CO2 Emissions from International Shipping

Possible reduction targets and their associated pathways

Appendix B – Technology and Operational intervention assumptions

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Preface

This report has been written by a team of experts from UMAS, UCL and LR for DSA.

Acknowledgements

This study builds on work undertaken in the Low Carbon Shipping (LCS) and Shipping in Changing Climates (SCC) projects. SSC is a £4m multi-university and cross-industry research project funded for 3.5 years by the UK Engineering and Physical Sciences Research Council (EPSRC). The SCC project uses a whole systems approach to understand the scope for greater energy efficiency of the supply side, understand the demand side drivers and to understand the supply and demand interactions and potential future evolution in shipping.

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1 Appendix B: Technology and Operational intervention assumptions

1.1 Introduction to this Document

This document contains a description of ship energy efficiency measures that are written (in Python) in the Whole Ship Model (WSM). The performance of energy efficiency measures on a thousands of ship sizes, types and speeds can be passed to GloTraM (a techno-economic global transport model for the shipping sector).

The WSM is an early stage design tool so this document focuses on calculation that can accurately estimate the performance of energy efficiency measures on a range of ships. r the shipping sector).

References are contained in each section, where particular technologies and methods are discussed, rather than at the end of the document.

1.2 List of Authors and Reviewers of Appendix B

The main authors of Appendix B are John Calleya, Santiago Suarez De La Fuente and Peng Wu. The authors would also like to thank Lloyds Register, Hans Otto Kristensen, Carsten Manniche and the other members of the Danish Shipowners Association for their comments.

Verification and comments and verification were also provided within UCL as well by Giles Thomas, B Blanca Peña and Manish Tiwari.

1.3 About the Whole Ship Model

The Whole Ship Model (WSM) is an integrated modelling and design tool that has been developed over two different projects – Shipping in Changing Climates (SCC) and Low Carbon Shipping (LCS) – to allow the evaluation of the design, performance and cost impacts of a range of technological and operational approaches with the aim of reducing ships' carbon dioxide emissions. The SCC project has seen the re-development of the software from the original MATLAB implementation into PYTHON. This was accompanied by a significant change to the software architecture to better integrate more sophisticated models of the various technological and design options, with a particular interest in allowing the project to identify potential synergies between combinations of options [Calleya et al. 2016].

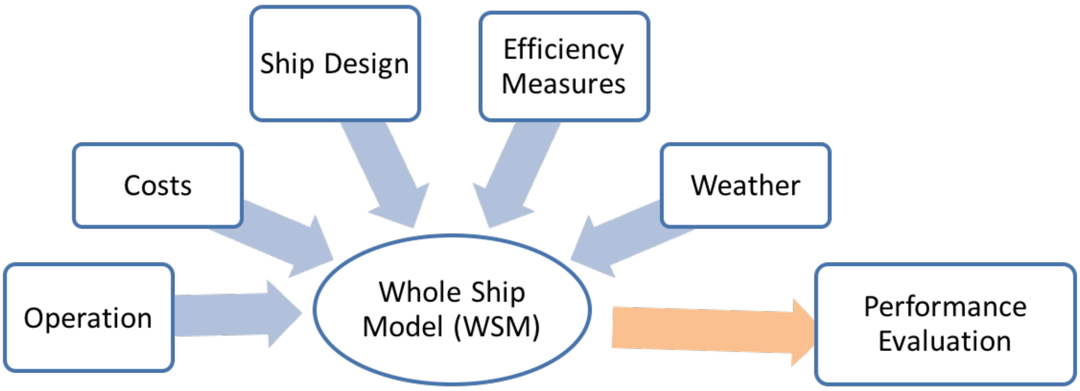

Figure 1: Inputs to the Whole Ship Model [Calleya et al. 2016].

The output from the WSM contains many calculated parameters describing how the ship system is designed and operated, such as energy requirements, engine fuel consumption, propeller efficiency, hull shape, etc. For each ship – of which thousands of variants can be calculated, information on the design points, energy flows and efficiencies of the component parts of the ship can be analysed [Calleya et al. 2016].

The WSM is a robust but flexible tool which incorporates different configurable options at the design point such as propeller type, blades and speed, ship characteristics (e.g. beam), hull characteristics, engine rating, applicable regulations, etc. Although The WSM allows for a range of ship input parameters to be used, for this study the default characteristics were set using the Third IMO Greenhouse gas study [Smith et al. 2014].

1.4 Output from WSM

The WSM works at a ship level and is run for all possible conditions, aggregates are calculated in the WSM and its output file is saved as a Comma Separated Variable (CSV) file. The output can also be passed to the Global Transport Model (GloTraM) and other tools for aggregating and exploring results.

