and RPM, are the draft, Beaufort Number, wind direction and time since the ship was built (considered indicative of hull and propeller degradation and fouling). Therefore, as these variables are kept constant except for the Beaufort Number, the constant slip lines seen on the GPD can be considered to represent each Beaufort Number. The constant conditions were: laden draft at 16 m, bow quartering seas, time equal to zero.

Two Recorded Points (RP) at different loads are shown in Figure 58 and these correspond two sets of RPM and speed values recorded in the sea trial data for the case study ship. Using the GPD to predict the brake power given the recorded RPM and speed and comparing it to the recorded brake power; the error was 3.8% for the RP close to 13 knots, and 0.35% for the other.

The Beaufort Number indicated for the two RP’s using the GPD is around BN2. It is noted in the Sea Trial Document that the trials were carried out in a moderate breeze and slight sea state; therefore the predicted BN2 does not seem unreasonable. The power used for the comparison with the RP’s was the uncorrected power values: i.e. representative of the weather conditions experienced.

Many GPD's could be plot varying each of the input conditions, including time.

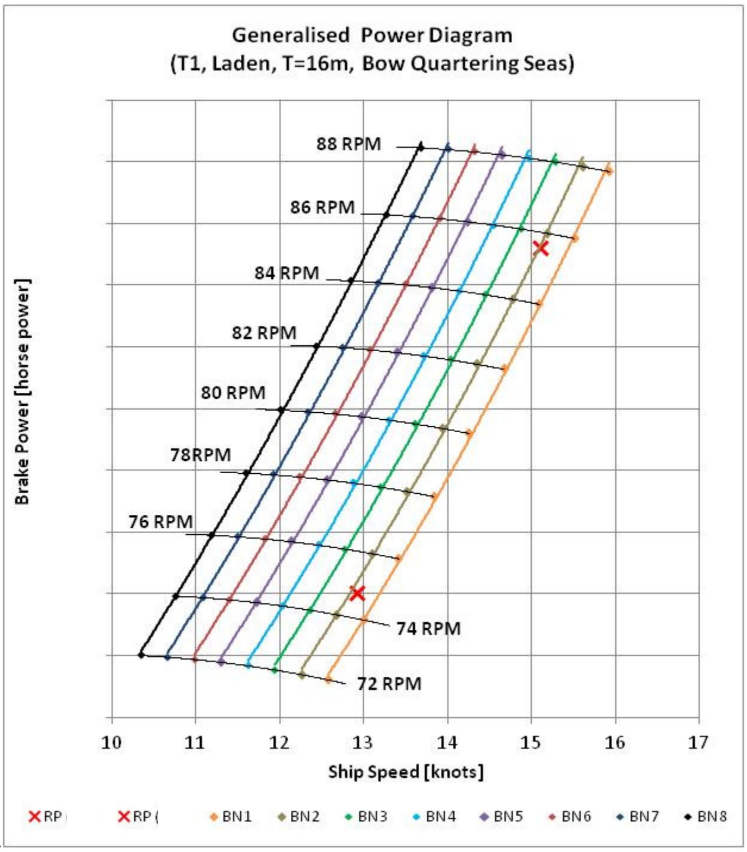


Figure 58: GPD general trends example, Ship T1

Note: the power axis is not shown to remove sensitivity of data as the SOPP model has been developed for a specific case study ship

10.1.3 Speed Loss Example

Sub-section 2.4.3 discussed performance changes due to added resistance determined via direct measurements; (Townsin & Kwon 1982), (Aertssen 1963) and (Aertssen 1957; Bhattacharyya 1978). In the references mentioned the change in ship performance due to added resistance was presented as speed loss.

The SOPP model was used to determine the speed loss at constant power: Figure 59. The most evident observation is that the SOPP model has not captured the exponential increase in speed loss above Beaufort Number 5. It instead presents a linear relationship. The following comments can be made regarding the graph on the left in Figure 59:

- Up to Beaufort Numbers 4 to 5 the speed loss is around 7% to 11%. This is higher than the presented speed loss by (Townsin & Kwon 1982) shown in Figure 61 for a large tanker; and by (Aertssen 1963) and (Aertssen 1957; Bhattacharyya 1978) for container ships.
- Above Beaufort Number 5, until around Beaufort Number 7, the speed loss presented by (Townsin & Kwon 1982), (Aertssen 1963) and (Aertssen 1957; Bhattacharyya 1978) becomes exponential: above 20%. However for the SOPP model the speed loss is around 13% to 16% and is evidently underestimated at higher Beaufort Numbers.
- The over estimation up to Beaufort Number 5 and under estimation above Beaufort Number 5 are most likely due to the liner relationship derived from the least squares method used for the multi-linear regression analysis.

The correlation plots analysed during the exploratory analysis (Sub-section 9.3.2) prior to the regression analysis, did not demonstrate a correlation trend significantly different from linear between Beaufort Number and the other variables. However, in light of this model application, it is suggested that future improvements of the SOPP model include a transformation on the Beaufort Number in either or both the resistance or speed regression analyses, to better represent the practical observations.

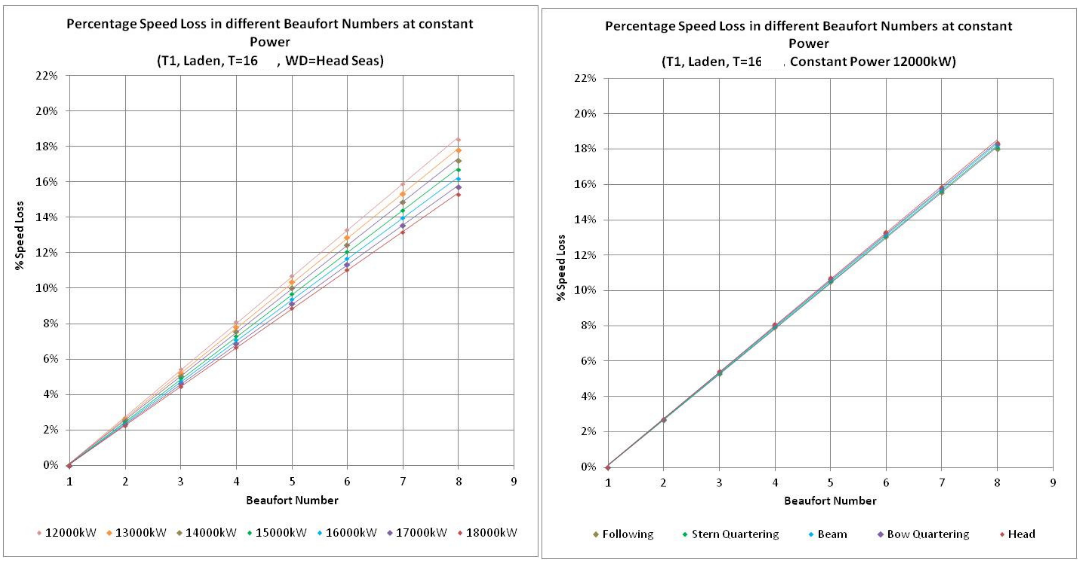


Figure 59: Percentage speed loss due to Beaufort Number and change in wind direction

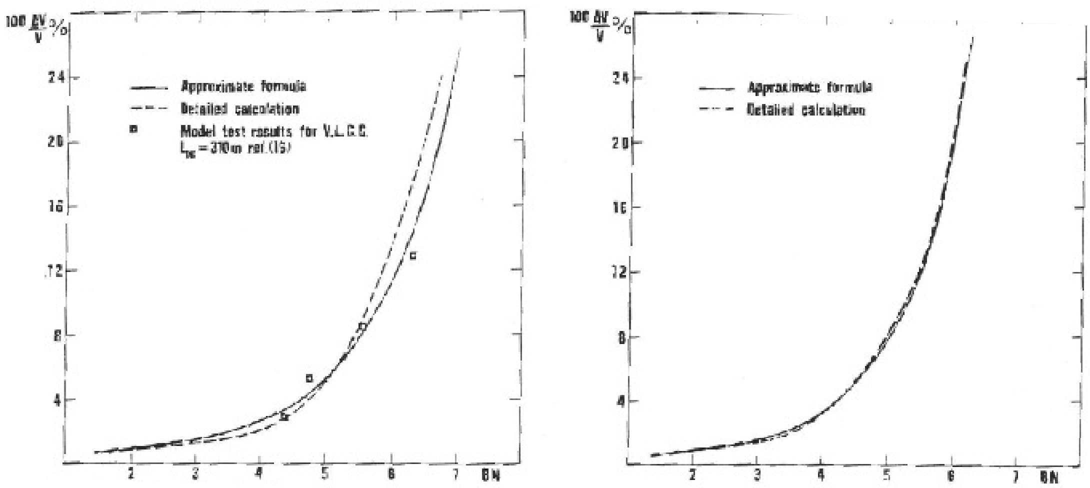


Figure 60: (left) Large Tanker, Laden, Vol Dis = 350000m^3, Fn=0.15, C$_B$=0.84, L$_{BP}$=336m (Right) Small Tanker, Laden, Vol Dis = 11700m^3, Fn=0.15, C$_B$=0.84, L$_{BP}$=233m (Townsin & Kwon 1982)

The graph on the right in Figure 59 demonstrates the impact of different wind directions at constant power. It appears that the impact due to a change in wind direction at increasing Beaufort Number has not been captured in the SOPP model. This can be seen in comparison with the results presented in (Aertssen 1957; Bhattacharyya 1978), where the speed loss away from head seas is much less than for head seas, and even negative for following seas up to around Beaufort Number 4 (when the impact of ship motions will become more predominant). Not being able to capture the change speed loss in different sea directions is a limitation of the developed SOPP. Again a transformation could be applied to the wind direction during future improvements of the SOPP model. However, as the change in wind direction has a relatively small impact on ship performance comparative to the other input variables, detecting the non linear relationship (achieved via transformations) may be limited by the capabilities of multi-linear regression.

10.1.4 Resistance Increase Example

In addition to speed loss, an increase in resistance is also of interest as a performance indicator. The percentage increase in resistance due to hull and propeller surface degradation and fouling, over the sea trial baseline predicted by the SOPP model, has previously been presented in chapter Section 9.7.

(Belibassakis 2009) presents the analysis of measured continuous monitoring data for an Aframax tanker. The percentage of additional resistance experienced was given above the calm water conditions (BN1) at each given speed, in the range of 11.5 to 15.5 knots: seen on the right in Figure 61. A comparative graph was produced using the SOPP model: seen on the left in Figure 61.

Firstly, the SOPP presents a constant percentage increase in resistance at a given speed, with an increase in Beaufort Number. The results by (Belibassakis 2009) indicate that the percentage increase in resistance is much greater at Beaufort Numbers 6 and above: in line with the results presented for speed loss previously. However, it should be cautioned that a direct comparison between the two graphs in Figure 61 cannot be made. This is because the results presented by (Belibassakis 2009) are based on Beaufort Number derived from measured wind speed: whereas, the Beaufort Number recorded in the Ship Report (SR) datasets for Ship T1 is a subjective observation; which may or may not have been derived from relative wind speed. Thus it may be possible that SOPP model captures performance changes in line with practical observations: rather than a change in measured wind speed, which is potentially more difficult to observe.

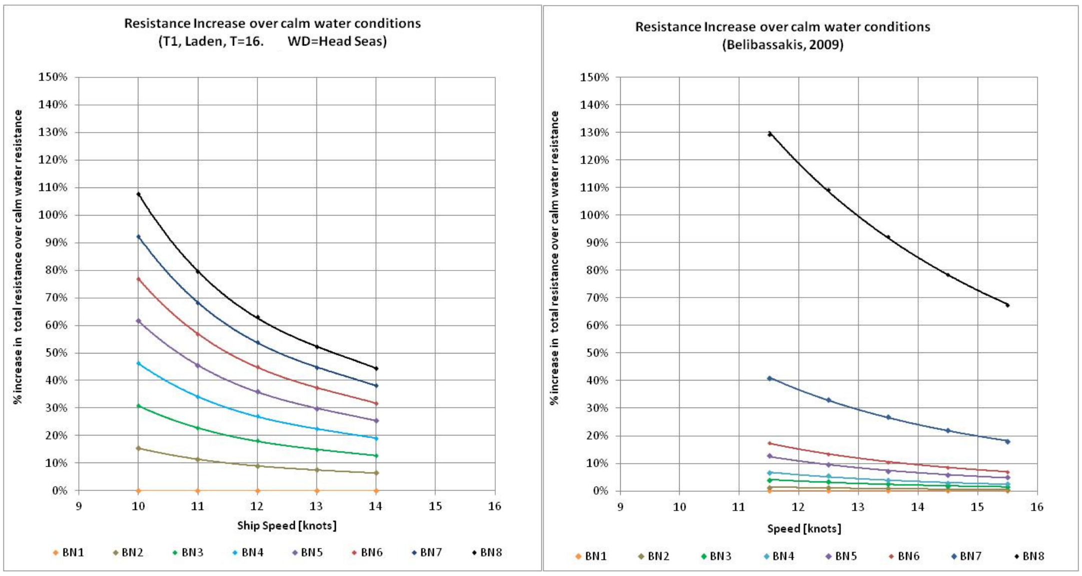


Figure 61: The relationship between resistance and ship speed at different Beaufort Numbers, results of the study presented in (Belibassakis 2009)

10.2 Ship Operational Performance Monitoring

It is the intention, that with further refinement and testing, the SOPP model could be developed into a Ship Operational Performance Monitoring (SOPM) system, widely usable within the industry. The real time aspect will be limited to the frequency of data input (i.e. typically 24 hours for SR's). For longer term analysis (i.e. for identification of hull and propeller surface degradation and maintenance) a sensitivity analysis would first be required to determine how many data entries' are required before a performance change can be determined, and not considered to be due to variation because of data and modelling uncertainty.

To achieve a SOPM system, the SOPP model would require programming into an automated software package with a designed interface. The functionality of such a SOPM system is described Table 41:

Table 41: Functions of a Ship Operational Performance Monitoring System

At SOPM Set Up		
Process	**Function**	**Comments**
1) User Inputs	Ship principal dimensions and information	In addition to principal dimensions, this includes dry docking dates and details, hull coating type, installation of energy efficient technologies, key dates of events that may affect ship performance.
	Historic ship report data	Imported in a standardised excel or csv file (i.e. in the correct format under standardised column headings).
	Power-speed curve	From the Sea Trial Document
	Average draft at midship at 0.5 intervals and the corresponding: L_{wL}, LCB, C_B, C_p, C_w, C_M and Δ.	From the Trim and Stability Booklet. For more details refer to Sub-section 9.2.3
	Recorded Thrust and Torque values for a given trial condition	From the Propeller Document For more details refer to chapter Section 7.1
	Specific Fuel Oil (recorded in the SR), if not the Load-Specific Fuel Oil curve for the main engine	Preferably from operational data, if not shop trials, if not the main engine project guide
2) System processes	Data processing	See Chapter 7.
	Operational Profile Analysis	See Chapter 8
	Data Elaboration Process	See Section 9.2
	Regression Analysis	See Section 9.3
	Data Normalisation	See Section 9.5
	Time dependent analysis	See Section 9.6
3) System outputs	Summary report on the SOPP model set up and validation results	
	Summary of ship operating profile	Past and current operating profiles. Averaged per month/year/over a specified interval

	Summary of ship operational performance trends	See chapter Section 10.1.
	Summary of ship operational performance, including identification of predicted performance loss due to hull fouling and degradation.	Past and current performance. Averaged per month/year/over a specified interval
After SOPM Set Up, Use in real time		
Process	**Function**	**Comments**
1) User Inputs	Continual data entry of ship reports	Manual entry or automated. As an individual SR record or batch of SR records.
2) System Functions	Typical functions of any computerised system, such as; back up, restore, user preferences.	
	Automated, or on request of the user: run the development of a new SOPP model based on the updated SR dataset, and produce the desired summary reports.	
	Automated, or on request of the user: run the analysis of operating profiles and produce the desired summary reports.	
	Alert if a large error is detected between recorded and predicted data	
	Predict ship performance for specified ship operational conditions	An example is given in chapter Section 10.3.
	Perform a benefit analysis for given scenarios (for a life cycle or a specified time period)	An example is given in chapter Section 10.4.
	Calculation and summary of any selected performance values, indices or indicators, over the defined time period of interest.	

The SOPM should provide an option to set up a profile for many ships within one System so that the operational performance of two or more ships can be compared; or combined to determine group or fleet average performance. This will also be useful for feedback reports for distribution to the relevant internal stakeholders: i.e. Business, Commercial, Ship and Technical Management and seafarers.

10.3 Ship Operational Performance Prediction

Given an input scenario, the SOPP model can be used to predict the performance of the specific ship that it has been developed for. The performance can be presented in terms of resistance, power, fuel consumption, and carbon emissions. The fuel cost can also be deduced from the fuel consumption if the price per tonne of fuel is known, or estimated. This prediction application is beneficial for estimating expected performance for a given reporting period, or on a route where the input operational conditions are known. Input variables that can be changed by operational practices (i.e. speed, Beaufort Number if the route is changed) can then be considered with an optimisation for best performance outputs. The example case study in this section demonstrates a simple interface to perform a prediction estimate.

10.3.1 Example Interface and Application

The operational input conditions used in this example were taken from a SR record randomly selected out of the sample of Ship Report (SR) records for the case study Ship T1, that correspond to operation in laden and with a power and RPM value recorded. The input operational conditions are shown in Table 42.

Table 42: SR record values, selected for example 1 to test within the SOPP interface, Ship T1

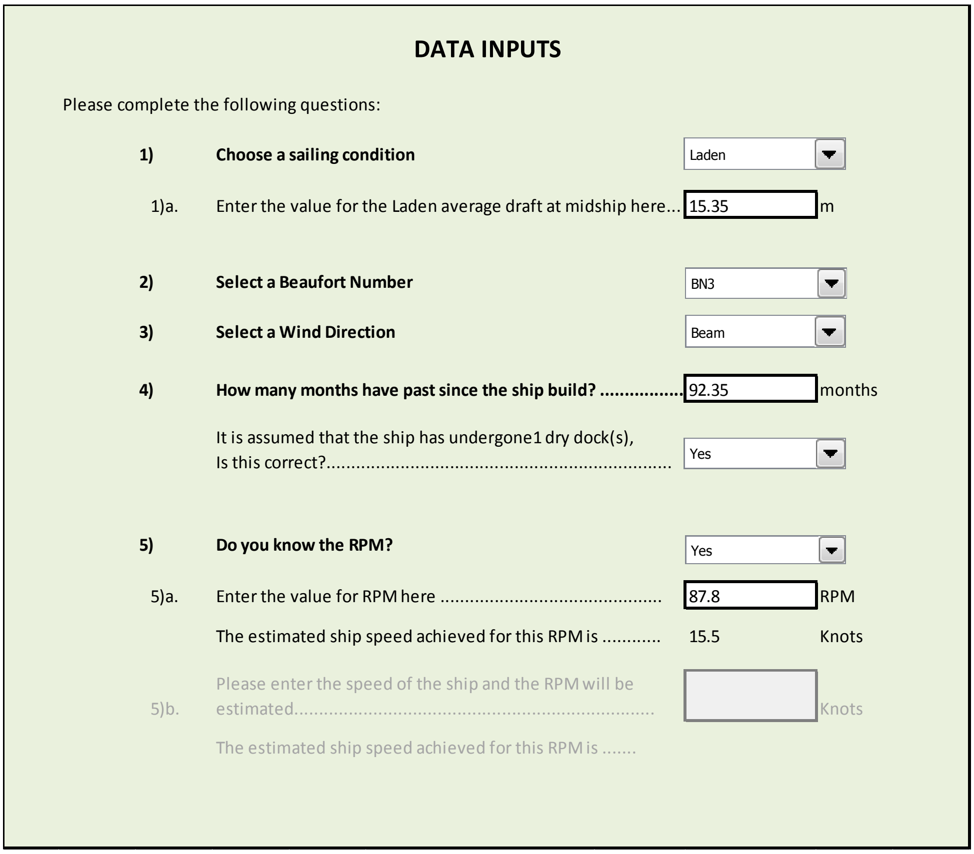
Information		
Report ID	T1_V235_R2184	
Passage Type	Laden	
Input variables		
Month Since Build	92.35	months
Average Draft at Midship	15.35	meters
RPM (calculated)	87	
Beaufort Number (recorded)	3	
Wind Direction (recorded)	90	degrees
Validation variables		
Fuel Flow Rate (recorded)	64	tonnes per day
Ship Speed (recorded)	15.5	knots
RPM (recorded)	88	
Brake Power (recorded)	14280	Kilowatts

Approximate values shown for validation variables

The Input interface is shown in Figure 62. The following key points are highlighted:

- The time since build is used to estimate the number of dry docks that the ship has undergone: where it is assumed that a dry docking interval is every 58 months (based on the information provided for case study Ship T1)
- Part 5a (the preferred input compared to 5b) allows for an RPM value to be entered and then the ship speed is calculated based on the input conditions and the speed prediction equations (see Section 9.4).
- Part 5b allows for the speed to be entered and RPM to be calculated based on the input conditions and using the speed prediction equations rearranged.

In Figure 62 the calculated speed can be seen to be the same as the recorded ship speed given in Table 42, when rounded to 1 decimal place.



DATA INPUTS

Please complete the following questions:

1) **Choose a sailing condition** Laden

1)a. Enter the value for the Laden average draft at midship here... 15.35 m

2) **Select a Beaufort Number** BN3

3) **Select a Wind Direction** Beam

4) **How many months have past since the ship build? ....** 92.35 months

It is assumed that the ship has undergone1 dry dock(s),
Is this correct?.. Yes

5) **Do you know the RPM?** Yes

5)a. Enter the value for RPM here .... 87.8 RPM

The estimated ship speed achieved for this RPM is .... 15.5 Knots

5)b. Please enter the speed of the ship and the RPM will be estimated.. Knots

The estimated ship speed achieved for this RPM is ....

Figure 62: SOPP input interface, example 1, Ship T1

INFORMATION OUTPUTS

1) Ship performance for the input operational condition:

Input Operational conditions: RPM = 87.8, Ship Speed (knots) =15.5 , Time Since build (months) =92.35 , BN = 3 , Wind Direction = 90 , Draft at midship (m) = 15.35

Resistance	**1342**	**kN**
Break Power	**14120**	**kW**
Fuel Consumption	**63.9**	**tonnes per day**
Carbon Emissions	**199**	**tonnes of CO2 per day**

2) Calm water [no hull surface fouling and degradation] baseline performance :

Calm water baseline input conditions: RPM = 87.8, Ship Speed (knots) =15.5 , Time Since build (months) =0 , BN = 0 , Wind Direction = 0 , Draft at midship (m) = 15.35

Resistance	1294	kN
Break Power	12681	kW
Fuel Consumption	57.4	tonnes per day
Carbon Emissions	179	tonnes of CO_2 per day

3)a. Components of additional resistance due to operation above the calm water [no hull surface fouling and degradation] condition (i.e. comparing part 1 to part 2):

Resistance (Calm water and no hull surface fouling and degradation):	*1294*	*kN*
Additional Resistance (due to operating in a Beaufort Number different from BN1):	*50.26*	*kN*
Additional resistance (due to operating in a wind direction different from head seas):	*-13.20*	*kN*
Additional resistance (due to time dependent hull surface degradation and fouling):	*10.52*	*kN*
Gives:		
Ship performance for the input operational condition:	**1342**	**kN**

3)b. Components of additional resistance [part 3)a.] as a percentage increase above the calm water conditions:

Additional Resistance (due to operating in a Beaufort Number different from BN1):	3.88%
Additional resistance (due to operating in a wind direction different from head seas):	-1.02%
Additional resistance (due to time dependent hull surface degradation and fouling):	0.81%

3)c. Performance changes due to the components of additional resistance [part 3)a.]:

	Brake Power	
Resistance (Calm water and no hull surface fouling and degradation):	12681	kW
Additional Resistance (due to operating in a Beaufort Number different from BN1):	492	kW
Additional resistance (due to operating in a wind direction different from head seas):	-129	kW
Additional resistance (due to time dependent hull surface degradation and fouling):	103	kW
	Fuel Consumption	
Resistance (Calm water and no hull surface fouling and degradation):	57.4	tonnes per day
Additional Resistance (due to operating in a Beaufort Number different from BN1):	2.2	tonnes per day
Additional resistance (due to operating in a wind direction different from head seas):	-0.6	tonnes per day
Additional resistance (due to time dependent hull surface degradation and fouling):	0.5	tonnes per day
	Carbon Emissions	
Resistance (Calm water and no hull surface fouling and degradation):	179	tonnes of CO_2 per day
Additional Resistance (due to operating in a Beaufort Number different from BN1):	7	tonnes of CO_2 per day
Additional resistance (due to operating in a wind direction different from head seas):	-2	tonnes of CO_2 per day
Additional resistance (due to time dependent hull surface degradation and fouling):	1	tonnes of CO_2 per day

Figure 63: SOPP output interface, example 1, Ship T1

The output interface is shown in Figure 63. Comparing the predicted ship performance (Figure 63) to recorded the values (Table 42) the error in fuel consumption prediction was 0.3%, and 1.1% for brake power. In further refinements of the SOPP interface, confidence intervals should be provided with the performance predictions.

10.4 Support for Strategic Operational Decisions

As suggested as a function of a SOPM system, the SOPP model could be used to perform a benefit analysis related to the implementation of different operational decisions.

Whilst a benefit analysis could be carried out for any specified time period, a Life Cycle Analysis (LCA) has been selected for the example case studies described in this section. The lifetime benefit of performing an in-water hull cleaning between each dry dock was selected as the operational decision to investigate.

It should be stressed that this example presents the functionality of how the SOPP model could be used to support operational decisions: thus the principals of how it could be applied to other operational decision scenarios are demonstrated, rather than provision of an accurate prediction. Quantification of the uncertainty in the input data, modelling and LCA assumptions would need to be understood before an accurate prediction could be made. This is an area for future work.

10.4.1 Case Study Description

Two Case Studies (CS) are used in this example. The scenarios for each CS are as follows:

- CS1 determines the LCA performance based on assumed typical hull maintenance practice: i.e. dry docking carried out inline with class surveys.
- CS2 determines the LCA performance based typical hull maintenance practice as in CS1, but with an in-water hull cleaning carried out between each dry dock.

For both case studies the LCA is assumed to be over a 26 year ship life. The in-water hull cleaning scenario was selected for the example as it was considered that a ship would not be put into dry dock before the required survey interval unless extreme hull and propeller surface fouling and degradation was identified. This is because dry docking is expensive and requires the ship to be out of service. However, considerations such as the ports that will allow in-water hull cleaning to take place would need to be taken into account (as discussed in Sub-section 2.4.3).

LCA in itself is a comprehensive area of research; including the mapping of historical trends and forecasting future scenarios. Therefore, to provide the example case studies in this section, the assumptions given in Table 43 were made.

Table 43: LCA, benefit analysis, case study assumptions

Assumption value	Why an assumption is required	Assumptions supported by	Assumed values
Fuel cost	The price of bunker oil fluctuates over time and between ports.	The estimated high, medium and low values of the Bunker World Index (a weighted average of the price at the main ports) over years 2014 and 2012 for IFO180 fuel.	High estimate: US$850 per tonne Medium Estimate: US $570 per tonne Low Estimate: US$290 per tonne
Beaufort Number and Wind direction	The weather and sea conditions fluctuate over time.	Global wave statistics (British Maritime Technology Ltd. n.d.) and other weather sources could be used. However, for simplicity, the average Beaufort Number and wind direction recorded in the SR dataset for Ship T1 were used.	Beaufort Number = 4 Wind direction = Beam seas
Average Draft and Passage type	Depends on the time spent in port or sailing, sailing in ballast or laden, and the amount of cargo or ballast taken onboard, amongst other items.	Similar to the operating profiles presented in Chapter 8, the passage type operating profile was analyses for case study Ship T1. The average draft for the ballast and laden sailing conditions was then found.	Passage type distribution: 37.1 % of the time in port 31.3% of the time sailing in ballast 31.6% of the time sailing laden Draft in Laden = 16m Draft in ballast = 8m
RPM and ship Speed	Vary dependent on operating conditions, contract requirements, and operational decisions	The average RPM recorded in the SR data set for Ship T1 was determined for ballast and laden. The speed was calculated from the RPM but was found to be very close to the average speeds from the SR data set: 14.5 knots laden, 14.42 knots ballast.	RPM laden = 84.4 RPM ballast = 77.07 Speed Laden (calculated) = 14.28 knots Speed Ballast (calculated) = 14.34 knots

Maximum resistance attained due to time dependent performance changes (Rmax)	Depends on previous maintenance, the hull surface condition, the amount of fouling build up.	This value is required to calculate the time dependent performance change due to hull degradation and fouling: see Sub-section 9.6.2. Without performing a number of different case studies and applications of the SOPP model to determine how the Rmax value varies, it was considered constant to the values found for case study Ship T1.	Maintenance parts following new build and a full blast: Rmax = 140kN for laden and 166kN for ballast. Maintenance parts following any regular dry dock where a full blast has not been carried out: Rmax= 53 kN for laden, and 30 kN for ballast.
Hull Maintenance intervals	Varies with survey requirements and the scheduling of the ship.	The maintenance interval for case study Ship T1 (Section 9.6) was used and kept constant. The assumption of this interval was supported by results presented in chapter Section 8.5 for the average dry docking period for the case study tankers (being 4.7 years, corresponding to 56.5 months). Furthermore, a 5 year dry docking period was assumed for the analysis carried out in the Third IMO GHG study (Smith et al. 2014).	Dry docking and hence hull maintenance interval = 58 months, where hull spot repairs and painting are carried out along with hull cleaning and a painting. A full blast carried out at the dry dock around 15 years of operation.
Savings achieved from hull maintenance	Varies with: hull condition on entry to the dry dock, the type and quality of cleaning, the type of surface finish (paint type and application quality) applied before dry dock departure	Without performing a number of different case studies and applications of the SOPP model to determine how performance savings vary, the savings were considered constant to those found in chapter Sub-section 9.6.3, for case study ship T1. A saving was assumed to be gained from in-water hull cleaning, rather than a loss due to hull surface damage from poor maintenance. The saving selected for in-water hull cleaning was assumed half of the saving achieved during dry docked.	Savings are given as a percentage reduction in the resistance only due to time dependent performance changes (i.e. not including the baseline resistance). Savings Dry dock, Laden: 31.6% Dry dock, Ballast: 16.9% In water hull cleaning, Laden: 15.8% In water hull cleaning, Ballast: 8.4% Full Blast, Laden & Ballast: 80%
Ship Life	Varies with the ships condition and ship and the economic viability of the ship and company	The assumptions was based on (MAN Diesel & Turbo 2009)	Average life of a tanker ship: 26 years.

Summarising from the assumptions given in Table 43, the operational baseline input conditions used for the example case studies are shown in Table 44.

Table 44: Operational baseline for example case studies

	Ballast	Laden
RPM	84	77
Average draft at midship	16	8
Beaufort Number	4	4
Wind Direction	90	90
Time	Changing with time	Changing with time

10.4.2 Case Study Results

The case study results are demonstrated by first presenting the LCA performance prediction for CS1, then for CS2. A comparison is then made between CS1 and CS2 to determine the benefit of performing an intermediate in-water hull clean.

▪ CS1 LCA Performance Prediction Results

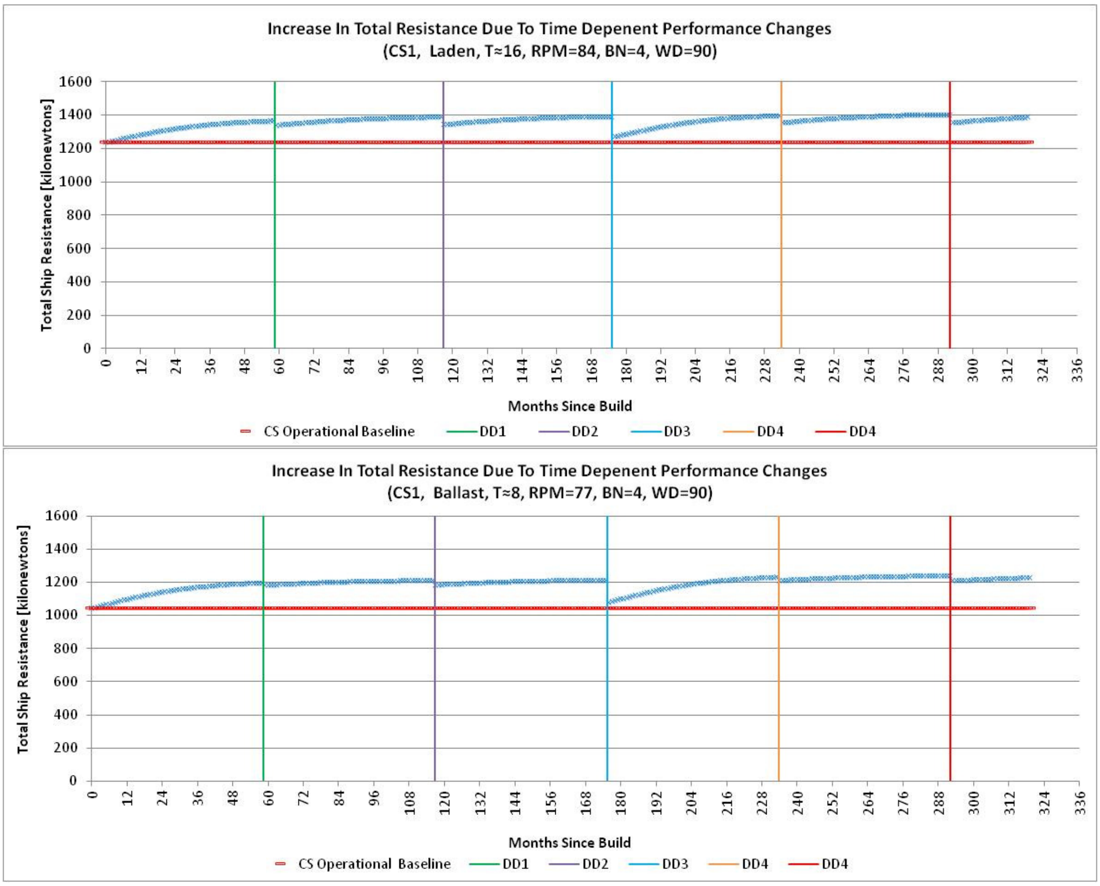


Figure 64: LCA CS1 results for total ship resistance, Ship T1

Figure 64 demonstrates the calculated total ship resistance for the input case study operating conditions. The operational baseline (Table 44) is shown in the figure, where the resistance seen above the baseline is considered due to time dependent performance changes: i.e. hull and propeller degradation and fouling. The faster rate of fouling increase can be seen directly after build and after the full blast. The rate of increase is slower after a dry dock where only spot repairs were carried out. The impact of maintenance carried out during dry docking is shown to have a greater impact in the laden condition than in ballast. This is considered because there is a larger underwater surface in laden and thus the impacts of improving surface roughness has a greater impact on the ship's frictional resistance.

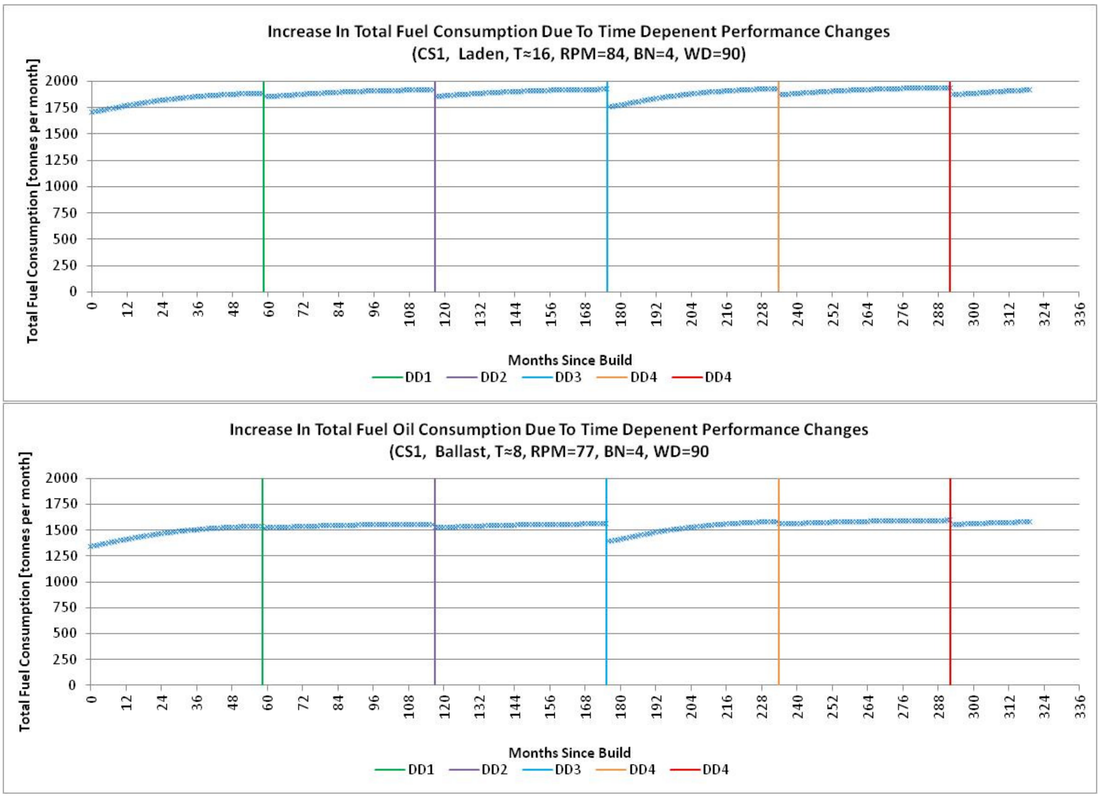


Figure 65: LCA CS1 results for fuel consumption, Ship T1

Figure 65 demonstrates the predicted total fuel consumption per month[28].

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[28] *Calculated by computng resistance (Figure 64) to brake power, to total fuel consumption per day. Then multiply by 30 to obtain the predicted total fuel consumption per month.*

Multiplying the total fuel consumption (Figure 65) by the three fuel price scenarios (see Table 43), Figure 66 demonstrates the predicted fuel cost per month. As expected, the cost savings are emphasised with a higher fuel cost.

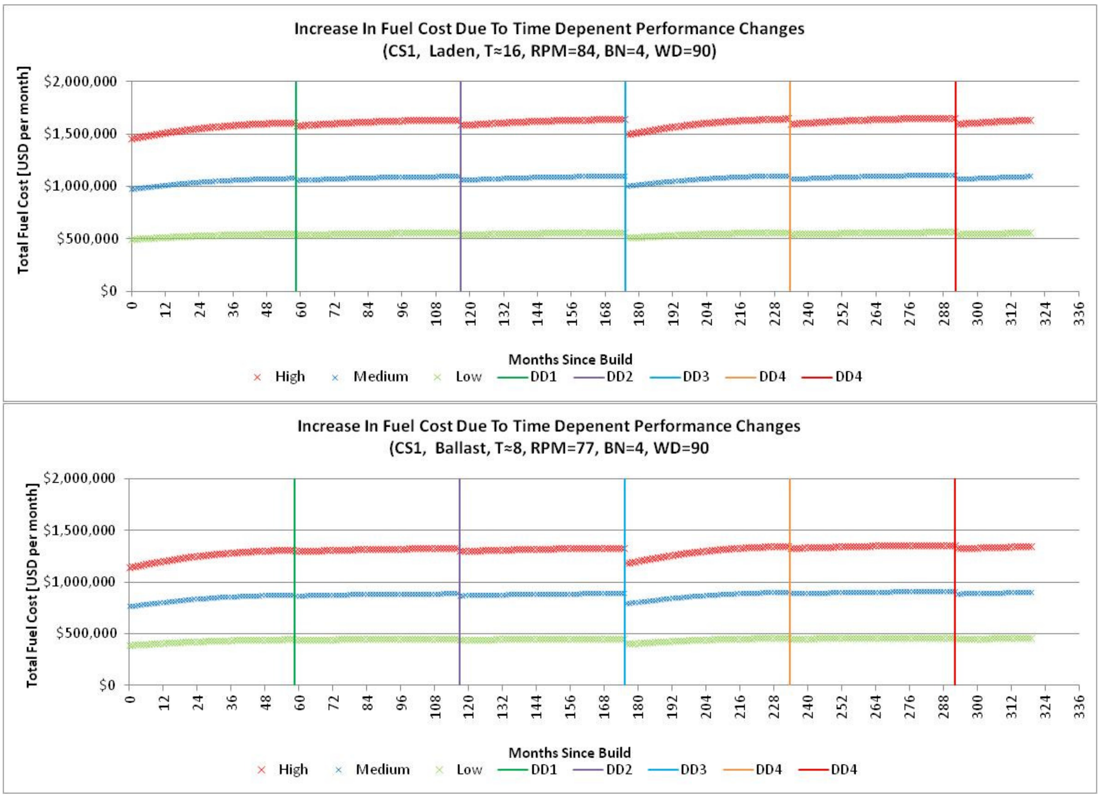


Figure 66: LCA CS1 results for fuel cost, Ship T1

A summary of CS1 results are given in Figure 67. The totals at the top of the figure are the predictions if 100% of the time was spent sailing in ballast and laden. These totals are then multiplied by the proportional percentage of time spent sailing in ballast and laden each year (refer to Section 8.2); before being summed to produce the final prediction for the ship's life.

It is predicted that for CS1 approximately 345,000 tonnes of HFO will be consumed by the main engine for Ship T1 over the specific LCA for the CS scenario. This corresponds to approximately 1 million tonnes of CO_2 emissions. There is also a difference of nearly $200 million between the different fuel cost scenarios (based on very crude assumptions). The results will be discussed further during the comparison of CS1 and CS2 at the end of this sub-section.