1.5 WSM to GloTraM

The WSM works at a ship level. When doing a run for GloTraM the WSM is required to run a range of ships that represent the international shipping fleet. Over 1000 different design and technology options are calculated, which then are passed to GloTraM as a look-up database. GloTraM can then select ship designs (with technologies) at a fleet level based on profitability considering future trade demands and regulation.

Different fuel and operational speeds are core to both models and are evaluated separately from the technologies in this document.

1.6 Compatibility between Technologies

The WSM and Glotram use an incompatibility table which records what technologies can or cannot be combined in a particular ship. As seen in Figure 2, zero tells the codes that the technologies are compatible, while one is given when they are incompatible. The list has been built with UCL experience and discussion with the industry.

Technology Name	Bulbous Bow	Rudder Bulb	Preswirl Stator Duct	Trim and Draught Optimisation	Vane Wheels	Contra-rotating Propeller	Tip Loaded Propeller	Stern Flaps	Biocide Hull Coating	Foul Release Hull Coating	Future Hull Coating	Air Lubrication	Sails	Block Coefficient Reduction	Flettner Rotor	Kite	Superstructure Mass Reduction	Superstructure Aerodynamic Improvements	Solar power	Energy Saving Lighting	Steam WHR	Organic Rankine Cycle WHR	Turbocompound Series	Turbocompound Parallel	Hybrid Turbocharging	Engine Tuning	Engine Derating	Common Rail	Variable Speed Control of Pumps and Fans	Energy Storage System	Autopilot Upgrade	Hull Cleaning
Bulbous Bow	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rudder Bulb	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Preswirl Stator Duct	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Trim and Draught Optimisation	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Vane Wheels	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Contra-rotating Propeller	0	0	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tip Loaded Propeller	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Stern Flaps	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Biocide Hull Coating	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Foul Release Hull Coating	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Future Hull Coating	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Air Lubrication	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sails	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Block Coefficient Reduction	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Flettner Rotor	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kite	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Superstructure Mass Reduction	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Superstructure Aerodynamic Improvements	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Solar power	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Energy Saving Lighting	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Steam WHR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Organic Rankine Cycle WHR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Turbocompound Series	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0
Turbocompound Parallel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
Hybrid Turbocharging	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0
Engine Tuning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Engine Derating	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Common Rail	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Variable Speed Control of Pumps and Fans	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Energy Storage System	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Autopilot Upgrade	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Hull Cleaning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Figure 2: Incompatibility table used in WSM and GloTram for technology combination on board the ships.

1.7 The Role of Fleet Management and Operational Measures

The Danish Shipowner's Association highlighted an important role of effective fleet management and operational measures. In response to feedback from the Danish Shipowners association a few operational measures that could be modelled on a global level were included in this study, such as trim and draught optimisation.

However, some measures particularly those involving human behaviours and third parties, were not modelled due to the difficulty in generating robust and reliable models that can adapt to different situations; these measures were not included in this study:

- Vessel or operational improvements by Third parties.
- Operational performance monitoring and guidance (note that a "generic" autopilot function is included).

As seen in **Error! Reference source not found.**, zero tells the codes that the technologies are compatibles, while one is given when they are incompatible. The list has been built with UCL experience and discussion with the industry.

References

Calleya, J. Gaspar, H. Pawling, R. and Ryan, C., Using Data Driven Documents (D3) to Explore a Whole Ship Model, SoSE 2016, Kongsberg, Norway.

Smith, T.W.P., Jalkanen, J.P., Anderson, B.A., Corbett, J.J., Faber, J., Hanayama, S., O'Keeffe, E., Parker, S., Johansson, L., Aldous, L., Raucci, C., Traut, M., Ettinger, S., Nelissen, D., Lee, D.S., Ng, S., Agrawal, A., Winebrake, J., J.; Hoen, M., Chesworth, S. & Pandey, A., 2014. Third IMO GHG Study 2014, London.

2 Bulbous Bow

Description of WSM function: Bulbous Bow uses Holtrop-Mennen [1982] assuming that wave resistance is reduced; other Bulbous Bow influences have been ignored.

Fuel Consumption Reduction: The reduction in fuel consumption calculated in the WSM ranges from %0 to 18% (note that 18% is an extreme case), between 3% and 7% is more typical of the savings that are being calculate on large cargo carrying ships.

Included in Baseline Ship specification (fitted to every ship): Yes (if required)

Retrofitted to Existing Ships: Yes

2.1 Mechanism for Energy Efficiency Improvement

Traditionally, a bulb's primary aim is to generate a wave forward of the ones being generated by the hull that cancel out the waves generated by the hull. The bulbous bow is a major aspect in a ship's geometry that affects the hull's hydrodynamic profile that does not directly affect the payload capacity or major machinery items of the vessel, although there are also impacts on seakeeping, structure and some other practical considerations that should be considered as detailed by Grech La Rosa et al. [2015].

The performance of a bulbous bow depends on the Froude number and draught in which the ship is being operated. A bulbous bow is not always appropriate and may cause and increase in resistance away from its design condition.

2.2 Modelling Assumptions and Implementation

Kracht [1978] did develop specific geometric coefficients in order to distinguish different bulbous bow designs, but the bulbous bow correction in Holtrop and Mennen [1982] contains a regression method for calculating the impact of bulbous bows that can be used for the range of ships that can be calculated in the WSM. The size of the bulbous bow was selected to match the bulb to ship ratios used in Holtrop and Mennen [1982], this is a bulb area of 0.0625 x beam x draught and a bulb height of 0.4 x draught. Figure 3 shows that this Selected Bulbous Bow size seemed sufficient compared to the model test data of a Ro-Pax ship that was tested at Marintek [Nervik, 2000].

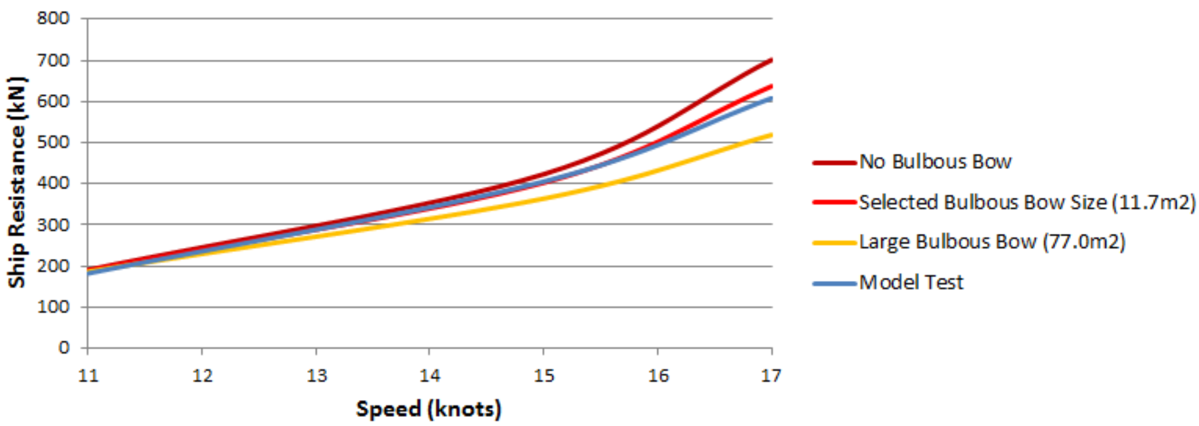

Figure 3: comparing the impact of bulb size using Holtrop-Mennen [1982] to a Ro-Pax ship model test [Nervik, 2000].

From inspection of the equations in Holtrop-Mennen [1982] the bulbous bow is assumed to only scale with the residual (or wave-making) resistance of the ship, which is a function of Froude number. Although Figure 3 shows that a bigger bulb reduces resistance, this was considered unrealistic

because it does not account for the increase in the wetted surface area that would occur and other effects, which are explained by Grech La Rosa et al. [2015].

If no reduction in resistance is found when this technology is fitted, then it is not fitted to the ship.

2.3 Costing Assumptions

The costs were adapted from the IMO document MEPC/Inf.7 [Russell et al., 2011]. The integrated propeller and rudder upgrade cost was assumed to be the same as the cost of fitting a bulbous bow, assuming an annual effective discount rate of 5% from 2007.

2.4 Feedback from Lloyds Register/Alejandro Caldas Callazo

It is dependent on the Froude number; the higher the Froude number the higher the potential improvements due to a bulbous bow. It is quite dependent on the condition (draught). The bulbous bow can even be a penalty to the efficiency for certain conditions (if the bulb was designed for 15 knots at design draught it can be a bad design for 15 knots in ballast or for a different speed).

Regarding the methodology, Holtrop-Mennen is not the best method to measure the effect of a Bulb on resistance. On top of being a statistical method, it is based on bulb designs of 30 years ago. CFD or more recent Towing tank data are recommended for detailed design. By assuming that the performance of the bulbous bow acts to reduce wave-making resistance, it is assumed that the use of a bulbous bow is always beneficial, this is not strictly true.