Dry Dock Interval: every 58 months
Blast in Month: 234 (During Dry Dock 3)

		Laden	Ballast	Port
Assumeing operation in the Laden/ballast for the full duration	Total Fuel Consumption	603449	492835	-
	Total Fuel Cost (Low)	$175,000,180	$142,922,233	-
	Total Fuel Cost (Medium)	$343,965,870	$280,916,113	-
	Total Fuel Cost (High)	$512,931,561	$418,909,993	-
	Total Carbon Emissions	1879381	1534886	-

Calculated for the following average operational conditions:

	Laden	Ballast	Port	
RPM	84	77	-	
Draft	16	8	-	meters
Beaufort Number	4	4	-	
Wind Direction	90	90	-	
Speed (calculated)	14.28	14.34	-	knots

Percentage of time spent in each operational mode of operation:

Laden	Ballast	Port
32%	31%	37%

		Laden	Ballast	Port
Assumeing operation in the Laden and ballast for the average percentage of time	Total Fuel Consumption	190690	154257	-
	Total Fuel Cost (Low)	$55,300,057	$44,734,659	-
	Total Fuel Cost (Medium)	$108,693,215	$87,926,743	-
	Total Fuel Cost (High)	$162,086,373	$131,118,828	-
	Total Carbon Emissions	593884	480419	-

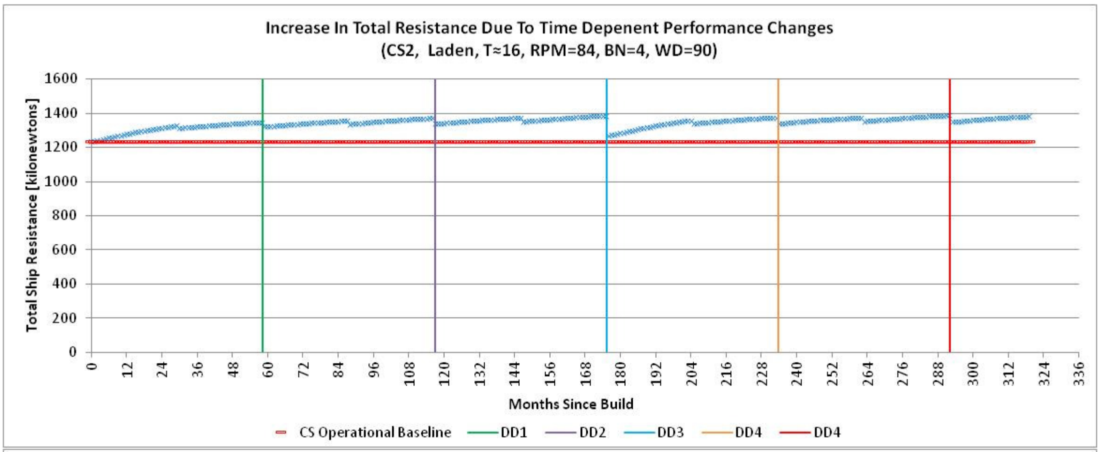
Total for the ship's life

Total Fuel Consumption	**344947**
Total Fuel Cost (Low)	**$100,034,716**
Total Fuel Cost (Medium)	**$196,619,958**
Total Fuel Cost (High)	**$293,205,201**
Total Carbon Emissions	**1074304**

Figure 67: Summary of results for life cycle case study 1, Ship T1

▪ CS2 LCA Performance Prediction Results

Figure 68, Figure 69 and Figure 70 demonstrate the same format of results as given for CS1, but with the addition of an in-water hull clean carried out midway between each dry dock. Figure 71 again presents a summary of the totalled results.



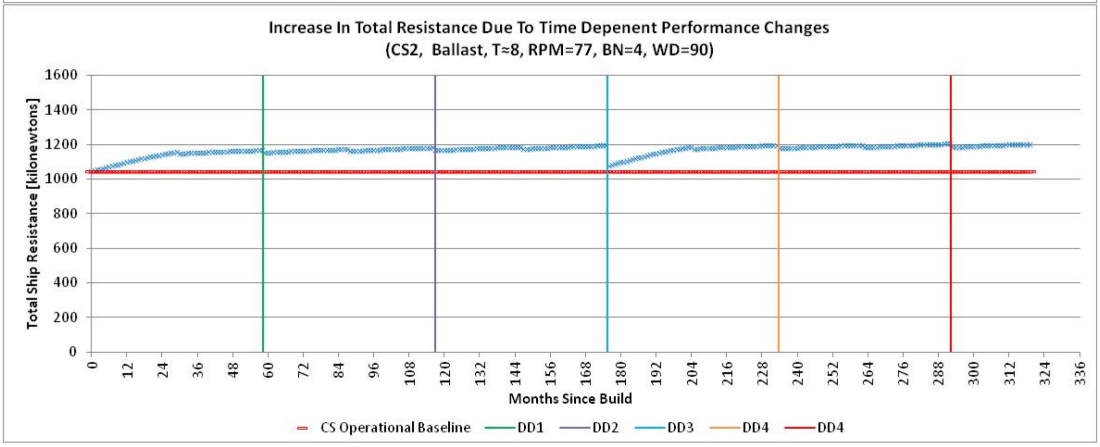


Figure 68: LCA CS2 results for total ship resistance, Ship T1

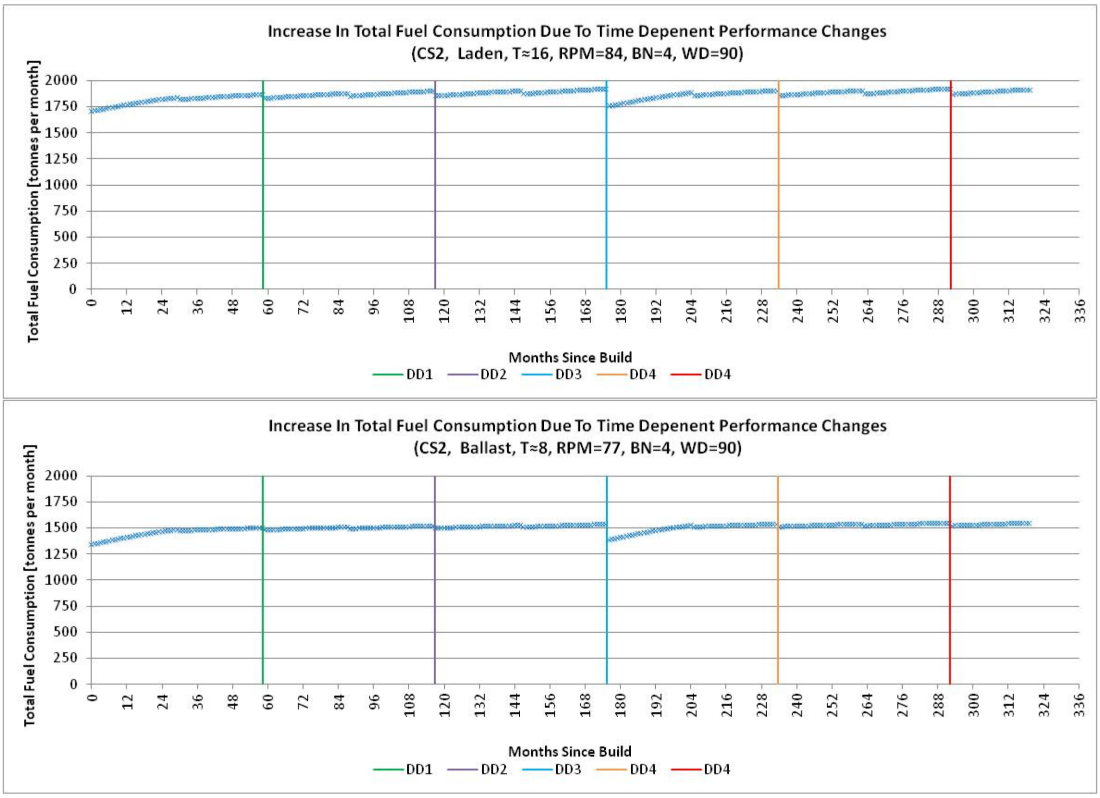


Figure 69: LCA CS2 results for fuel consumption, Ship T1

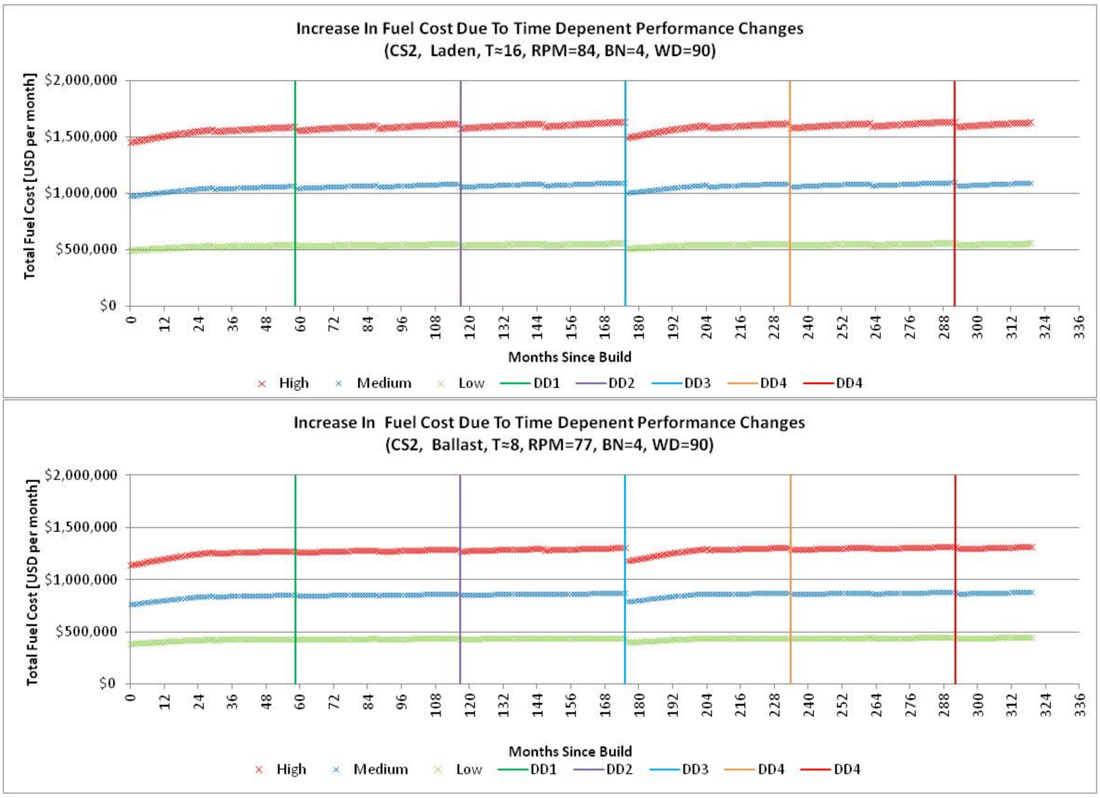


Figure 70: LCA CS2 results for fuel cost, Ship T1

Dry Dock Interval:	every	58.43	
Cleaning Interval:	every	29.22	(Between Dry Docks)
Blast in Month:		234	(During Dry Dock 3)

Assumeing operation in the Laden/ballast for the full duration

	Laden	**Ballast**	**Port**	
Total Fuel Consumption	589000	482683	-	
Total Fuel Cost (Low)	$170,810,120	$139,978,049	-	
Total Fuel Cost (Medium)	$335,730,236	$275,129,269	-	
Total Fuel Cost (High)	$500,650,352	$410,280,489	-	
Total Carbon Emissions	1834383	1503268	-	
Calculated for the following average operational conditions:				
RPM	84	77	-	
Draft	16	8	-	meters
Beaufort Number	4	4	-	
Wind Direction	90	90	-	
Speed (Calculated)	14.28	14.34	-	knots
Percentage of time spent in each operational mode of operation:				
	32%	31%	37%	

Assumeing operation in the Laden and ballast for the average percentage of time

Proportion of Total:			
Total Fuel Consumption	186124	151080	-
Total Fuel Cost (Low)	$53,975,998	$43,813,129	-
Total Fuel Cost (Medium)	$106,090,755	$86,115,461	-
Total Fuel Cost (High)	$158,205,511	$128,417,793	-
Total Carbon Emissions	579665	470523	-

Total for the ship's life	
Total Fuel Consumption	337204
Total Fuel Cost (Low)	$97,789,127
Total Fuel Cost (Medium)	$192,206,216
Total Fuel Cost (High)	$286,623,304
Total Carbon Emissions	1050188

Figure 71: Summary of results for life cycle case study 2, Ship T1

Figure 71 demonstrates that it is predicted for CS2 that approximately 337,000 tonnes of HFO will be consumed by the main engine for Ship T1 over the specific LCA for the CS scenario. This corresponds to approximately 1 million tonnes of CO_2 emissions. Again there is also a difference of nearly $200 million between the different fuel cost scenarios (based on very crude assumptions).

▪ Comparison and Discussion of CS examples

A comparison between the values of CS1 and CS2 are shown in Table 45. The saving from performing in-water hull cleaning is in the range of $1.4 million and $4 million over the life of the ship, for the low and high fuel cost scenarios respectively. If the cost of in water hull cleaning is in the range of $20,000 to $30,000, it can be considered that there is a financial benefit to implementing in-water hull cleaning. For each fuel scenario the reduction translates to a 1.4% saving. However, it should be noted that many assumptions were made to demonstrate this saving and it cannot be assumed accurate.

Other practical consideration to consider when deciding whether or not to implement in-water hull cleaning include; time required out of operation to perform the maintenance; the risk of damage to the hull coating system, split incentives. Another practical consideration is the importance the company places on the reduction of carbon emissions. Acknowledgement that the emission of 15,140 tonnes of CO_2 could be averted may further encourage the decision to perform in-water hull cleaning, even if the cost savings are not as significant.

Table 45: Comparison of life cycle case study fuel cost, Ship T1

	Total for the ship's life		
	Case Study 1	**Case Study 2**	
Total Fuel Consumption	344947	340086	Tonnes of HFO
Total Fuel Cost (Low)	$100,034,716	$98,624,856	
Total Fuel Cost (Medium)	$196,619,958	$193,848,856	
Total Fuel Cost (High)	$293,205,201	$289,072,855	
Total Carbon Emissions	1074304	1059163	Tonnes of CO_2
	Life time Savings achieved (comparison)	**% saving compared to CS1 total**	
Total Fuel Consumption	4862	1.41%	
Total Fuel Cost (Low)	$1,409,859	1.41%	
Total Fuel Cost (Medium)	$2,771,102	1.41%	
Total Fuel Cost (High)	$4,132,345	1.41%	
Total Carbon Emissions	15141	1.41%	

This case study has demonstrated how the SOPP model could be used to assess life cycle decisions. Such decisions do not have to be over the lifetime of the ship; a shorter time period could be selected for analysis. Such application of the SOPP model can be used to predict payback periods from the implementation of different operational practices.

10.5 Operational Performance Quantification for Useful Feedback

Within the Framework identified to support the increase of energy efficient ship operations (Section 5.4), providing feedback was highlighted as a key enabler. The analysis of operating profiles and development of the SOPP model, were considered as requirements to support the delivery of such feedback. This case study example demonstrates how each can be used to demonstrate performance feedback either within a SOPM system interface, or printed as a report.

Figure 72 demonstrates a very simple integrated interface for ship performance (in terms of fuel consumption) and operating profile feedback. It should be noted that different performance variables or performance indicators could be included depending on the feedback requirements identified as important for each stakeholder.

The performance and profiles for voyage 161 to voyage 186 for the case study Ship T1 are shown in Figure 72. However, any number of voyages between selected dates could be chosen for viewing. Furthermore, averaged and summed values over a given time period, such as per month or per year, could be provided rather than per voyage.

Note: Some of the axes in the following figures have not been shown to remove sensitivity to a specific ship's data.

The following comments can be made regarding Figure 72:

- The top plot demonstrates the total recorded (blue) and predicted (red) fuel consumption for the voyage, along with the percentage difference (green). Whilst not evident in this example, if a large percentage difference was observed, the voyage could be flagged for further investigation (an example of an individual voyage analysis will be shown in Figure 73 for voyage 183).

- The second plot demonstrates the average voyage speeds (the purple line), which appears to decrease over the time period selected. It also shows the average draft at midship (red dashes). The differences between laden and ballast drafts are evident: where the laden draft varies but the ballast draft remains constant between voyages. Whilst the average speed does not differ greatly, typically there appears to be a slight increase in speed for the laden voyages.
- The ballast voyage 167 demonstrates the largest voyage fuel consumption. It can quickly be seen that the average voyage speed and draft, and the average Beaufort Number and wind direction, were not that different from the other voyages. It is visually and quickly evident that the high fuel consumption is therefore due to the voyage duration (third plot from the top).

Figure 73 demonstrates the performance and profile for one voyage, where the total performance and average values are given for each SR record made for the voyage. This could be used to investigate the causes of a performance prediction discrepancy if identified. From Figure 73 the following observation was made:

- The voyage speed decreases over the course of the voyage. Whilst this might be due to adjusting speed for on time arrival, observing the other profiles in Figure 73 makes it evident that the decrease in speed correlates with an increase in Beaufort Number to 6 and operation in head seas (i.e. wind direction equal to zero: no purple columns shown).

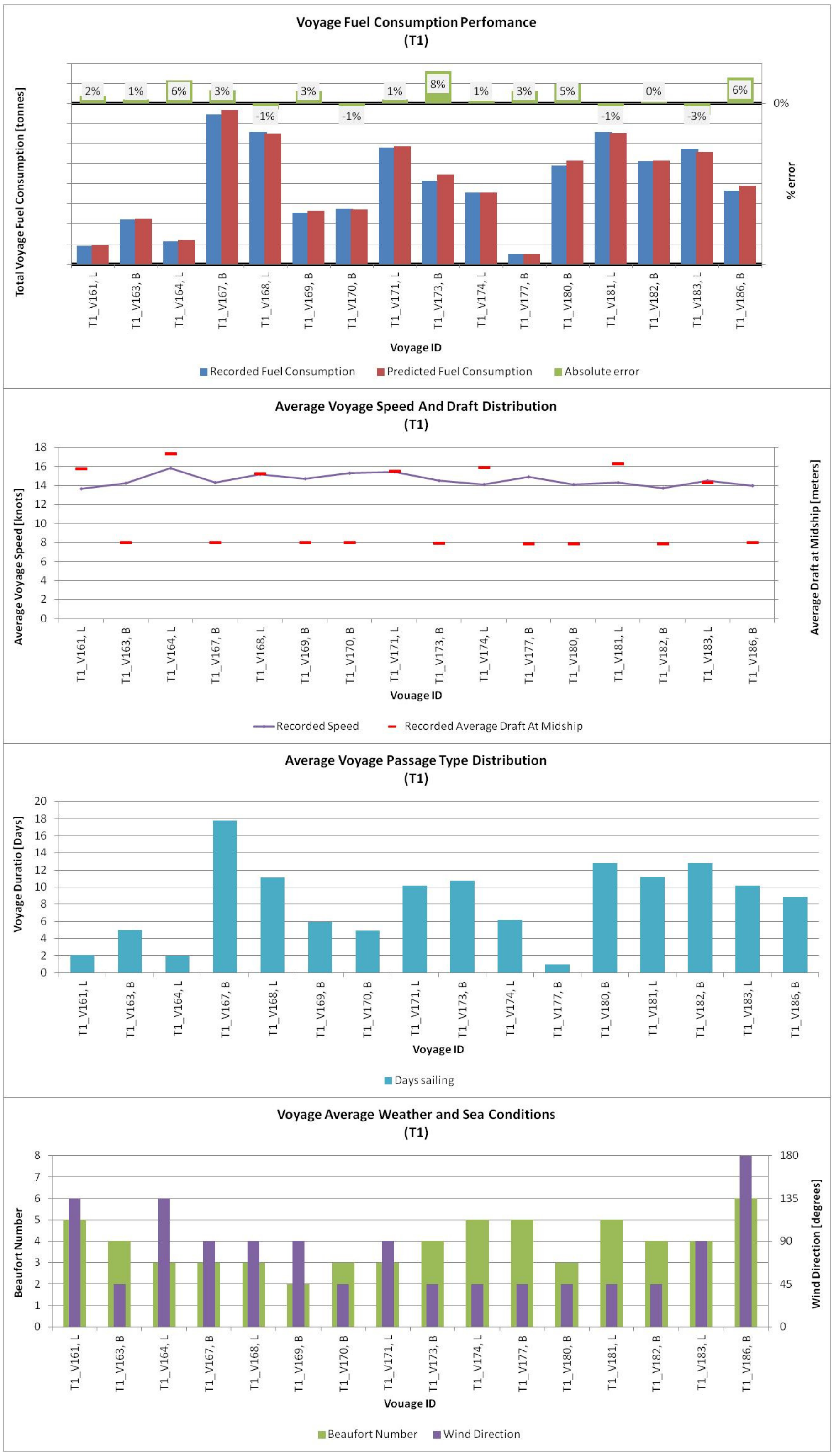


Figure 72: Feedback graphs for voyage averages, example, Ship T1

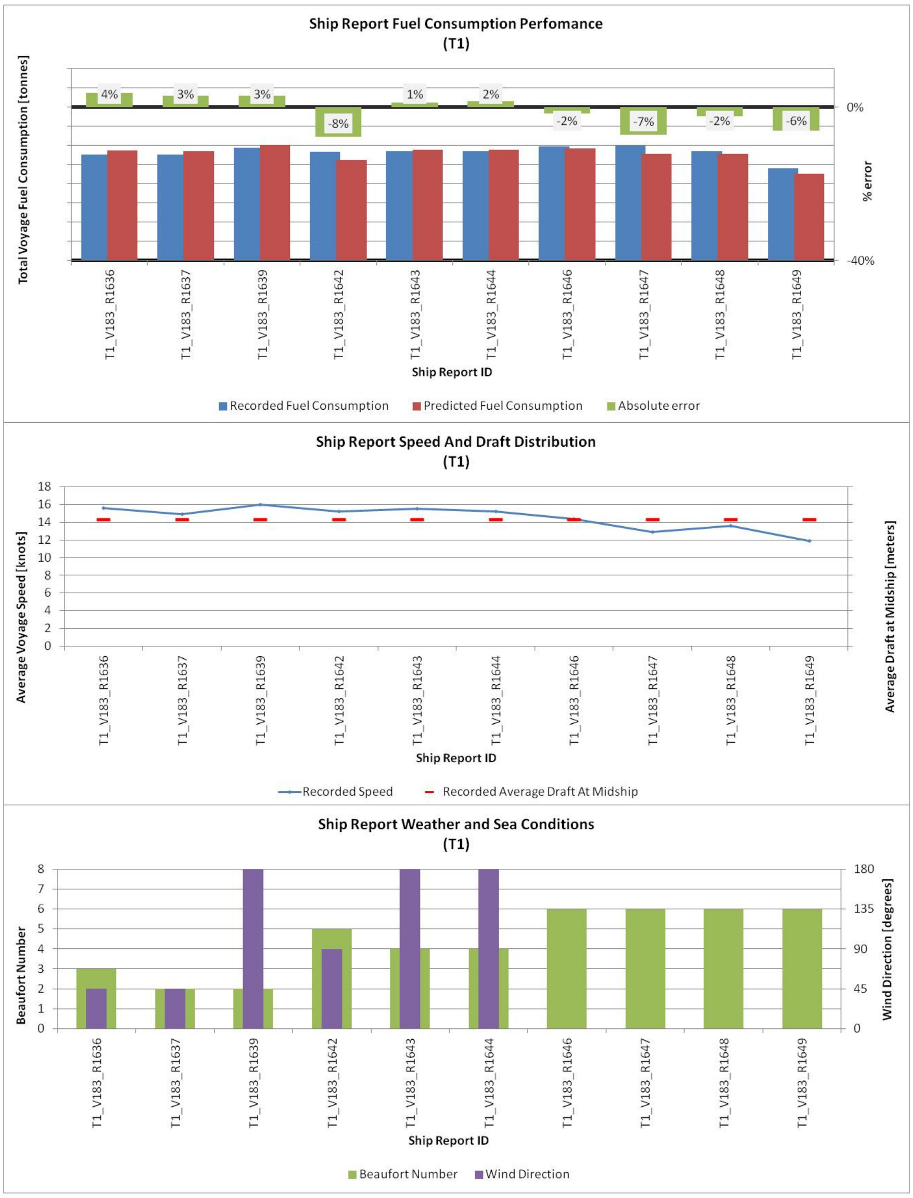


Figure 73: Feedback graphs for the voyage, example, Ship T1

CHAPTER SUMMARY

The SOPP model has been discussed with application to fast easy and flexible mapping of ship performance parameters. Specific mapping examples were given including the development of a Generalised Power Diagram and assessing speed loss and resistance increase. Suggestions were made for future refinement of the SOPP to better capture observed performance trends; i.e. via transformations of the input variables to the regression analysis.

An example input and output interface was demonstrated for the use of the Ship Operational Performance Prediction (SOPP) model to predict ship performance given an input scenario. The performance is given in terms of resistance, brake power, fuel consumption and carbon emission. The components of resistance due to operation away from sea trial conditions are also identified.

The functionality of using the SOPP model and analysis of operating profiles within a Ship Operational Performance Monitoring system (SOPM) is described.

The SOPP model was used to perform a life cycle analysis where the benefit of performing an in-water hull clean between each dry dock was assessed. The analysis demonstrated the functionality of how the SOPP model could be utilised, although the prediction itself was based on many assumptions. Nevertheless the life time fuel cost saving by performing in-water cleaning was determined to be 1.41%, in the range of $1.4 million to $4.1 million depending on the fuel cost scenario: considering only the saving in main engine heavy fuel oil consumption and no implementation or other costs.

Examples were given as to how the SOPP model and the operating profiles analysis can be used to develop useful feedback, relevant for different internal stakeholders.

11. CONCLUSIONS AND RECOMMENDATIONS

CHAPTER INTRODUCTION

The aim of this chapter is to summarise the key contributions to the field of research that have been presented in this thesis. The novelties in the contributions are highlighted. How the presented research has addressed the research aim and objectives is also discussed. Remaining gaps and suggestions for future work are identified, before the final conclusions of the research are presented.

11.1 Review of Research Objectives

The aim of this research was to contribute towards energy efficiency in the shipping industry through improved operational practices that reduce fuel consumption; hence exhaust emissions and the amount of carbon dioxide released into the atmosphere. This is in line with meeting global emission reduction targets and the mitigation of Climate Change. To quantify achievement of the above aim, a method to quantify fuel consumption and carbon emission reductions on a wide scale is required, along with implementation of this research in the industry. This was not practically feasible to assess as a standardised quantification method has not yet been identified. However the presented research contributes a method that could enable assessment of this aim in the future. The research achievements identified in the following bullet points, which are in line with the research objectives, describe the ways in which this research provides enabling mechanisms to effectively achieve wide spread energy efficiency improvements in practical shipping scenarios.

- **Research Achievements**

A1) Identification of perceptions and current and best practices related to energy efficiency in the shipping industry

Current energy efficiency practices and perceptions were identified, along with best energy efficiency practices, the influences of operational structures, and the key barriers and enablers for achieving best practices. It was identified that many operational measures are available to the shipping industry to help achieve improvements, yet barriers to their implementation include split incentives and lack of: integrated operations and human factor awareness; knowledge and skills; methods to quantify ship operational performance and savings; performance feedback mechanisms. It was also identified that there is limited awareness of existing operating profiles, and no widely established or standardised method to monitor ship performance. Whilst there are many methods available for Ship Operational Performance Monitoring (SOPM) that offer solutions with considered accuracy, they typically require measurement devices and sensors that are not widely installed onboard the world fleet. Thus it was concluded that enabling methods towards energy efficiency improvements need to be identified and developed, that can be used in the shipping industry to provide practical, operational and strategic solutions, without large investment costs, hence allow for wide spread application. Further discussion on these findings can be found in: Chapter 2 (a review of existing literature); Section 5.1 (field study industry visits), Section 5.3 (field study interviews and questionnaire analysis investigating seafarers' options).

A2) Development of an Operational Framework for practically improving ship energy efficiency within the industry

Based on the findings from A1, a Framework was developed identifying the following three areas for development: Maritime Education and Training (MET) on energy efficiency, analysis of Operating Profiles, and a Ship Operational Performance Prediction (SOPP) model. It was discussed how these developments could be used to support Ship Operational Performance Monitoring (SOPM) and the update of operating procedures. A SOPM system should be used to provide feedback (hence awareness and knowledge) about ship performance to different stakeholders involved with ship operations; where the feedback should be tailored to the stakeholders needs, e.g. individual ship daily performance feedback to seafarers and ship management personnel, and fleet monthly averages to business management personnel. A SOPM model should also be utilised to help inform strategic operational decisions, such as when hull and propeller maintenance is required.

Feedback of performance could prove a significant motivator towards implementing improvements, by increasing awareness and knowledge and generating self and ship competitiveness. The SOPM and feedback mechanisms should be incorporated into company operating procedures, along with provision of energy efficiency MET. In addition to MET, awareness and knowledge of energy efficiency best practices and performance should also be distributed via other means suitable to the specific company: i.e. via bulletins, an employee online forum, or posters.

The update of operational practices should also include management strategies, e.g. the update of company objectives to reflect common goals such as energy efficiency. Supported by performance feedback these updates should help enable transparency, hence motivation towards making improvements, and highlight where further improvements can be made.

The developed Framework therefore addresses both technical and human factors related to the practical implementation of energy efficiency best practices. Both aspects are imperative to consider for identification and implementation of industry solutions: whilst ship operation and systems efficiency is very important, the shipping industry also heavily relies on personnel driven activities. The Framework was presented in Section 5.4 and the development of the three identified elements were presented in the following chapters: Chapter 6, Maritime Education and

Training (MET); Chapter 8, Analysis of operating profiles; Chapter 9 the Ship Operational Performance Prediction (SOPP) model. How the developments could be used to support the implementation of energy efficiency best practices within the Framework, such as for SOPM, was presented in Chapter 10.

A3) Development of a Maritime Education and Training (MET) Course on Energy Efficiency

A MET course was developed to raise awareness, knowledge skills and motivation of the target groups, including cadets, seafarers, and onshore management. The key topics included in the MET started with the background to Climate Change as a driver towards energy efficiency requirements, to help the target group gain awareness and hopefully motivation towards an energy efficiency culture. Course subjects, such as communication, teamwork, leadership and situational awareness, were identified as required for focusing on development of human factor skills related specifically to the energy efficiency objective. Technical material content was collated and developed into the training material to deliver awareness, knowledge and skills related to best operational practices of the ship, machinery and equipment onboard; considering a holistic and integrated approach. The integration of operations (not just onboard systems) was also included as a topic focusing on how technical improvements can be realised in the complicated, and ever changing, operational structures and scenarios in shipping. Interactive discussions and exercises were highlighted as a key to develop higher cognitive level skills, such as problem solving, which are considered critical skills in order to select the best energy efficiency solutions in different scenarios. The findings from A1, specifically the field study questionnaire results, were used to highlight and address target group concerns and perceptions. The operational profiles and the SOPP model developments (discussed in A5 and A6) were incorporated into the training material as case study examples, to populate exercises, and for use as interactive learning tools. The development of the MET was discussed in Chapter 6.

A4) The collection of a large amount of very sensitive and fragmented ship operational data and information from many sources

Whilst the data and documents collected should be available to shipping companies for their ships, the commercial sensitivity of the data and documents means that they are not usually shared: hence they are difficult to be acquire for research purposes. It was only through the field study visits (described in Section 5.1) that the extensive data and information collection, as well as insight into shipping company operational practices, was feasible for this research. Furthermore, collation of the fragmented datasets into a standardised format was another achievement. Both the collection and collation tasks allowed for understanding of the data and how it can be utilised, and improved, with little or no additional workload for seafarers: which is a key aspect for a practical widespread solution. This data most often otherwise remains unanalysed in terms of ship operational performance; particularly as it is often collected by different operational departments and not distributed, hence the transparency of availability is not there either. Yet this research demonstrates that this data is a significant source of operation performance insight. A balance is understood between striving for increased accuracy versus sufficient informative information generation. This is not saying that SOPM methods with increased accuracy are not required; on the contrary they are imperative for future improvements. However, their widespread application presents a longer term solution due to implementation barriers, such as investment costs. This research presents methods that should be feasible for implementation by most companies now. Furthermore it identifies the key attributes of the data (including measurement methods and uncertainty) which could help assist ship operators to identify where improvements can be made for the collection of data for increased analysis benefits. The operational datasets that were collected for 21 ships, including tanker, container and bulk carrier ships, were Ship Reports (SR's), commonly known as noon reports. Their content and processing was presented in Chapter 7.

A5) SR datasets for 21 case study ships were used to analyse Operating Profile trends

Passage type, speed, cargo load and trim profiles were analysed. The key differences between the operation of different ship types and sizes were identified along with the influences of each profile on ship performance. For example, the voyage length varied by ship size and this was shown to influence the amount of time spent in port or sailing in ballast or laden; hence the transport work efficiency of the ship, which is reflected in energy efficiency indicators such as the EEOI. As a ship's performance is typically optimised for operation at the design parameters, understating and considering these profiles is clearly important for ship design. Moreover, operational profiles are also important for considering strategic operational improvements, such as: identifying where improvements can be made; informing retrofit or maintenance decisions; optimisation of ship operation considering the holistic performance of one ship or several ships. Presentation of the operating profiles in different and the most appropriate formats will be beneficial to many levels of personnel, including those in the commercial, ship and technical departments and to seafarers. Furthermore, the analysis of specific voyage time history profiles can be used to identify typical operating practices, hence stimulate thinking about their improvement. For example: is average voyage speed reduced in bad weather; are currents utilised for speed or fuel consumption gains; is one trim always selected and could it be changed to gain fuel savings. The integration of operating profiles into a Ship Operational Performance Monitoring (SOPM) system and its use for performance feedback was described in Sections 10.5.

A6) The development of a Ship Operational Performance Prediction (SOPP) model

The development of the SOPP model was presented in Chapter 9 in five steps. The first step involved a Data Elaboration Process during which additional variables (e.g. resistance) were calculated using only the collected SR datasets and ship information as inputs. Ship resistance and propulsion principles were applied as well as established prediction methods: such as Holtrop and Mennen and the Wageningen B4-series. Step 2 and 3 included a multi-linear regression analysis used first to predict ship resistance, and then ship speed: both using the same input variables. Step 4 included a data normalisation process to identify the performance contribution due each input operational conditions accounted for in prediction equations, determined from step 2. Step 5 involved a time dependent analysis used to identify and model the time dependent performance changes in the normalised resistance, i.e. considered due to hull and propeller degradation and fouling. The construction of the SOPP model demonstrated that SR data can be used to predict and hence understand ship performance: this was demonstrated to be within 3% for the prediction of fuel consumption and brake power, compared to recorded values for the case study ship. A further positive acknowledgement is that there is scope for improvements of the SOPP model; as discussed in Section 11.3. Thus it is emphasised again that SR datasets do provide a valuable source of ship operational information that, despite the considered uncertainties and limitations due to recording frequency and averages, they can and should, be utilised by shipping companies to gain an insight about ship performance and harness this information to support operational energy efficiency improvements. Furthermore, this can be done without the need for investment in additional measurement devices, other than those already installed, nor increasing the reporting workload of seafarers. Improvements in data collection could be addressed by ensuring awareness and understanding of the recorded data values and the ways in which the data is used, as well as by updating reporting procedures; with the potential to make the reporting process clearer and easier to follow. The model steps were presented in each of the sub-sections of Chapter 9. The utilisation of the SOPP model and the analysis of Operating Profiles (Chapter 8) as part of a Ship Operational Performance Monitoring (SOPM) system was discussed in part in Chapter 10.

A7) How the proposed Framework can be implemented to enable the improvement of energy efficiency of operational strategies

In Chapter 10 it was discussed how the SOPP model and the analysis of Operating Profiles could be used: to map performance changes; to predict ship performance for given operational conditions or assessment over a period of time; to provide a holistic performance overview. This was discussed in line with the development of a Ship Operational Performance Monitoring (SOPM) system that could be used within the Framework for improving ship operational energy efficiency, by the industry, to monitor, assess, develop and implement best strategies.

11.2 Major Contributions and Novelties

The following are considered to be the primary contributions of this research, and the novelties in each contribution are identified:

- **Detailed insight into the perceptions and opinions of a large number seafarers regarding the implementation of energy efficient ship operations**

This was the first time such a comprehensive study was performed to investigate the opinions of a large seafaring target group (317 participants). Published research had only focused on management level stakeholders. The success of the study was supported by the interest and involvement of major shipping companies proactively trying to address carbon emission reductions and energy efficiency; they believed this research was important for identifying solutions. The key conclusions from the questionnaire study included:

- Only 20% of participants had gained knowledge about the effect of carbon emissions via a MET course; where further details about the courses identified a focus on environmental issues, but not carbon emissions.
- The most popular sources of knowledge acquisition regarding carbon emissions (i.e. TV documentaries and news, and newspapers) do not provide information with technical content or specific to carbon emission and energy efficiency, particularly in relation to shipping.
- Only 46% of participants had discussed the subject with others; hence it is not a topic of focus or attention.
- A positive correlation between energy efficient implementation efforts and knowledge about carbon emissions, was demonstrated.
- Barriers to implementation include: lack of integrated operations between operational departments; existing operating procedures and work loads; lack of knowledge and available training; lack of performance monitoring and feedback.

The questionnaire research results and conclusions have proven fundamental to understanding current practices in the industry at a practical implementation level. This research formed a significant contribution to the joint industry and research 'Low Carbon Shipping Project' (Low Carbon Shipping – A Systems Approach, EPSRC Grant No: EP/H02004/1) and continues to support the 'Shipping In Changing Climates Project' (Shipping In Changing Climates, EPSRC Grant No: EP/K039253/1).

- **An Operational Framework for improving the energy efficiency of ship operations**

This is the first time the key enabling features and development elements of the Framework have been explicitly identified as required to achieve practical operational energy efficiency improvements within the shipping industry. The need to address organisational management and human factor improvements, in addition to technical improvement, was introduced as essential.

The key features of the Framework include:

- Ship Operational Performance Monitoring (SOPM), for performance feedback distribution and supporting operational strategic decisions
- Updates, changes and additions to existing Operating Procedures

To achieve these features the following elements were identified for development:

- Maritime Education and Training on energy efficiency
- Analysis of ship Operational Profiles (a key part of SOPM and improving operational strategies)
- A Ship Operational Performance Prediction (SOPP) Model (required to support SOPM)

- **Developed curriculum and material for a Maritime Education and Training course on Energy Efficiency**

The novelty in the developed MET was in the following areas:

- Uniqueness in full content at the time of development (the IMO model course is now published addressing some of the same topic areas)
- Provision of practical knowledge, examples and scenarios contributed by personnel working within the industry, based on their expertise and experiences, and supported by actual data
- Innovative topic material focusing on job role objectives, human factors and integrated operations for energy efficient ship operations.
- A comprehensive training material document to provide a level of awareness and knowledge to all trainers delivering the course

- **Collection of Ship Report (commonly known as noon report) data and ship information, for many case study ships, used to demonstrate its value for achieving energy efficiency improvements with limited or no added workload to seafarers**

A large amount of very sensitive and fragmented information and data was collected, which was utilised to generate understanding and for the analyses presented in this research. Such a comprehensive collection of data from so many sources has not been reported in other research. The significant value that can generated from the analysis of Ship Report data is described in the following contribution points. This study also clearly highlighted the need for a standardised way of collecting the ship operational data.

▪ **Analysis of Operating profiles**

This is the first time that the analysis of operational data has been presented as a structured analysis of Operating Profiles. Such an informative analysis for several case study ships has not been presented before, and contributes the following:

- Information about average trends for case study ships, which can be used to inform design, operation and logistic practices, and for inclusion in MET
- An example of an Operating Profile analysis that can also be generated by companies to inform their specific design, operation and logistic practices
- Information about operational time histories to identify current practices, and support improvement strategies

The key conclusions of the operating profiles analysis are as follows:

- For all types of the case study ships analysed, the larger ships spent less time in port; a characteristic of longer voyages
- The larger case study tanker ships spent a larger proportion of the year sailing in ballast; most likely a characteristic of their routes and destination ports
- The distribution of average operational speeds decreased over the years and became wider; most significantly around 2008, for all case study ship types
- In the laden condition the tanker and bulk carrier case study ships operated at a draft between 70% and 90% of their design loaded draft
- In the laden condition the case study container ships predominantly operated at a draft between 60% to 75% of their design loaded draft

- **A method for elaborating data variables contained within a ship operational dataset to predict ship resistance, brake power and fuel consumption**

The novelties in the presented method include:

> ➢ It only utilises Ship Report (SR) records and typically available data for all ships as the source of input data
>
> ➢ It applies established ship resistance and propulsion formulae in an innovative sequence to calculate resistance, brake power and fuel consumption.

The utilisation of existing operational data records and information for Ship Operational Performance Prediction (SOPP) is significant. This is because fuel consumption monitoring is identified as one of the most significant enablers to energy efficiency improvements; yet currently there is no standardised method that provides sufficient accuracy, flexibility and information generation, without the need for investments. Most methods currently being developed present valuable but longer term solutions for achieving wide spread industry implementation due to the need to overcome barriers, such as investment costs, first.

- **A Ship Operational Performance Prediction model based on data widely available in the industry**

The discussion for the previous contribution also applies to this contribution, along with the following:

> ➢ Functions of the model identify performance contributions due to operation at different RPM's and drafts, in different Beaufort Numbers and wind directions, and with different levels of hull and propeller degradation and fouling (assumed as a function of time since build and the last dry dock).

- The construction of a curve function to capture, hence model, the time dependent change in ship resistance i.e. considered due to hull and propeller degradation and fouling.

Whilst investigations for improvement of these contributions are recommended in Section 11.3, the model provides a practical, fast and flexible approach to monitor and assess ship performance. The understanding generated from the assessments can then be used to develop best operational strategies for energy efficiency.

11.3 Gaps and Future Work

Throughout the discussion of the research developments presented in this thesis, consideration points for improvements, further investigation and expansion have been highlighted. The following is a summary of the main points that are thought could enhance and build upon the contributions of this research.

- **Complete the development of all Maritime Education and Training (MET) course**

A draft of the training material has been completed for the designed Energy Resource Management course. The material, and all supporting documentation (including the model course, training material, trainer guide, training aids, teaching hand outs, assessment scheme) for the three designed courses, should be fully developed and reviewed to a level ready for distribution and implementation. The review should be carried out by MET providers and by shipping industry personnel to maintain emphasis on capturing practical and effective solutions.

- **Trial the MET course on energy efficiency**

After completion of development, the MET courses should be trialled in accordance with a testing plan; assesses the short and long term benefits gained from delivery of the course to seafarers and cadets. Feedback from the trainers and the trainees should be captured. Testing methods may include questionnaires and interviews for short term assessment, and periodic questionnaires and interviews and quantification of ship performance over time (i.e. using a SOPM system) for longer term assessment.

- **Uncertainty and sensitivity analysis of the data elaboration process and developed Ship Operational Performance Prediction (SOPP) model.**

It was highlighted in Sections 2.4 and 7.2 that Ship Report data sets include a large inherent uncertainty. Specifically Table 11 in Section 7.2 started to identify the uncertainties associated with each data variable and its measurement. It was emphasised that the uncertainty should be understood, so that company operating procedures for data recording can be considered to improve the quality of data collected for the purpose of Ship Operational Performance Monitoring (SOPM). As discussed in Chapter 9, a sensitivity analysis based on the method used for SOPM (i.e. the developed Ship Operational Performance Prediction (SOPP) model presented in Chapter 9) should also be assessed to identify which variables should be the focus of improvement efforts. Uncertainty in the SOPP model was addressed to a level in Chapter 9 by considering the coefficient of determination (R^2) between predicted, calculated and recorded data values, along with average absolute and standard error. However, further investigation into error propagation through the SOPP model should be assessed, along with the sensitivity analysis.