2.5 Feedback from Danish Shipowners Association/Hans Otto Kristensen/Cartsen Manniche

Fully agree that it is Froude number dependent. Recommend checking,

The work by Page 9 and 10 in SNAME 2009 Transactions paper by Cerup, Jan de Kat et. al. is recommended.

May I suggest that the bulbous bow topic is changed from the vessel having a bulbous bow or not to if the vessels bow has been modified with new and optimized bulb for new speed requirements?

The APM-M study is focused on the savings by ensuring the expected operational pattern is included in the original design – and not if the vessel has a bulbous bow or not.

In addition there is a tendency to design slower vessels without a bulbous bow with vertical stem, which should not be neglected.

Let me suggest the vessels should be credited by having a design optimization by third party (e.g. consultancy, Class) of 3-8% for faster vessels and 2-5% for slower vessels (e.g. above/beyond 16 knots design speed)?

References

A. Grech La Rosa, G. Thomas E. Muk-Pavic and T. Dinham-Peren, Bulbous Bows for Energy Efficient Ships: Towards A Novel Design Approach, 2015.

Holtrop, J. and Mennen, G., “An Approximate Power Prediction Method” International Shipbuilding Progress, 29, pages 166-170, 1982.

Kracht, A.M. ‘Design of Bulbous Bows’, SNAME Trans. SNAME Transactions, 1978.

Nervik, A. Chemical Tanker Performance Tests (Report No. 601736.00.01). Internal Marintek Report, 2000.

Russell, B.A., Bruce, St Amand, D., Faber, J., Wang, H. and Nelissen, D. Marginal Abatement Costs and Cost Effectiveness of Energy-Efficiency Measures, SNAME, International Maritime Organisation, MEPC62/Inf.7, 2011.

3 Rudder Bulb

Description: A Rudder Bulb reduces propeller hub losses a constant propulsion efficiency improvement has been assumed that can be fitted easily to existing rudder.

Fuel Consumption Reduction: The reduction in fuel consumption calculated in the WSM is around 2%.

Included in Baseline Ship specification (that is in every ship run by Whole Ship Model): No

Retrofitted to Existing Ships: Yes

3.1 Mechanism for Energy Efficiency Improvement

According to Hollenbach and Friesch [2007] model test conducted at Hamburgische Schiffbau-Versuchsanstalt (HSVA) found that a rudder bulb would produce a 2% reduction in fuel consumption. This propeller rudder bulb acts to reduce Hub Vortex Losses [Hollenbach and Friesch, 2007].

3.2 Modelling Assumptions and Implementation

It is assumed that the rudder bulb increases the propulsion efficiency by a constant 2% for all ships. No existing work was found to determine how a rudder bulb scales with speed and draught, or other ship specifications.

3.3 Costing Assumptions

The costs were adapted from the IMO document MEPC62/Inf.7 [Russell et al., 2011]. The rudder bulb was assumed to be three times the price of propeller boss cap fin, assuming an annual effective discount rate of 5% from 2007.

3.4 Feedback from Lloyds Register/Alejandro Caldas Callazo

If it is made in terms of prices, the substitution of the rudder by a twisted rudder with a costa bulb is not cheaper than a Mewis duct.

The propulsion efficiency improvement is not constant it varies with the propeller load for each specific each specific condition of the ship.

Also the distinction based on the "mechanisms" it is not correct as each and every Propulsion Enhancing device acts on more than one mechanism.

3.5 Feedback from Danish Shipowners Association/Hans Otto Kristensen/Cartsen Manniche

According to Jens Ring (MAN Diesel) a rudder bulb seems to be able to reduce the propulsion power by up to 4% when combined with a Kappel Propeller (Motor Ship Paper from 2012).

It could well be; more than 1000 PBCF's are installed with several from newbuilding.

References

Hollenback, U. and Friesch, Efficient hull forms – What can be gained?, 1st International Conference on Ship, Efficiency, Hamburg, 2007.

Russell, B.A., Bruce, St Amand, D., Faber, J., Wang, H. and Nelissen, D. Marginal Abatement Costs and Cost Effectiveness of Energy-Efficiency Measures, SNAME, International Maritime Organisation, MEPC62/Inf.7, 2011.

4 Preswirl Stator Duct

Description: A preswirl stator duct is a propeller duct connected to a ship with blades that direct the flow of water into the propeller a Mewis duct was assumed to scale with propeller thrust loading coefficient.

Fuel Consumption Reduction: 0% to 3% has been output from the WSM, literature review suggests that up to 6% might be possible.

Included in Baseline Ship specification (that is in every ship run by Whole Ship Model): No.

Retrofitted to Existing Ships: Yes.