- **Evaluate the impact of changing the Normalisation Baselines on the identified time dependent performance change**

The Normalisation Baseline used to identify the time dependent performance change in Sections 9.5 and 9.6 corresponded to one RPM value and draft, Beaufort Number and wind direction; and therefore one ship speed (predicted using the Speed Regression Equations, Section 9.4). A systematic investigation should be undertaken to change each and all of the baseline inputs to fully assess the impact they have on the results. Reasoning for the low prediction of additional resistance, brake power and fuel consumption due to the time dependent change may become apparent, as discussed in Section 9.7. For the presented SOPP model, the time dependent performance change is assessed as the difference between the time dependent increase and the Sea Trial Baseline. Therefore, as draft, Beaufort Number and wind direction are changed away from the corresponding sea trial conditions (i.e. calm water) the Sea Trial baseline will no longer be representative of the comparative performance. Therefore a different baseline should be defined; perhaps using the

SOPP model to define a baseline, or from additional ship trials in different conditions, or using other empirical and analytical methods.

- **Refine the model by applying transformations to the regression input variables**

It was identified in Section 10.1 that the SOPP model had not captured the exponential increase in power above Beaufort Number 4 or 5, nor the impact of sailing in different wind directions. Whilst it was highlighted that the SOPP model is based on observational categorical data, rather than measurement scales, it is still considered that modifications of the SOPP model should be investigated to determine if they provide a better representation of the expected relationships and overall prediction of the model. The modifications suggested for investigation include the application of transformations to the input variables in the Resistance Regression Analysis and or Speed Regression Analysis. Input variable transformations are discussed in (Tabachnick & Fidell 2007).The exploratory analysis correlation matrix plots (Sub-section 9.3.2) did not demonstrate a clear need for transformations to be applied, therefore they should be selected based on expert judgement of ship performance rather than statistics results. As with the previous bullet point, the application of different transformation may alter the determined impact of time dependent changes over the comparative baseline selected for use.

- **Apply the modelling process to several case study ships**

The development of the SOPP model should be applied to many case study ships to determine the model prediction capabilities. Furthermore, the models developed for each case study ship could be compared, to identify if a generalised model can be determined: e.g. for different ship types, sizes or for sister ships.

- **Program the SOPP model and operating profiles into a Ship Operational Performance Monitoring (SOPM) system**

To enable practical utilisation of the developed SOPP model and analysis of Operating Profiles as stand alone tools, or as part of a SOPM system (described in Section 10.2), they should be programmed into a user friendly software package. This will also address the very intensive data processing and analysis time by automating each of the data analysis steps. Furthermore, based on the required inputs to the SOPM model and findings from this research, a recommendation for a data collection standard should be developed.

- **Gather industry feedback and then trial and test the application of the Framework within a company**

The aim of this research was to develop a method for practical and wide spread use in the shipping industry. Thus implementation, feedback and review of the Framework and each of the developed elements by different industry personnel is important for future developments.

11.4 Research Outputs

- **Journal papers:**

Banks, C., Turan, O., Incecik, A., Lazakis, I., Lu, R. 2014. Seafarers' Current Awareness, Knowledge, Motivation and Ideas towards Low Carbon-Energy Efficient Operations. Journal of Shipping and Ocean Engineering, 4, pp. 93–109.

Lu, R., Turan, O., Boulougouris, E., Banks, C., Incecik, C., 2015. A semi-empirical ship operational performance prediction model for voyage optimization towards energy efficient shipping. Ocean Engineering (under review)

- **Conference papers:**

Banks, C., Lazakis, I., Turan, O., Incecik, A. 2011. An approach to education and training of seafarers in Low Carbon - Energy Efficiency operations. In Low Carbon Shipping 2011. Glasgow, UK., pp. 1–11.

Banks, C., Turan, O., Incecik, A., Theotokatos, G.,Izkan, S.,Shewell, C., Tian, X., 2013. Understanding ship operating profiles with an aim to improve energy efficient ship operations. In Low Carbon Shipping 2013, London, UK, pp. 1–11.

Lu, R. Banks, C. Turan, O. Incecik, A. Boulougourils, E. Theotokatos, G., 2014. A Comparison of Three Prediction Models for the Performance of a Ship in an Operational Sea Way. In International Conference on Maritime Technology, Glasgow, UK

- **Joint Industry Research Projects:**

This research has contribution to the joint industry and research 'Low Carbon Shipping Project' (Low Carbon Shipping – A Systems Approach, EPSRC Grant No: EP/H02004/1) and continues to support the 'Shipping In Changing Climates Project' (Shipping In Changing Climates, EPSRC Grant No: EP/K039253/1).

11.5 Conclusions

- This research identified the urgent need for a systematic approach to improve the awareness, knowledge skills and motivation of the target groups (cadets, seafarers and onshore management personnel) to achieve the targeted levels of energy efficiency and emissions.

- This research demonstrates the potential ways that the industry could achieve practical energy efficiency improvements with very limited, or without, investment costs and utilising existing resources, by addressing key technical and management issues in parallel.

- A comprehensive field study questionnaire carried out in 2011/2012 with the support of major shipping companies identified the following:

  a) Awareness and motivation towards energy efficiency to reduce carbon emissions needs to be increased: only 46% of participants had discussed the subject with others, hence it is not a topic of focus or attention.

  b) An energy efficiency culture is not yet established.

  c) The most popular sources for knowledge acquisition regarding carbon emissions were identified as TV documentaries and news and newspapers; these sources do not contain technical content specific to the reduction of shipping carbon emissions. Hence this content need to be provided via maritime education and training.

  d) It was demonstrated that participants with more knowledge about carbon emissions had increasingly tried to implement energy efficiency improvements.

  e) Barriers to implementing energy efficiency improvements include: lack of integrated operations between operational departments; existing operating procedures and workloads; lack of knowledge and available training; lack of performance monitoring and feedback.

- A Framework of solutions are required to achieve effective and wide spread energy efficient ship operations; not just one element. Features of the Framework to increase awareness, knowledge, skills and motivation of all personnel include:

  a) Ship Operational Performance Monitoring (SOPM), for performance feedback distribution, and for supporting operational strategic decisions

  b) Updates, changes and additions to existing Operating Procedures

  To achieve these features the following elements are required for development:

  c) Maritime Education and Training on energy efficiency

  d) Analysis of ship operational profiles (a key part of SOPM and improving operational strategies)

  e) A Ship Operational Performance Prediction (SOPP) Model (required to support SOPM)

- MET for energy efficient should include topics on: job role objectives, responsibilities and communications; barriers and enablers to the practical achievement of best practices in different scenarios; skill development of human factors (i.e. teamwork, leadership, communication, situational awareness) to help achieve integrated operations.

- An analysis of operating profiles for case study tanker, container and bulk carrier ships, demonstrated that most often they operate away from their design points. This should be considered in ship design but also in operation, to increase awareness and knowledge (e.g. by providing feedback) about ship performance, hence identify energy efficiency improvement options.

- The developed SOPP model in this research provides a method to:
  - **a)** Predict total fuel consumption, brake power and resistance with considered accuracy (within 3% absolute average error for fuel consumption and brake power for the case study ship)
  - **b)** To identify performance contributions due to different operational conditions, including:
    - At different RPM and drafts
    - In different Beaufort Numbers and wind directions
    - With different levels of hull and propeller degradation and fouling (assumed as a function of time since build and the last dry dock).
  - **c)** Predicting ship performance based only on inputs that should be widely available for all ships.

- Ship Reports (i.e. noon reports) as input data limits the application of the developed SOPP model to SOPM applications in real time and to a required accuracy: due to the frequency of data collection and uncertainties. For these applications methods utilising improved data sources are required. Nevertheless, the SOPP model utilising Ship Reports should not be overlooked as a valuable insight into actual ship operations and performance, which is feasible for implementation on a wide scale within the industry, and within a Framework of efforts could enable ship operational energy efficiency improvements.

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APPENDICES

Appendix A – List of Equations

E.1 : General form of Resistance

$$R_x = \frac{1}{2}\rho V^2 S C_x$$

Where: x denotes the component of resistances in question in relation to: for example, T, Total; F, frictional; A, air resistance; W, wave making. The definition of total resistance considered for a specific model determines which components of resistance considered.

E.2 : General form for the prediction of brake power

$$P_B = \frac{R_T V_S}{\eta_{PT}} = \frac{P_E}{\eta_{PT}}$$

E.3 : Total propulsion system efficiency

$$\eta_{PT} = \eta_s \eta_o \eta_r \eta_H = \eta_s QPC$$

E.4 : General form for the prediction of fuel consumption

$$FFR = SFOC \times P_B$$

E.5 : Apparent slip

$$Sa = 1 - \frac{\mathrm{V}}{\mathrm{p} \times \mathrm{n}}$$

E.6 : Real slip

$$Sr = 1 - \frac{\mathrm{V_A}}{\mathrm{p} \times \mathrm{n}}$$

E.7 : Apparent flow velocity into the propeller

$$V_a = V(1-\omega)$$

E.8 : Propeller open water efficiency

$$\eta_o = \frac{J\,K_T}{2\pi\,K_Q}$$

E.9 : Advance coefficient

$$J = {V_A}/{nD}$$

E.10 : Thrust coefficient

$$K_T = {T}/{\rho n^2 D^4}$$

E.11 : Torque coefficient

$$K_Q = {Q}/{\rho n^2 D^5}$$

E.12 : K_T & K_Q Wageningen Series

$$K_Q = \sum_{n=1}^{47} C_n (J)^{S_n} (P/D)^{t_n} (A_E/A_O)^{M_n} (Z)^{v_n}$$
$$K_T = \sum_{n=1}^{39} C_n (J)^{S_n} (P/D)^{t_n} (A_E/A_O)^{M_n} (Z)^{v_n}$$

E.13 : Delta K_T & K_Q Wageningen Series

$$\begin{aligned}\Delta K_T = {} & 0.000353485 - 0.00333758(A_E/A_O)J^2 - 0.00478125(A_E/A_O)(P/D)J \\ & + 0.000257792(logR_n - 0.301)^2(A_E/A_O)J^2 \\ & + 0.0000643192(logR_n - 0.301)(P/D)^6 J^2 \\ & - 0.0000110636(logR_n - 0.301)^2(P/D)^6 J^2 \\ & - 0.0000276305(logR_n - 0.301)^2 Z(A_E/A_O)J^2 \\ & + 0.0000954(logR_n - 0.301)Z(A_E/A_O)(P/D)J \\ & + 0.0000032049(logR_n - 0.301)Z^2(A_E/A_O)(P/D)^3 J\end{aligned}$$

$$\begin{aligned}\Delta K_Q = {} & -0.000591412 + 0.00696898(P/D) - 0.0000666654Z(P/D)^6 \\ & + 0.0160818(A_E/A_O)^2 - 0.000938091(\mathrm{LogR_n} - 0.301)(P/D) \\ & - 0.00059593(\mathrm{LogR_n} - 0.301)(P/D)^2 \\ & + 0.0000782099(\mathrm{LogR_n} - 0.301)^2(P/D)^2 \\ & + 0.0000052199(\mathrm{LogR_n} - 0.301)\mathrm{Z}(A_E/A_O)J^2 \\ & - 0.00000088528(\mathrm{LogR_n} - 0.301)^2\mathrm{Z}(A_E/A_O)(P/D)J \\ & + 0.0000230171(\mathrm{LogR_n} - 0.301)Z(P/D)^6 \\ & - 0.00000184341(\mathrm{LogR_n} - 0.301)^2\mathrm{Z}(P/D)^6 \\ & - 0.00400252(\mathrm{LogR_n} - 0.301)(A_E/A_O)^2 \\ & + 0.000220915(\mathrm{LogR_n} - 0.301)^2(A_E/A_O)^2\end{aligned}$$

E.14 : K_T & K_Q Wageningen Series (with Re correction)

$$K_T(\mathrm{R_n}) = \{K_T(\mathrm{R_{n=2\times10^6}})\} + \{\Delta K_T(\mathrm{R_n})\}$$
$$K_Q(\mathrm{R_n}) = \{K_Q(\mathrm{R_{n=2\times10^6}})\} + \{\Delta K_Q(\mathrm{R_n})\}$$

E.15 : Reynolds Number

$$R_n = VL/\nu$$

Where ν is the kinematic viscosity which was taken to be constant at 1.19x10-6 m^2s^{-1}. If further information about the average temperature during the SR reporting period was available a varying and more accurate estimation could be made.

E.16 : Wageningen Series Polynomials

Provided in (Carlton 2012)

E.17 : Wake fraction (Holtrop & Mennen 1982)

$$\omega = c_9 C_V \frac{L}{T_A}\left(0.0661875 + 1.121756 c_{11}\frac{C_V}{1-C_{P1}}\right) + 0.24558\sqrt{\frac{B}{L(1-C_{P1})}} - \frac{0.09726}{0.95-C_P} + \frac{0.011434}{0.95-C_B} + 0.75 C_{stern} C_V + 0.002 C_{stern}$$

Where:

$$c_9 = c_8 \quad [if\ c_8 < 28] \qquad or \qquad c_9 = 32 - 16/(c_8 - 24) \quad [if\ C_8 > 28]$$

$$c_8 = BS/LDT_A$$

$$c_{11} = T_A/D \quad [if\ T_A/D < 2] \qquad or \qquad c_{11} = 0.0833333(T_A/D)^3 + 1.33333 \quad [if\ T_A/D > 2]$$

$$c_V = (1+k)C_F + C_A$$

$$(1+k) = c_{13}\left\{0.93 + c_{12}(B/L_R)^{0.92497}\left(0.95 - C_p\right)^{-0.521448}\left(1 - C_p + 0.0225lcb\right)^{0.6906}\right\}$$

$$c_{12} = (T/L)^{0.2228446}\ [if\ T/L > 0.05]$$
$$or \qquad c_{12} = 48.20(T/L - 0.02)^{2.078} + 0.479948 \quad [if\ 0.02 > T/L > 0.05]$$
$$or \quad c_{12} = 0.479948 [if\ T/L < 0.02]$$

$$\frac{L_R}{L} = 1 - C_P + 0.06 C_P lcb/(4C_P - 1)$$

$$c_{13} = 1 + 0.003 C_{stern}$$

$$C_F = \quad 0.075/(log_{10}Re - 2)^2 \quad \text{(ITTC 2002b)}$$

$$C_A = 0.006(L+100)^{-0.16} - 0.00205 + 0.003\sqrt{L/7.5}\, C_B^4 c_2 (0.04 - c_4)$$

$$c_2 = exp\left(-1.89\sqrt{c_3}\right)$$

$$c_3 = 0.56 A_{BT}^{1.5}/\left\{BT\left(0.31\sqrt{A_{BT}} + T_F - h_B\right)\right\}$$

$$c_4 = T_F/L \quad [if\ T_F/L \le 0.04\,] \qquad or \qquad c_4 = 0.04 \quad [if\ T_F/L > 0.04\,]$$

$$c_{P1} = \ 1.45 C_P - 0.315 - 0.0225 lcb$$

$$C_{stern} = 0\ for\ normal\ section\ shape$$

Where C_P is the prismatic coefficient, lcb is the longitudinal centre of buoyancy forward of 0.5L as a percentage of L, B is the beam, T is the draft, L is the waterline length, Re is the Reynolds number, T_A is the draft aft, T_F is the draft forward

E.18 : Thrust deduction relationship with Resistance

$$R_T = T(1 - \tau)$$

E.19 : Thrust deduction coefficient (Holtrop & Mennen 1982)

$$\tau = 0.001979\mathrm{L}/(\mathrm{B} - \mathrm{BC_{P1}}) + 1.0585\mathrm{c_{10}} + 0.00524 - 0.1418\mathrm{D}^2/(\mathrm{BT}) + 0.0015\mathrm{C_{stern}}$$

where

$$c_{P1} = 1.45C_P - 0.315 - 0.0225lcb$$

$$c_{10} = B/L \quad [if\ \ L/B > 5.2] \quad or \quad c_{10} = 0.025 - 0.003328402/(B/L - 0.134615385) \quad [if\ \ L/B > 5.2]$$

$$C_{stern} = 0\ for\ normal\ section\ shape$$

E.20: Hull efficiency

$$\eta_\mathrm{H} = \frac{(1-t)}{(1-\omega)}$$

E.21 : Relative rotative efficiency Wake fraction (Holtrop & Mennen 1982)

$$\eta_\mathrm{R} = 0.9922 - 0.05908\,\mathrm{A_E}/\mathrm{A_O} + 0.07424(\mathrm{C_P} - 0.0225\ \mathrm{lcb})$$

Where C_P is the prismatic coefficient, lcb is the longitudinal centre of buoyancy forward of 0.5L as a percentage of L, A_E/A_o is the blade area ratio

E.22 : Shaft efficiency (SNAME 1990)

$$\eta_\mathrm{s} = 0.99\ \times \mathrm{Load\ factor}$$

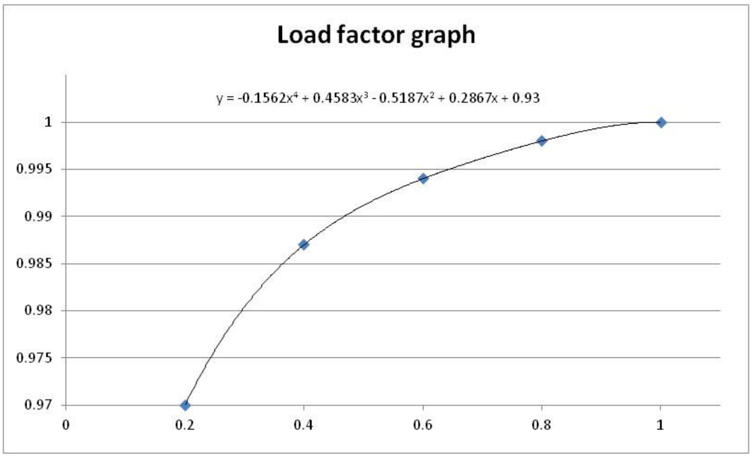


Figure 74: Relationship between the engine load and the mechanical drive system load correction factor (SNAME 1990)

E.23 : General form for the prediction of carbon emissions

$$CO_2 = FFR\ x\ C_{F,fuel\ type}$$

E.24 : Admiralty coefficient

$$AC = \frac{\Delta^{\frac{2}{3}} V^3}{P}$$

E.25 : Fuel Consumption coefficient (Molland et al. 2011)

$$FC_{ratio} = \frac{draft\ \times V^3}{FC}$$

Appendix B – Quotes from the Questionnaire Analysis

The following quotes support the discussion and conclusions for the questionnaire field study presented in Section 5.3.

'… each country has to be responsible not target, the seafarers … Why we are targeted because we are the easy catch …'

Quotes 1

'Keep the main engine parts in tiptop condition to guarantee the performance recommended by maker.'

'During cargo operation, there is great potential to optimizing the use of cargo pumps.'

'The deck team should stop cargo service machines in time after cargo operation and inert gas generators.'

'Route and speed instructions should be given to the vessels, where the eco speed must be better defined to ensure all utilise the lowest possible steady main engine load point during a given voyage.'

'Hull Scrubs.'

'Prop Polish and high performance antifouling.'

'Good quality fuel should be used.'

'By reducing unnecessary operation of machinery.'

'Steady running of the vessel at sea.'

'The safest and shortest route should be selected.'

'Reduce use of incinerator.'

'Good support should be provided from the company by providing vessel spare parts to maintain vessels machinery'

'Train bridge personnel to think further ahead to be able to minimize alterations of course.'

Quotes 2

'All deck officers should be at least familiar with all engines on board. Thus they can plan work and this will lead for the improvement of the environment.'

Quotes 3

'The ships management should educate and train all ship present personnel to be efficient and be given support from owners and charterers to run the vessel smoothly and efficiently.'

Quotes 4

'Coordination between bridge and engine room.'

Quotes 5

'Proper knowledge, training and motivation are not there.'

'Well it depends on the topic, but in general, with respect to carbon reductions, the problem is not the knowledge, but the motivation to use the knowledge and information'

Quotes 6

'Very busy on board, extremely busy. It is better to stop using your car and continue with bicycle.'

'Limited by operation requirements and resources. Lack of time and man power.'

'This priority is not so high in my mind'

'No time to think about that'

'Not much mainly because I am part of the deck department, but I do my best to contribute for the carbon emission cause.'

Quotes 7

'Feedback that it actually works and makes a difference'

Quotes 8

'Anticipation is always a key word in this issue.'

Quotes 9

Appendix C – Maritime Education and Training Course on Energy Efficiency

C1: Discussion On Existing Resources Management Courses

A requirement for the MET course on energy efficiency was to deliver non-technical knowledge and skills as well as technical. It was therefore considered important to review lessons learned from the development and delivery of existing Maritime Resource Management (MRM) courses. An informal discussion active since May 2012 on Linkedin (a professional social media website), in the MRM discussion group page, identified many points to consider for the development of the Energy Resource Management course described in Chapter 6. The key conclusions are highlighted here:

- It is desirable for the MET course on energy efficiency to provide a consistent content and level of knowledge no matter where it is delivered.
- It was commented that the separation of courses into bridge and engine room specific, encouraged isolated department operations, where the aim is to encourage integrated operations. However it was acknowledged that this is also necessary to address specific knowledge and skill requirements.
- The discussion highlighted the importance of delivering knowledge, understanding and interpersonal skills to help promote the right attitude towards building a better culture. The teaching of human factor psychology in particular was emphasised, stressing the importance of non technical skills as much as technical skills for achieving successful resource management and operating procedures.
- Human factor theory subjects often taught on resource management courses include: leadership and team work, communication, workload management and situational awareness. Each of these human element skills are applicable for the MET course on energy efficiency.

- A particular comment, demonstrated the importance of emphasising incremental performance change awareness within the course material. Awareness can be increased by emphasising the critical systems that should be observed
- Recognising and acting on energy efficiency performance thresholds for a system could help to increase safety, if the safety threshold is higher and thus less likely to be encountered.
- The course should be flexible in material content and delivery format to address the specific learning requirements of the trainee group.
- The inclusion of behavioural management (e.g. to encourage an energy efficiency culture) is important.
- The discussion supported the findings of the questionnaire fields study presented in Section 5.3: emphasising that there is a need for companies to demonstrate good human factor management skills: i.e. organisational and behaviour management.

C2: Pedagogical Review

- **Curriculum development**

There are several learning theories that can be considered and adopted for curriculum development; including Behaviorism, Cognitivism, Constructivism, Informal and post-modern theories and Connectivism (Ertmer & Newby 2013) (Weegar & Pacis 2012) (Abcouwer & Smit 2008). However, the starting point selected for the development of the curriculum for an MET course on energy efficiency was to consider existing theories and structures used within current MET. One of the primary reasons why this was considered was to ensure the feasibility of the proposed MET course complimenting existing MET and MET course structures: i.e. to allow for possible merging with an existing course and to meet MET regulations and standards. However, it is noted that that existing MET and MET structures should not be followed blindly. Moreover, at all stages of development of the curriculum, course material and delivery techniques should be considered to provide the most effective and successful MET for the course subject, student group and resources, whilst maintaining compatibility.

Current MET is based on Competency-Based Training (CBT). This is an approach where the education is designed specifically to what the student is expected to do in the work place. Certification is issued once the student has shown that they are competent in carrying out the specified task(s) (Emad & Roth 2008). As imagined, this type of learning lends itself well to the maritime industry where cadets are being educated to complete a specific job at sea, and seafarers and onshore personnel are trained within their existing job roles. However, CBT is not just confined to learning in the workplace, it can also consist of learning the theory in a classroom based environment and practical exercises both in and away from the workplace: i.e. in an educational environment. For example, within the shipping industry the use of simulator training is used to educate cadets and train seafarers in addition to onboard experience. The use of different MET delivery methods and platforms should be considered, as discussed in the following appendices sub-sections.

▪ **Educational Approaches**

There are many different approaches to delivering awareness, knowledge, skills and motivation and no one method is sufficient alone, nor can be expected to suit every trainee’s learning preferences. Different educational approaches that can be considered include the following, although not an exhaustive list:

- Theory material, including; class/lecture notes, lecture slides, books and other sources of information. Beneficial for: teaching facts and ensuring that details of the knowledge are known.

- Exercises, including; numerical, calculation based, written answers, scenario based. Beneficial for: adding more context and relating theoretical knowledge to practical applications (scenarios, calculations); allowing trainees to apply, test and consolidate their knowledge.
- Case Studies: an extension to exercises but give further context to the real application. Beneficial for encouraging the higher-level cognitive skills (e.g. analytical skills).
- Discussions. Beneficial for: allowing debases and raising questions that need to be answered; forming personal opinions and viewpoints; further develop personal skills like communication and teamwork skills.
- Project Work. Beneficial for: encouraging all levels of skill to be drawn upon. Group projects can promote non-technical skills such as teamwork and communication skills.
- Practical Work, including workshops, onboard experience and simulator training. Beneficial for: developing their technical and non-technical (such as situational awareness) skills; application of knowledge and skills in simulated and or real life environments.

Furthermore, each of these educational approaches can be delivered by directed (i.e. trainer lead) or self learning (e.g. away from the class room learning)

Particularly for MET, care should be taken to develop the material for any one of the educational approaches ensuring that it is developed as close to a real scenario as possible. Not only will deviation from this reduce the opportunity for the trainee to practice applying their knowledge and skills to a real scenario, completion of a task not seen to be related or for the purpose or objective of learning could reduce the trainees trust, and hence interest and motivation, towards the learning.

▪ **Delivery Platforms**

Like educational approaches, there are several different platforms that can be used to deliver MET, each with its own advantages and disadvantages as well as effectiveness. Again a combination of platforms should be selected to ensure variation in the delivered MET, with elements to suit different learning preferences and to reduce repetitiveness of mundane learning. A non exhaustive list of different platforms that could be used is given below. It should be noted that the facilities and resources available at an MET institute will influence the delivery methods selected.

- Classroom based
- Workshops including; practical engineering workshop; computer labs running simulation tool.
- Onboard learning
- Simulator training

▪ **Approaches for Assessment**

Approaches for assessment can be delivered using any of the platforms described above and they should be complimentary to the educational material that has been taught and requires assessment. Examples of possible approaches include:

- Multiple choice questions presented as an exam or quick more informal test.
- Short written answers can be used to identify unprompted understanding, requiring quick and precise answers.
- Long written answers, such as an essay, have the benefit of the allowing the trainee to demonstrate their knowledge and train of thought: i.e. higher level learning objectives.
- Coursework or projects

- Oral Interviews and observations (e.g. when carrying out practical workshop tasks, or during onboard training)

C3: Target Group MET Requirements

The MET requirements for cadets include:

- It should be possible to integrate the developed MET course on energy efficiency into the existing MET curriculum in training institutes worldwide.
- It should be possible to deliver the material in hourly blocks to fit with a semester or yearly teach schedule (in contrast to an intensive 1 week course).
- The course structure should be flexible to allow for delivery at the most suited time within the existing curriculums: i.e. during the first year of study, or after onboard training has been completed. Furthermore, it should be possible to deliver the material in non consecutive time periods: e.g. it may be best to introduce background material in the first year to start generating an energy efficiency culture, but deliver the technical level of knowledge the following year after the basic knowledge level has been taught.

The MET requirements for seafarers include:

- In contrast to cadets, seafarers are most likely to complete the MET training course on energy efficiency as an intensive course over a few days. The developed MET course should therefore be suitable for this type of delivery.
- The training course may be run by the crew management company/department, or undertaken by the trainee seafarer independently as part of their continual professional development (i.e. at a MET institute). The developed MET course on energy efficiency must therefore allow for delivery of a generic course (not tailored to one company), as well as

allowing for tailoring so that a company can introduce and relate the material to specific company procedures and operations.

- Seafarers often have to complete their MET courses during their time onshore, frequently during their leave time. It is known that many seafarers find such courses an inconvenience which can result in reduced motivation towards the course and its content. Therefore it should be ensured that the course can be delivered concisely to minimise any feelings that the course is taking up time unnecessarily. Although the same for all trainee groups, great care should be taken to make the course content interesting and dynamic. Providing as many interesting examples and exercises, close to real scenarios, can help to achieve this. Alternatively, development of the course into an eLearning course should be considered as future work so that seafarers could complete at least parts of the course remotely: either on leave or whilst onboard. For this reason the structure of the course should be developed so as not to inhibit further development into eLearning in the future.
- In many cases seafarers will rarely work with the same seafaring team and/or on the same ship. This is a disadvantage toward energy efficient ship operation as achieving teamwork and integrated operations to maximise energy efficient ship operation is all that much harder. Not only is teamwork harder when you don't know other colleagues knowledge, skills and personalities; but it is also it is harder to generate motivation toward improving the performance of a ship when no attachment and operational pride is generated towards the ship and team. This will be even harder if other team members do not have the motivation toward energy efficiency, most likely the case with only a newly developing energy efficiency culture. Furthermore, motivation is made harder with no recognition of effort made. Whilst it is recognised that company procedures will have a significant role to play in encouraging energy efficient ship operation, the developed MET

course on energy efficiency should therefore also promote and stress all benefits, other than just the company's benifit.

- In contrast to cadet, existing seafarers may have been working at sea for many years. During this time an energy efficient culture has not been a priority and therefore, current seafarers are likely to have more ingrained habits and viewpoint. It is not expected that an energy efficiency culture will develop over night: for example the safety culture observed onboard today has taken years to establish and can still be greatly improved. Therefore the course must be presented in a way to start increasing an energy efficiency culture as much as possible: noting that this is in parallel to and to no detriment of an improved safety culture.

The MET requirements for onshore personnel include:

- As with seafarers, it is most likely that onshore personnel will complete the MET course as an intensive training course; preferably with seafarers so that the practical implementation of energy efficiency best practices can be discussed to increase understanding. The design structure of the course should also be flexible for delivery in additional formats, such as an evening course.
- As expected, onshore personnel will not need to focus on the technical skills related to the direct operation of the ship in to the same level that is required by deck and engineering trainees. However it is the intention that they should gain an overview knowledge of some of the restriction and implications of practical onboard operations to improve integrated operations: i.e. understanding, knowledge, decision making and communication between ship and shore. Dependent on the onshore personnel's past education and job roles, they may or may not have worked as a seafarer or undergone onboard experience. Therefore the content of the course should be flexible so that

sections can be emphasised to ensure that the required awareness and knowledge is delivered to the onshore trainees.

C4: Specification Specific to MET Design and Development

This extends on the specification presented in Section 5.4.4. as it focuses on the more generic points related to the development of a MET on energy efficiency. The specification for the developed MET course on energy efficiency

- It must compliment existing MET.
- It must promote the delivery using best MET recourses and pedagogical methods for each delivery MET Institute and trainee group. Recourses to help trainers achieve this should be provided.
- The developed material for the MET course on energy efficiency must provide the trainer of the course with a minimum level of focused knowledge on energy efficient ship operations and the drivers for energy efficiency.
- The course structure, strategy and material needs to be flexible for the following reasons:
    - To be delivered as part of a: yearly curriculum, a condensed intensive course
    - To allow delivery using different platforms and resource , in different environments
    - To allow for different teaching techniques and styles
    - To allow for trainee groups' exiting experience, knowledge, skill levels and learning preferences.
    - To allow for delivery of generic or company specific courses
- The developed course should be suitable for assessment where a feasible for external certification in the future.
- The course material should encourage trainee motivation towards energy efficiency but providing understanding about carbon emissions and energy efficiency and highlighting key awareness, knowledge and behavioural aspects

- Ensure that the course content teaches both non-technical skills (including the human factor element) as well as further enhancing existing key technical skills of the trainees.
- Ensure that integrated operations are promoted and where possible a mix of operating departments are encouraged to be enrolled on one course.
- A sufficiently large knowledge, scenario, question and exercise bank should be developed for the course where the information used is kept authentic and realistic unless there is a benefit otherwise.
- The material must maintain consideration of other primary focuses, such as safety, thus offering practical solution,
- The material should promote all benefits of implementing the energy efficiency operations; not just those gained by the fuel paying stakeholder.
- The course should be sustainable with a plan for continual updates as energy efficiency is an area that is rapidly changing, new practices are being identified, and new ship designs and technologies being used.

C5: Framework for a MET Course on Energy Efficiency

Educational approaches and platforms have been discussed in C2 and it was highlighted that a combination of the different approaches and platforms should be selected based on:

- The most effective approaches and platforms to deliver the learning objective
- Varying the approaches and platforms to reduce repetitive mundane learning
- Varying approaches and platforms to consolidate knowledge and skills
- The resources and facilities available
- Trainer teaching preferences

- Trainee group learning preferences

The framework that was constructed to conceptualise the structure, development and delivery of the MET course on energy efficiency is shown in Figure 75 and the following points describe its main features.

- **Knowledge Bank**

The primary feature for framework shown in Figure 75 is the Knowledge Bank. This Knowledge Bank is representative of all the factual information that is required for the MET course on energy efficiency content. Prior to construction of the course training material this Knowledge Bank was created from the following:

- Published research papers, thesis's, published industry documents (some of which are summarised in Chapters 2)
- Knowledge, information, data and examples collected via several field studies (summarised in thesis Chapters 2 but predominantly Chapter 5)
- Information, data and examples generated from the analysis of ship operating profiles (Chapter 8)
- Information data and examples generated from the analysis of Ship Report (SR) data utilised in the developed Ship Operational Performance Prediction (SOPP) model (Chapters 7, 9 and 10).

- **Question, Scenario and Data Banks**

In conjunction with the Knowledge Bank, the framework presented in Figure 75 includes a Question Bank which can be utilised for both course teaching (i.e. for exercises, discussions, workshops) and for assessment. It has been mentioned that the educational material should be authentic and as close to a real scenarios as possible.

▪ Module Development

Based on the Question, Scenario, Data and Knowledge banks, the framework shown in Figure 75 demonstrates how the relevant content of each bank should be collated for each course topic. The framework was set up to demonstrate the flexibility of module construction so that it can be done both dependently with existing MET (i.e. when the MET will be combined with an existing course curriculum) and independently (i.e. when the course is run as an independent training course).

▪ Delivery Development

Based on the module topic material, the framework then demonstrates the flexibility in being able to decide the best delivery person, platform and approach, based on the recourse and requirements of the particular MET institute, trainer and trainee group.

▪ Expected Impacts after Delivery

The framework presented in Figure 75 demonstrates the expected impact for the trainee groups. These impacts include:

- Increased awareness: i.e. of the carbon problem, energy efficiency regulations, energy efficiency best practices and how improvements can be made.
- Increased knowledge: i.e. about carbon problem, energy efficiency regulations, energy efficiency best practices and how improvements can be made.
- Increased technical skills and problem solving skills: i.e. being able to identify where energy efficiency improvements can be made and implementing them, in varying and dynamic scenarios.

- Increased communication and teamwork skills: i.e. being able to implement improved integrated operations contributing to more efficient operation of the ship.
- Increased confidence and motivation: i.e. due to all of the above giving the trainee confidence by knowing how to implement improvements and hence, likely, increased motivation.

▪ **Course Sustainability**

It is recognised in the framework presented in Figure 75 that after completion of the course the trainees will gain experience, observation, opinions and generate additional knowledge, based on everything that they learnt during whilst undertaking the MET course on energy efficiency. Feedback of theses experience, observation, opinions and generated knowledge then becomes important to capture as they can be used to:

- Update and improve the course content
- Add additional scenarios and implementation case studies to the scenario and question banks.
- Report on the practicality of implementation and observed benefit from implementing energy efficiency best practices.

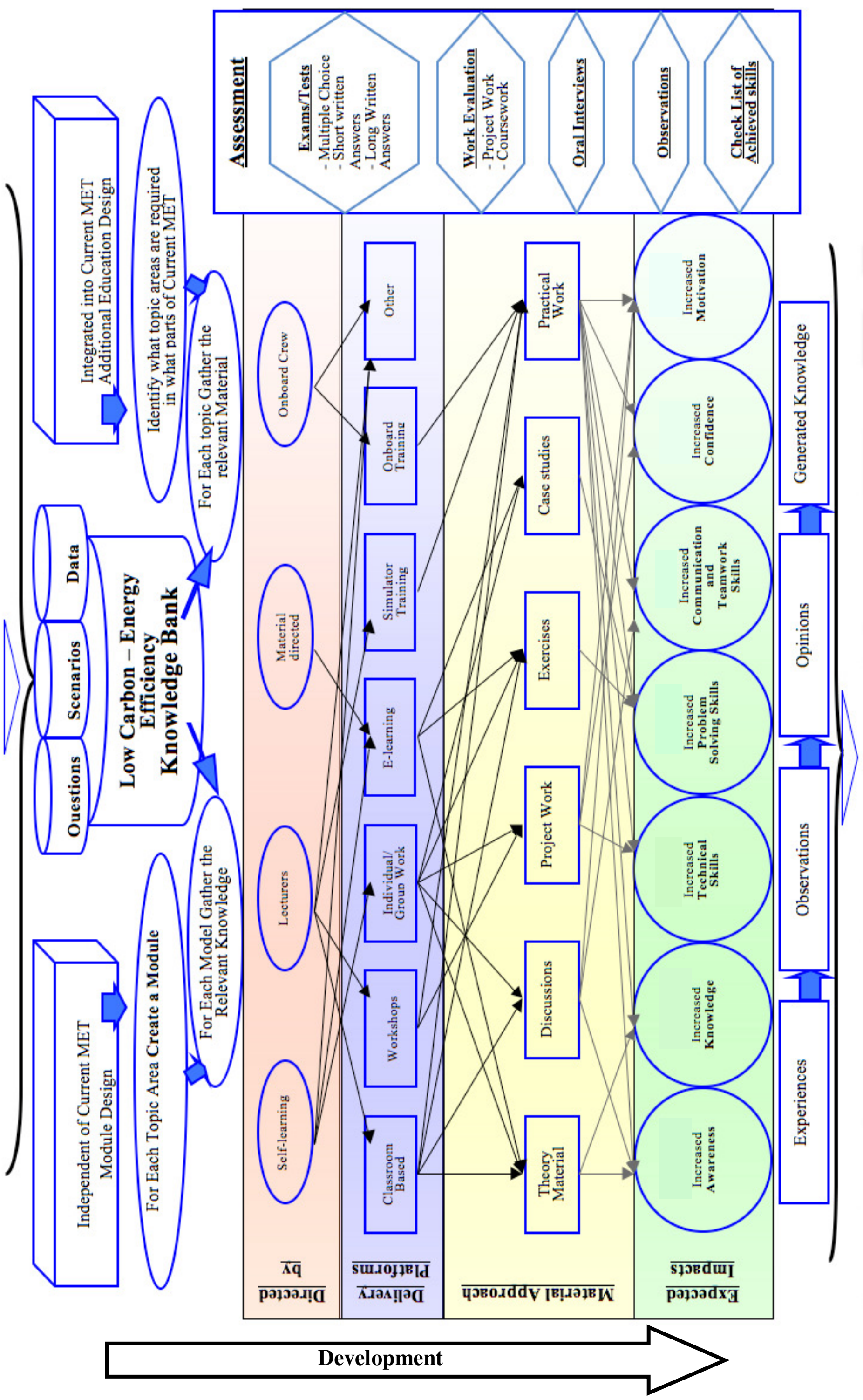


Figure 75: Curriculum framework for the development of a MET course for energy efficiency

Appendix D – Investigation of Ship Operational Performance Monitoring

This Appendix presents an initial investigation to examine the opportunities for Ship Operational Performance Prediction (SOPP) modelling using Ship Report (SR) datasets. The analyses presented were used to conclude that an alternative method for SOPP modelling using SR datasets was required; hence the SOPP model presented in Chapter 9 was developed. The case study Ship T1 (also used to demonstrate the development of the SOPP model) was used to provide examples in this appendix. A description of the data and information collected for this ship can be found in Chapter 7 and Sub-section 9.1.1.

Several methods for Ship Operational Performance Prediction (SOPP) and Monitoring (SOPM) were discussed in Section 2.4.5, including: analysis by filtering for specific conditions; combining parameters into relationships; regression analysis. It was identified that these methods provide predictions but with a large amount of uncertainty, particularly when using Ship Report (SR) operational datasets, commonly known as Noon Reports. Whilst it was not expected that the conclusions would be different, applications of these analysis methods using the collected SR datasets was considered important to start understanding: the data; its utilisation applicability and limitations for SOPP and SOPM; the case study ship performance. Thus results for the following analyses methods are presented in this appendix.

- Fuel Flow Rate (FFR) over time, no filtering
- FFR over time, filtering for: load type, dry docks
- Fuel Consumption Ratio over time
- FFR over time, filtering for: load type, dry docks, Beaufort Number, speed range

- FFR over time, filtering for: load type, dry docks, Beaufort Number, speed range, wind direction
- FFR Regression Analysis

D1: FFR over Time, no Filtering

The Fuel Flow Rate (FFR) represents the tonnes of heavy fuel oil consumed by the main engine per day. It is the single data recorded in the SR datasets that provides most information about ship performance (considering that brake power is not often recorded and only recorded in small proportion of the datasets for the case study ships.

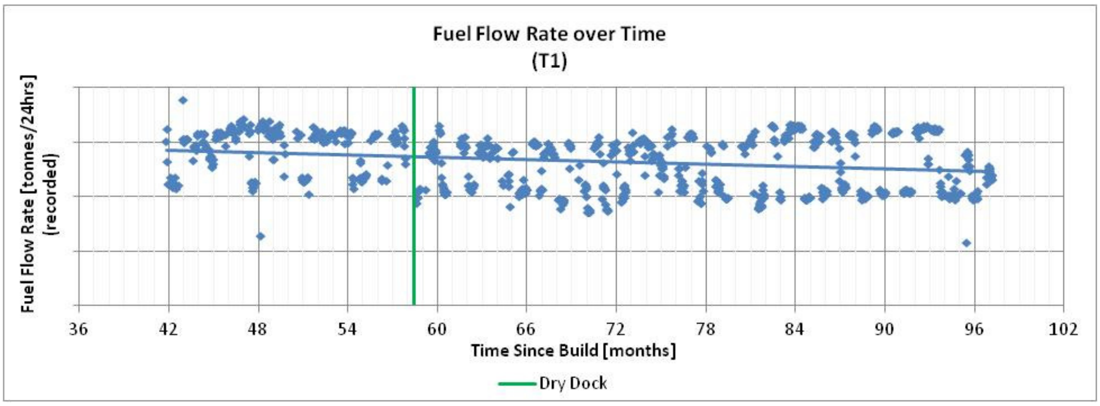


Figure 76: Fuel flow rate over time without any filters applied, Ship T1

The first, most simple analysis was to plot the FFR against time, applying no data filters. Using case study Ship T1 as an example, Figure 76 demonstrates the following:

- Using FFR without out any filters produces a large amount of scatter and a decreasing trend fuel performance over time: this is contrary to what would be expected with increasing hull and propeller fouling over time that would increase ship resistance and hence the FFR.
- Reasons for the decrease in FFR over time and the large scatter in the data are due to other operational influences, such as operation at and in different:

speed, draft and trim ranges; weather and sea conditions; hull and propeller fouling and degradation conditions, including before and after dry dock.

- Using Figure 76 alone and not knowing the dates of ship maintenance, it would be impossible to determine the time when Ship T1 went into dry dock (represented by the vertical green line).
- It can therefore be concluded that this very simple analysis of the FFR without applying any data filtering, offers very little insight into ship operational performance.

D2: FFR over Time, Filtering for: Load Type, Dry Docks

FFR was plot over time, but with the following filters were applied to the SR dataset:

a) Ballast or Laden operation

b) Before or after Dry Dock

Figure 77 presents the results for case study Ship T1, demonstrating the following:

- The benefit of dry docking appears to correspond to a FFR reduction of 10% in laden and 23% in ballast.
- Whilst there is clearly a benefit of using this analysis to assess significant changes in FFR, it cannot be considered that the FFR reduction percentage is solely due to the dry dock or maintenance event. This is because other operational factors that are known to influence ship performance have not been assessed for their impact: such as changes in operational speed or draft. This consideration is arguably supported by the FFR in MP3, for the laden condition, which is very slightly decreasing. This is not what would be expected if indicative of hull and propeller surface fouling and degradation alone.
- For these reasons it was concluded that filtering data for maintenance parts and loading conditions, provides an insight into FFR saving benefit gained

from carrying maintenance. However this analysis still cannot be considered suitable for making quantifiable predictions of the performance benefits related to hull and propeller maintenance.

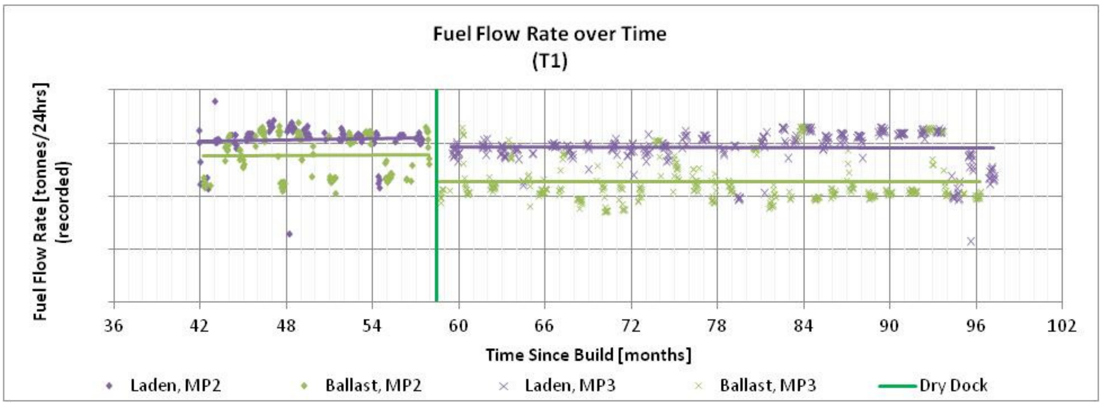


Figure 77: Fuel flow rate over time with ballast/laden and before/after dry dock filtering applied, Ship T1

D3: Fuel Consumption Ratio over Time

In Sub-section 2.4.5 the use of performance relationships, such as the Admiralty Coefficient (E.24 in Appendix A), for performance prediction monitoring methods was discussed. As power and displacement are not data variables commonly recorded in SR data sets, the Admiralty Coefficient could not be used for this analysis. Thus the comparative Fuel Consumption Ratio, utilising draft and FFR variables, was used. The Fuel Consumption Ratio, as presented in (Molland et al. 2011), is shown below:

$$FC_{ratio} = \frac{draft \times V^3}{FC}$$

Where: FC_{ratio} = fuel consumption ratio, V = ship speed, FC = FFR= fuel consumption in tonnes per 24 hours

Different from the previous analyses, the Fuel Consumption ratio captures the relationship between how the FFR changes with draft and ships speed cubed.

Figure 78 presents the analysis for case study Ship T1 with filters applied for load type and dry docks. It demonstrates that:

- For case study Ship T1 the Fuel Consumption Ratio decreases over time and increases after dry dock, seen in. This trend is expected as for a constant draft and ship speed and an increase in fuel consumption (i.e. due to an increase in fouling and degradation) the ratio will decrease.
- Whilst there is benefit of calculating the fuel consumption ratio as it identifies the FFR saving after the dry dock, a large amount of scatter is still evident.

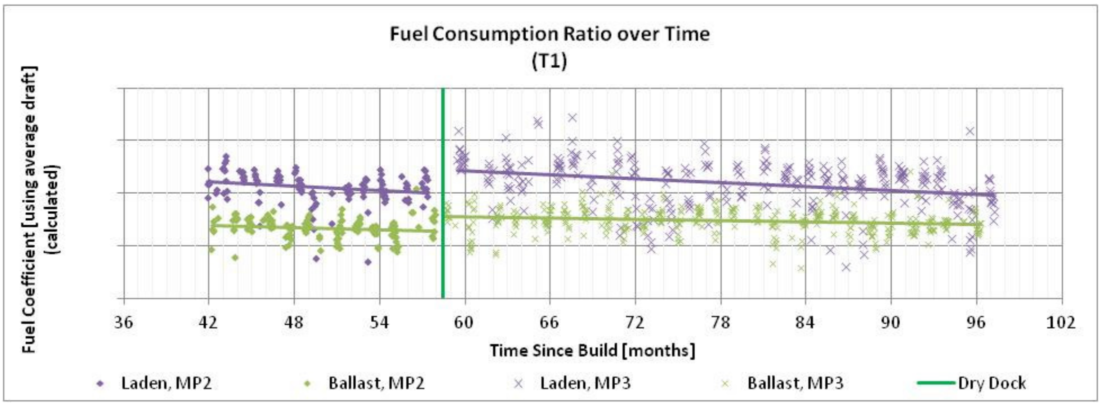


Figure 78: Fuel consumption ratio over time with ballast/laden and before/after dry dock filtering applied, Ship T1

To investigate the prediction capabilities of the Fuel Consumption Ratio, the trend lines equations produced for the ballast and laden conditions, in MP2 and MP3, were used to predict the FFR for reach SR record based on time since build.

Table 46 presents the absolute average error between the predicted Fuel Consumption Ratio using the trend line equations, and the ratio calculated from the recorded values in each SR record. The prediction errors ranges between 6.8% and 13.6% and cannot be considered sufficiently accurate for quantifying ship performance: particularly considering that a 10% error in the prediction of FFR corresponds to a significant difference in tonnage of fuel consumed, hence the predicted cost of fuel per day, voyage or over a longer period of time.

Table 46: Absolute Average Error using the Fuel Consumption ratio to predict ship performance, Ship T1

	Average Absolute Error	
	MP2	**MP3**
Ballast	13.65%	13.60%
Laden	6.82%	9.07%

D4: FFR over Time, Filtering for: Load Type, Dry Docks, Beaufort Number, Speed Range

FFR was plot over time, but with the following filters were applied to the SR dataset:

a) Ballast or Laden operation

b) Before or after Dry Dock

c) Beaufort Number

d) Speed Range (at 1 knot intervals)

Figure 79 presents the results for case study Ship T1 and the data points corresponding to Beaufort Number 3. Figure 79 demonstrates the following:

- Maintenance Part 2 demonstrates no consistent trends, although the FFR is shown to be less at lower speeds.
- For the speed ranges at 14 and 15 knots, there is a reduction if FFR after the dry dock, with an increasing trend thereafter.
- The scatter in reduced but not eliminated and inconsistent trends are identified, thus this level of filtering with SR data was not considered suitable for SOPM.

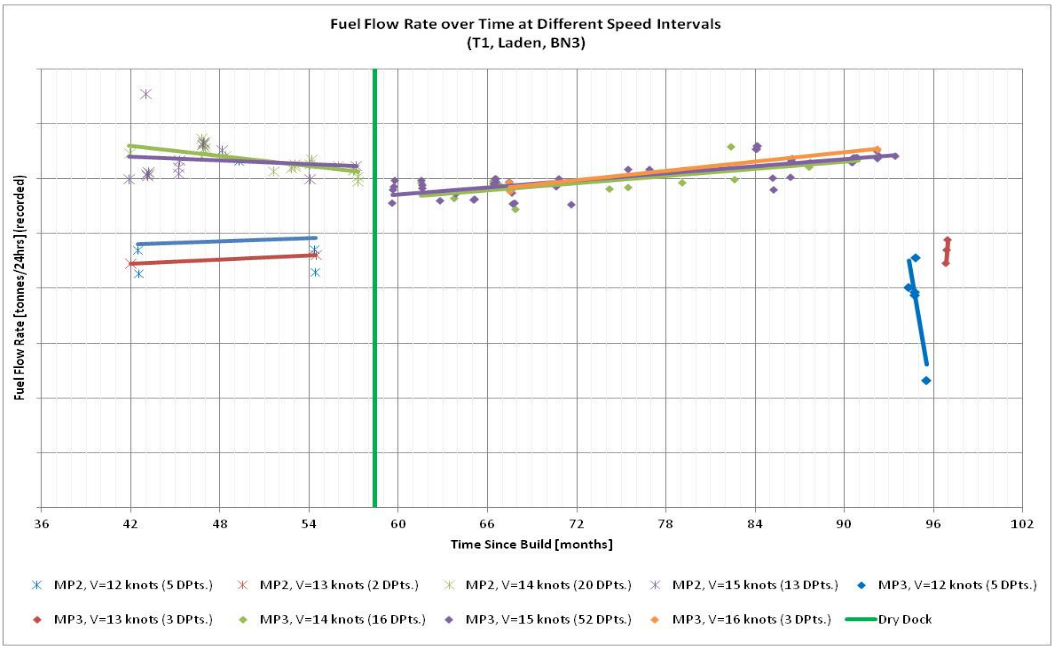


Figure 79: Fuel Flow Rate over time in Laden and Beaufort Number 3, for different speed ranges, Ship T1

D5: FFR over Time, Filtering for: Load Type, Dry Docks, Beaufort Number, Speed Range

The last filtering analysis carried out was to plot FFR over time, but with the following filters were applied to the SR dataset:

a) Ballast or Laden operation

b) Before or after Dry Dock

c) Beaufort Number

d) Speed Range (at 1 knot intervals)

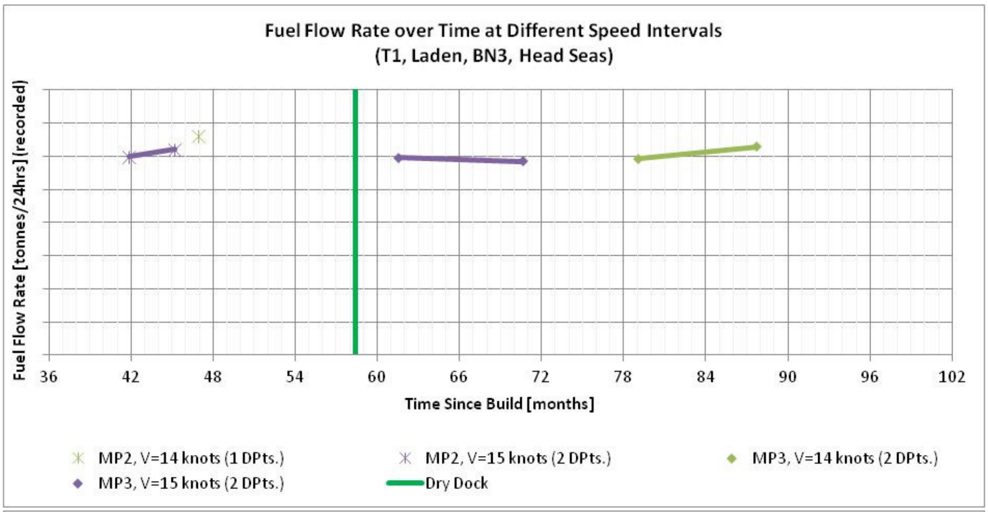
e) Wind direction

Figure 80 for case study Ship T1 demonstrates the following:

- Scatter once again appears to be reduced but inconsistent trends are identified.

- Despite having 56 months (over 4 years) of data to utilise for the analysis, filtering very quickly reduces the number of data points available to detect trends.

Ideally as many data points as possible would be required so that random error and uncertainty in the recorded data is averaged over time, and true performance trends become more accurately represented. For many of the case study ships, and at different Beaufort numbers, the number of data points available for analysis were even less than those shown in Figure 80.



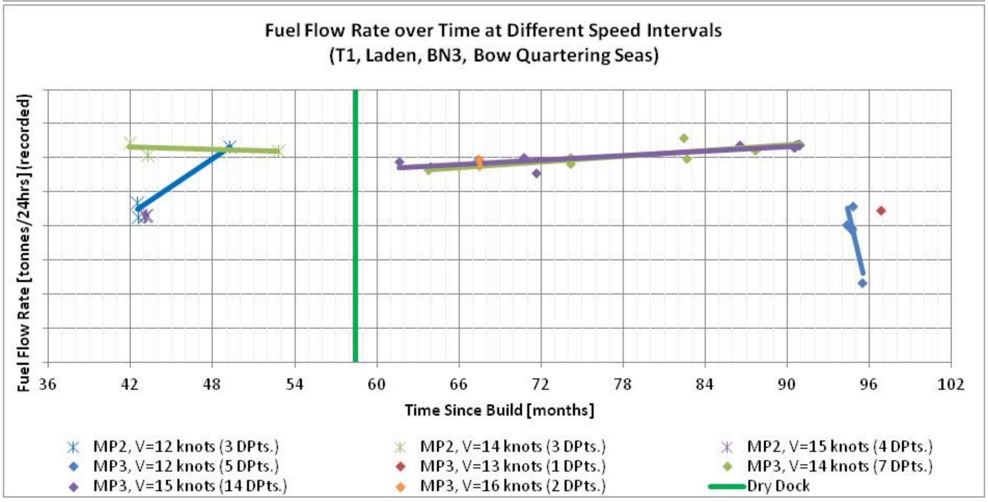


Figure 80: Fuel Flow Rate over time in Laden and Beaufort Number 3, for different speed ranges and wind directions, Ship T1: Part 1

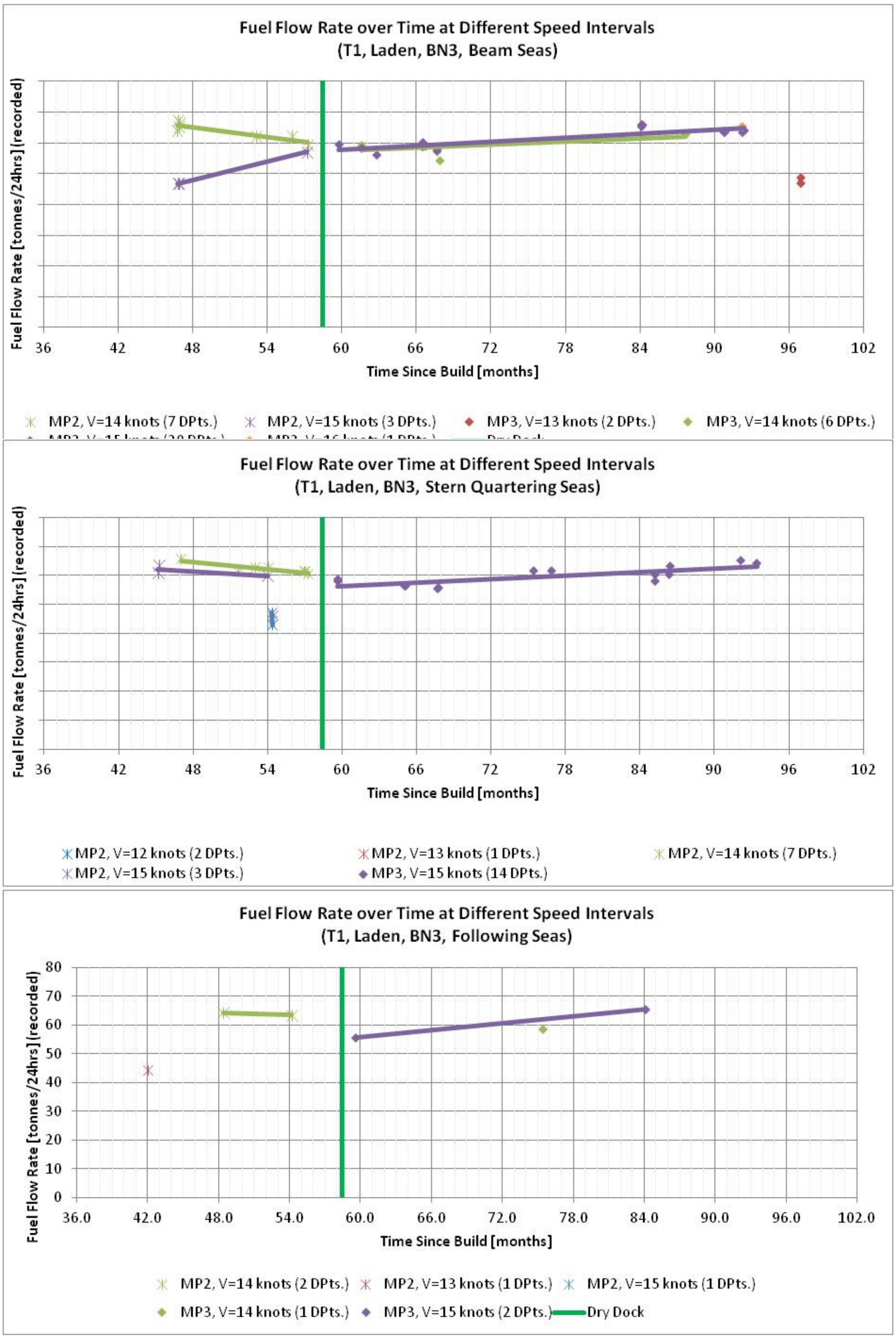


Figure 80: Fuel Flow Rate over time in Laden and Beaufort Number 3, for different speed ranges and wind directions, Ship T1: Part 2

D6: FFR Regression Analysis

A regression analysis was carried out using the same method described for the Resistance and Speed Regression Analyses presented in Sections 9.3 and 9.4. The Criterion Variable (CV) was selected to be the FFR, and the Predictor Variables (PV's) were ship speed, average draft at mid ship, Beaufort Number, and wind direction. How these variables were included in the regression analysis is discussed in the following appendix section.

- **Exploratory Analysis, Correlation Matrix Plots**

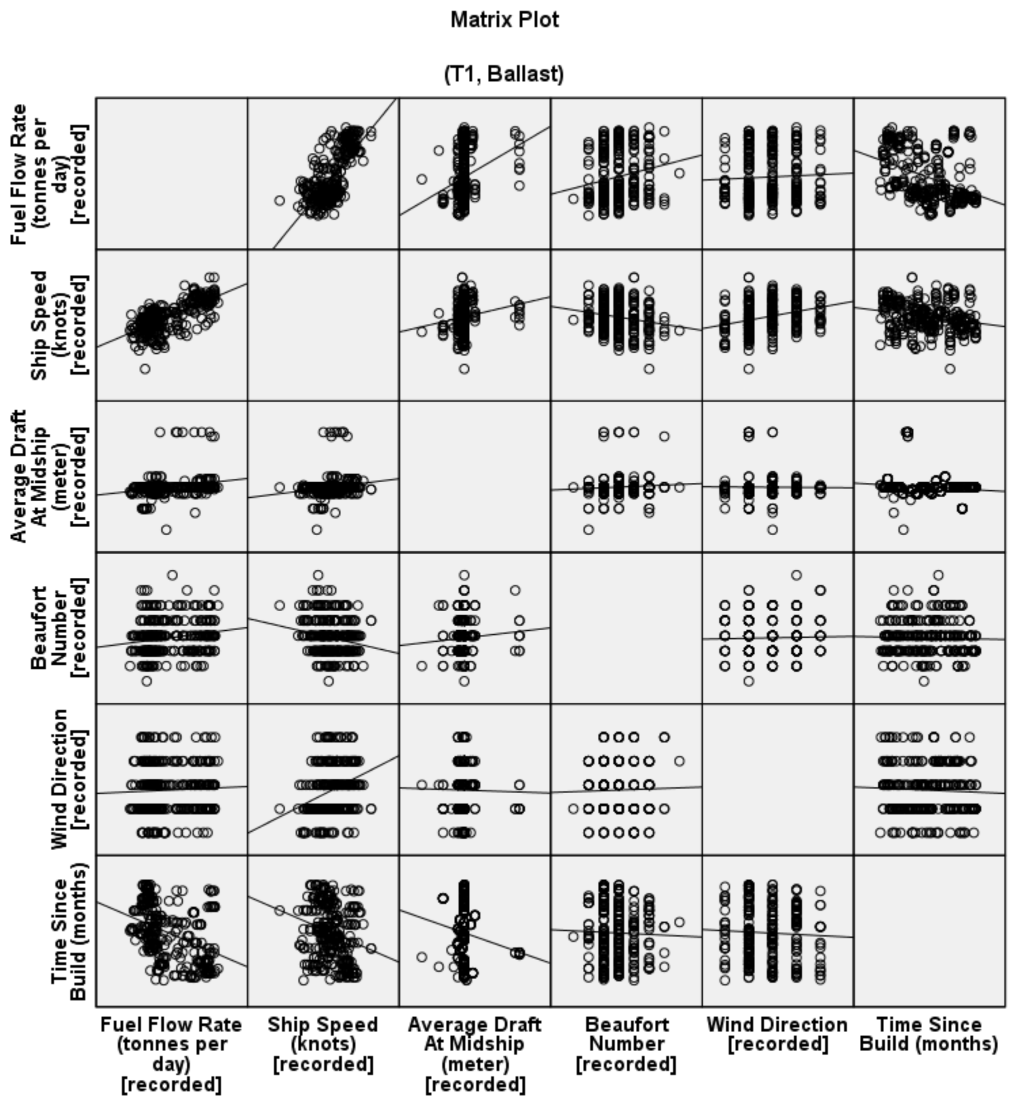


Figure 81: Correlation Matrix, Ship T1, Ballast

An exploratory analysis was carried out to observe the cross correlations between the CV and PV using a Correlation Matrix plot. Although not included as a PV, the time since build was included in the Correlation Matrix to observe the relationships it has on the other variables.

Figure 81 presents the Correlation Matrix for the ballast condition and it demonstrates the following:

- As the ship speed, average draft at midship and Beaufort Number increase, the FFR also increases. These relationships are expected considering principals of resistance and propulsion (as discussed in 2.4).
- The FFR increases slightly with increasing wind direction (i.e. moving from head seas to following). This relationship is not expected as the relative ship speed through the water in following seas is expected to be less than in head seas, a least in Beaufort Numbers less than 4 or 5.
- Related to the point above, ship speed increases with an increase in wind direction. This could indicate that the operational practices is to utilise the performance gain from following seas as a speed increase rather than power and hence fuel consumption reduction.
- As Beaufort Number increases, so too does the FFR, and the ship speed decreases.
- The FFR in ballast has decreased over time, which would not be expected with the impact of hull and propeller fouling and degradation. However, it can also be observed that the ship speed has too.
- The average draft at midship has not to change much over time (complimenting the conclusions made in Chapter 8: Data Analysis of ship operating profiles)
- The distribution of Beaufort number and wind direction with time since build is shown not to follow a trend and demonstrate a large amount of scatter. This

is expected as the weather and sea conditions are considered completely independent of the other PV's and random on the different routes of operation.

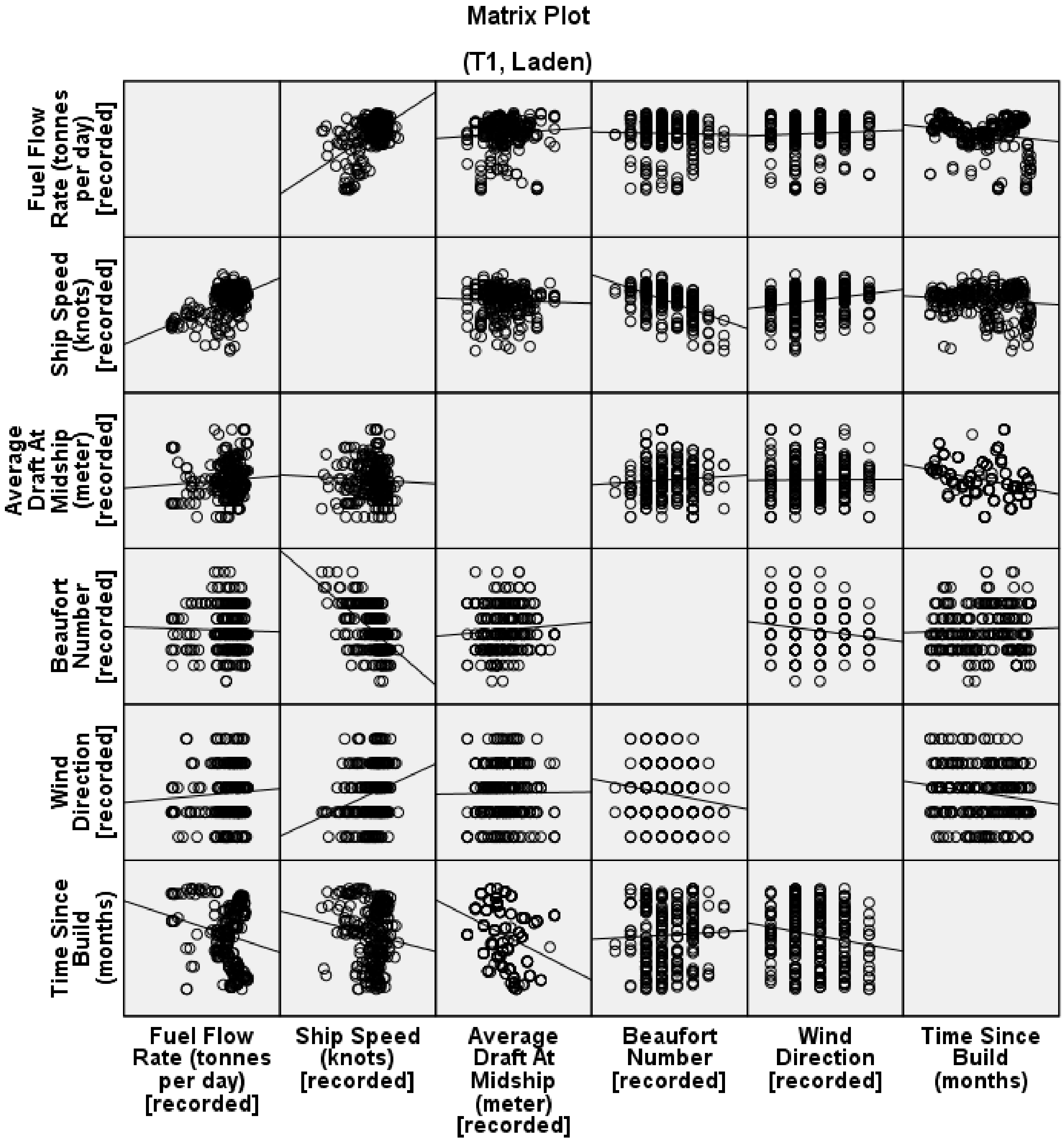


Figure 82: Correlation Matrix, Ship T1, Laden

Figure 82 presents the Correlation Matrix for the laden condition and demonstrates the following:

- The FFR increase with average draft at mid ship as expected. This correlation is stronger than in ballast most likely due to the wider range of sailing drafts utilised.
- The FFR increases with ship speed, comparable with the ballast correlation, but demonstrates greater scatter. This is considered reasonable as the FFR will be affected by the range of average drafts and the impact of the Beaufort Number and wind direction when operating at a larger draft.
- The FFR increases only slightly with an increase in Beaufort Number. However, there is a stronger negative correlation between Beaufort Number and speed than there was for ballast. This is considered most likely due to a voluntary reduction in speed when operating with a greater draft to avoid unsafe ship motions.
- The FFR increase very slightly with an increase in wind direction (noting that the scatter is too great to conclude a definite trend). As for the ballast condition, the speed increases with an increase in wind direction, most likely indicative of operational practice to utilise the performance gain as a speed increase.
- Similar to the ballast condition, the ship speed and FFR decrease over time.

▪ Exploratory Analysis, PV Transformations

From Figure 81 and Figure 82, visually, a sufficient linear relationship between the FFR and the ship’s speed can be observed, although there is a large amount of scatter. However it is known from resistance and propulsion principles that power increases approximately to the cube of ship speed. Therefore it was considered that a transformation should be applied to the ship speed to account for this non linear relationship. The sea trial power-speed curves for the case study Ship T1 were used to determine the exponent of speed in the relationship. The exponent was determined to be 3.6 for the ballast condition and 3.1 for the laden condition. This transformation improved the coefficient of determination (R^2) in the ballast condition very slightly; from 0.51 to 0.56 (shown in Figure 83). For Laden the R^2 value did not change. Whilst not demonstrated to be a great benefit statistically, the transformations were applied within the regression analysis.

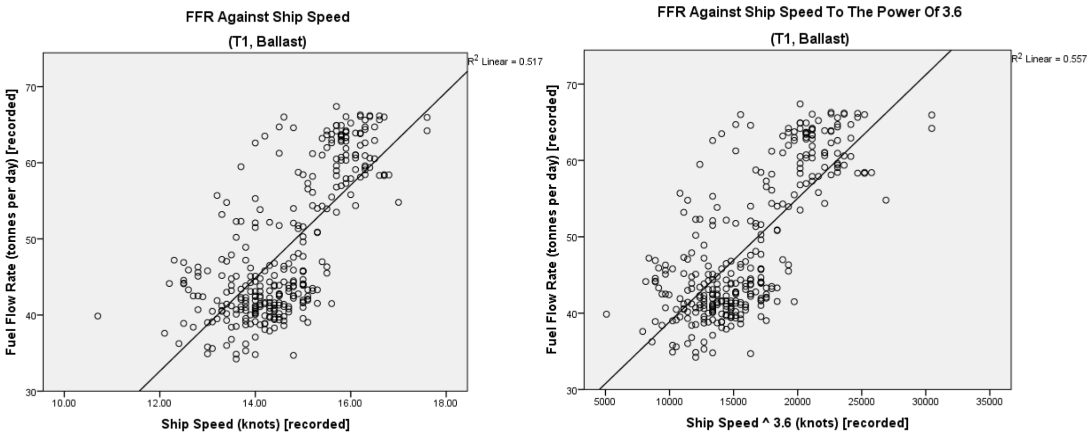


Figure 83: Correlation between the fuel follow rate and ship speed, Ship T1, Ballast

▪ The regression method

For the ballast condition regression analysis, the following variables were used:

- CV: FFR
- PV's: ship speed$^{3.6}$, average draft at midship, Beaufort Number, and wind direction.

For the ballast modelling sample, the stepwise regression method[29] was selected first for the multi-linear regression method in SPSS. No variables were excluded from the

[29] *For the Stepwise method selects which PV's are enter into the regression analysis based on their statistical significance with the CV*

regression prediction equation, meaning that all PV's were considered significant for inclusion.

For the laden condition regression analysis, the following variables were used:

- CV: FFR
- PV's: ship speed$^{3.1}$, average draft at midship, Beaufort Number, and wind direction.

The stepwise regression was also used first, but the wind direction was found to be statistically insignificant and was removed from the analysis. Therefore, the Entre method[30] was used for the analysis to ensure account was taken for wind direction, even if the influence is small.

The modelling samples for ballast and laden (described in 9.3.1) were used for the regression analysis.

▪ **Model Summary Statistics Results**

Table 47 presents the coefficient of determination (R^2) values for each generated prediction equation using the modelling data sample. It is demonstrated that:

- The ballast prediction equation accounts for 70% of the variability in FFR, given the input PV's
- The laden prediction equation accounts for only 40% of the variability in FFR, given the input PV's. This is considered a low prediction.

[30] *For the Entre method in SPSS each of the PV's are entered into the regression analysis and they can not be excluded.*

Table 47: Regression Model Summary Statistics, Regression Analysis, Ship T1

	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
Ballast	.837	.701	.697	5.19	0.960
Laden	.628	.394	.385	4.93	.695

▪ Performance Prediction Equation

The prediction equations generated by the regression analyses are shown below:

$$FFR_{Ballast} = \left(0.002 \times \mathrm{V_S}^{3.6}\right) + (3.348 \times \mathrm{T}) + (2.589 \times \mathrm{BN}) + (-0.040 \times \mathrm{WD}) - 14.174$$

E9.9

$$FFR_{Laden} = \left(0.005 \times \mathrm{V_S}^{3.1}\right) + (0.913 \times \mathrm{T}) + (1.678 \times \mathrm{BN}) + (-0.009 \times \mathrm{WD}) + 18.878$$

E9.10

▪ Validation

Table 48 and Table 49 demonstrate the ballast and laden condition results for the modelling and test samples. The following can be concluded:

- The average absolute error ranges from 6% to 11%. This is considered a large average error as it could equate to large error in daily, voyage or yearly fuel cost predictions.
- The sum of residuals is small indicating that even though the average absolute error is large, the over and underestimates cancel out. Thus a long term performance evaluation may identify average trends.

Table 48: Comparison of modelling and test sample statistics, Ship T1, Ballast

	Model Sample	Test Sample
Sample size	319	137
Sum of Residuals	1.38	0.10
Average ABS % Error	8.68%	10.47%
Max ABS % Error	38.35%	60.45%

Mean Calculated FFR	48.72	48.93
Standard Error	5.16	6.19
Standard Error %	9.92%	12.12%

Table 49: Comparison of modelling and test sample statistics, Ship T1, Laden

	Model Sample	Test Sample
Sample size	282	84
Sum of Residuals	0.47	3.84
Average ABS % Error	6.98%	6.11%
Max ABS % Error	38.76%	26.12%
Mean Calculated FFR	59.30	59.20
Standard Error	4.90	4.36
Standard Error %	8.27%	7.36%

D7: Conclusions of the Analyses

It was concluded from the analyses presented in D1 to D5 that data filtering techniques or performance relationships do not provide sufficient information to determine and quantify performance trends; particularly without a very large dataset available encompassing many years of data.

The conclusion from the FFR regression analysis presented in D6 was that a prediction of FFR can be made with a 6% to 11% absolute average error. This error is considered too large to be used for a SOPP model that meets the specification identified in Sub-section 5.4.6.

An alternative method is required to develop a SOPP model suitable for SOPM that fulfils the specification for a SOPP model identified in Sub-section 5.4.6.

Appendix E – Determined Total Propulsion Efficiency Relationships

During the development of the SOPP model in Chapter 9 the ***determined total propulsion system efficiency*** relationships were as part of the validation process: e.g. to convert the brake power for the sea trial power-speed curve, to resistance.

This appendix describes how the ***determined total propulsion system efficiency*** relationships were determined for the ballast and laden condition:

a) Select the following efficiencies calculated for each SR during the Data Elaboration Process (Section 9.2): propeller relative rotative efficiency, propeller open water efficiency, hull efficiency and hull efficiency.

b) Plot the data points for each SR record for each of the above listed efficiencies against the recorded ships speed (Figure 84 for the ballast condition and Figure 85 for the laden condition).

c) Determine the line equation for each efficiency-speed relationship

d) Use the line equations for each efficiency to calculate a value for each efficiency at 1 knot intervals of ship speed.

e) For each speed interval, sum the propeller relative rotative, propeller open water, hull and shaft efficiency to calculate the total propulsion system efficiency. Plot this against speed and determine the total propulsion efficiency-speed relationship: Figure 86.

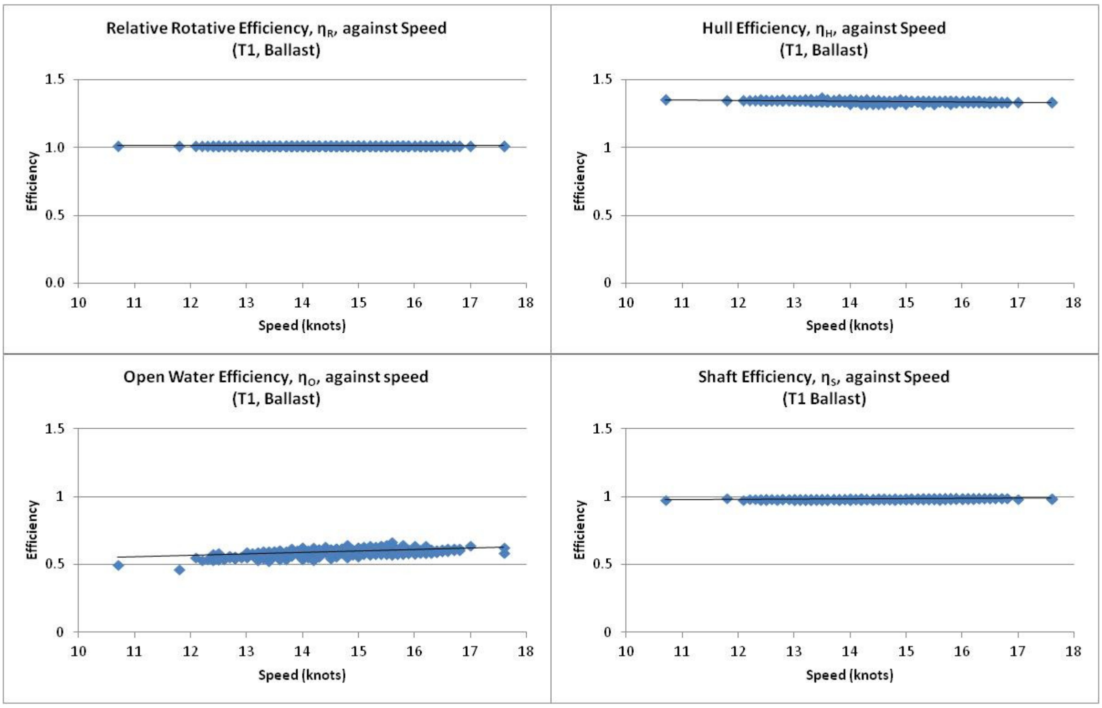


Figure 84: Propulsion system efficiencies against speed, Ship T1, Ballast

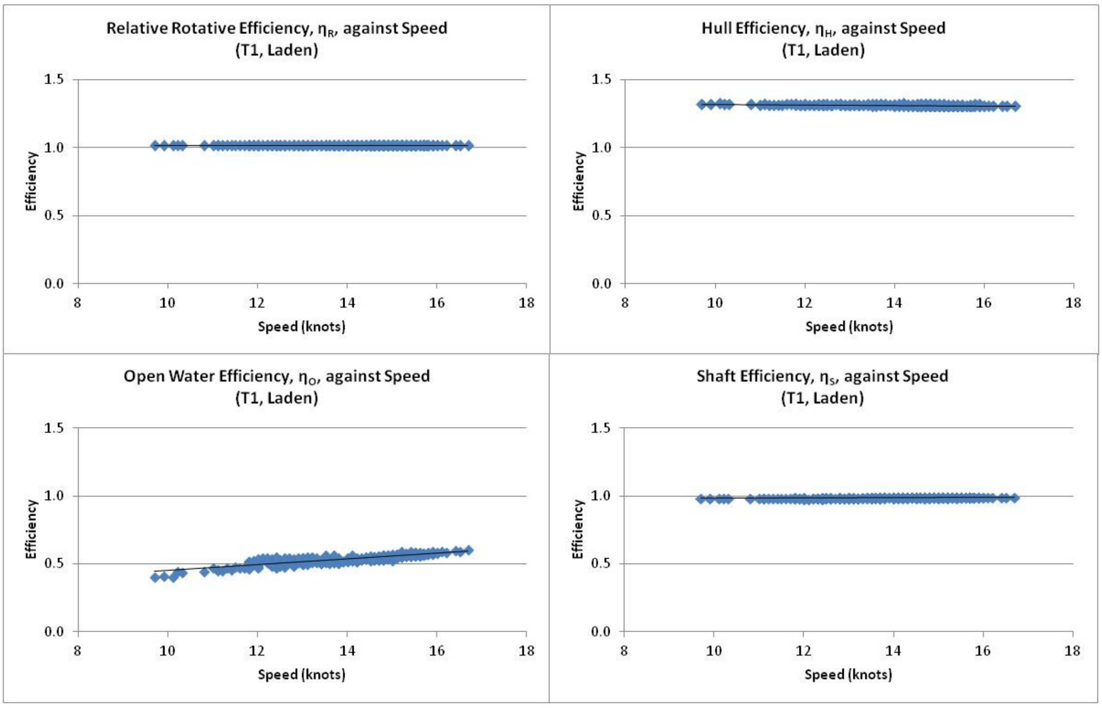


Figure 85: Propulsion system efficiencies against speed, Ship T1, Laden

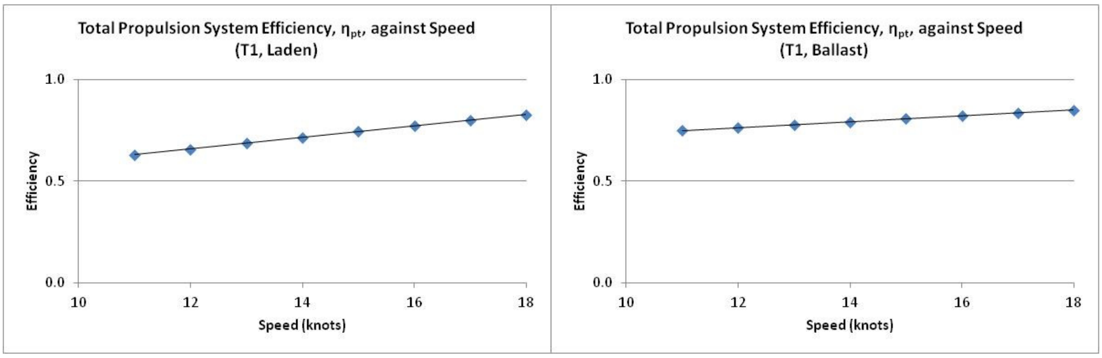


Figure 86: Average total ship propulsion system efficiency against speed, Ship T1

Figure 84, Figure 85 and Figure 86 demonstrates that all efficiencies remain relatively constant with ship speed except for the open water efficiency, which increases slightly with speed.

Figure 87 demonstrates the calculated total propulsion system efficiency for each SR record, compared to the determined total propulsion system efficiency trends identified in this Appendix. It demonstrates that the determined trends fit the data points well considering an average trend, although some scatter is still observed.

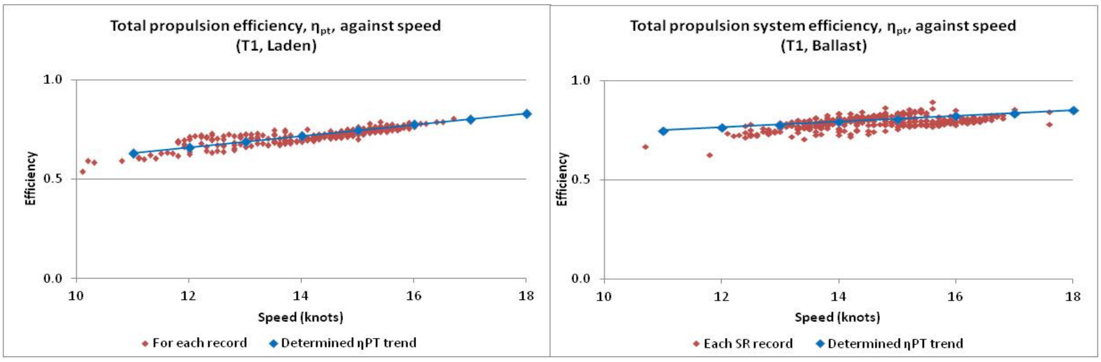


Figure 87: Determined total propulsion system efficiency against speed, compared to SR data points, Ship T1

Observing the change in total propulsion efficiency against speed using the methods described is a crude estimation. It is recommended that further work is undertaken to better represent changes due to other operational factors, and to plot the efficiency against load rather than ship speed.