4.1 Expected Efficiency Gain

The references here discuss specifically the Mewis Duct®, which is duct with pre-swirl blades before the propeller. The blades before the propeller act to improve the direction of water flow into the propeller. A fuel consumption reduction of up to 8% is claimed from a Mewis duct according to a paper by the technology developers, Mewis and Guiard [2011].

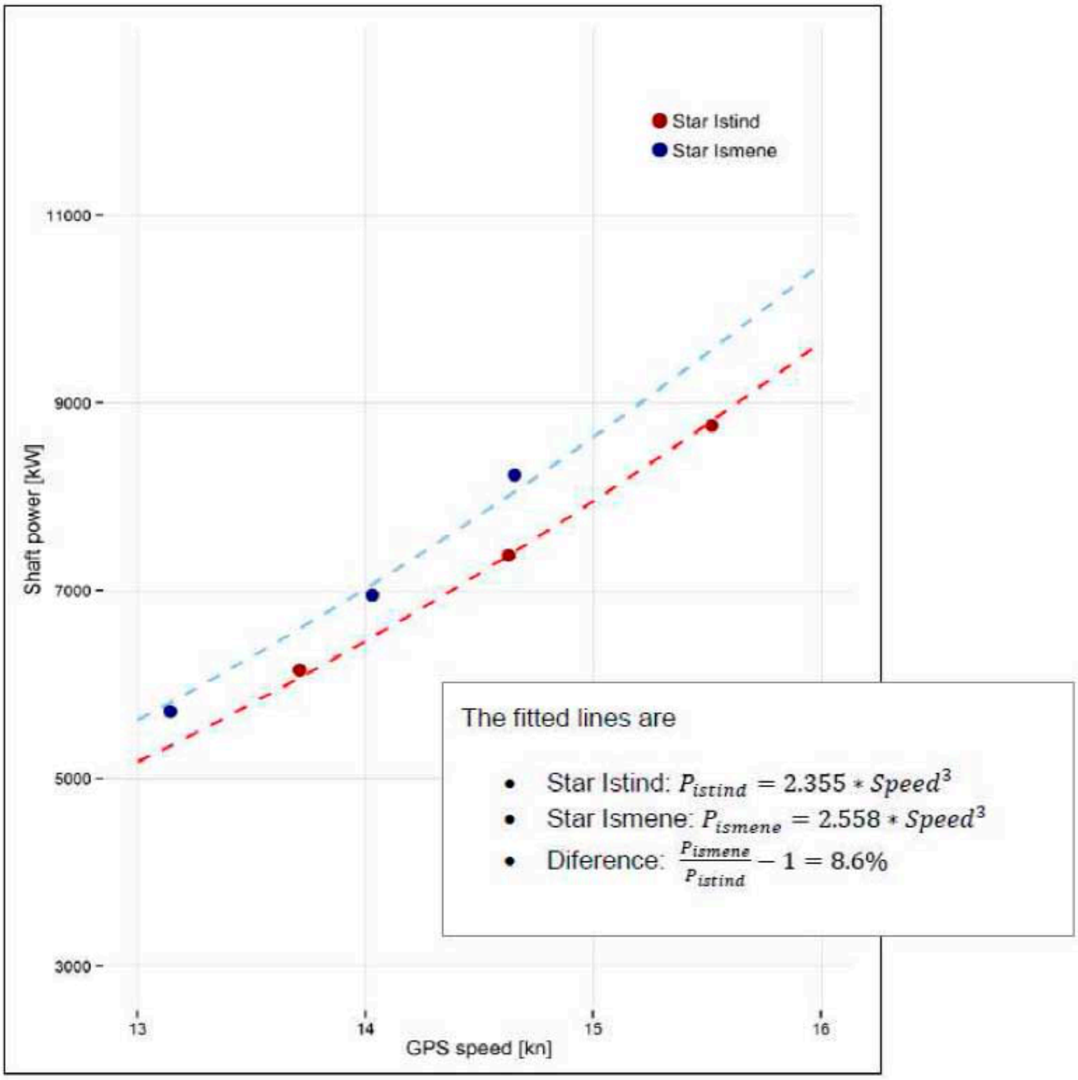

Figure 4: Performance comparison between *Star Isting* – with Mewis Duct® installed – and *Star Ismene* [Greig Star, 2009].

Model tests at HSVA showed a 3.8% power reduction on a 7090 TEU Container Vessel, *Hamburg Süd*, at 19kts with no observed cavitation problems [Mewis and Deichmann, 2013]. On behalf of Becker Marine Systems (BMS), model tests were carried out at HSVA for an open hatch bulker, owned by a Scandinavian Shipping Group, to be refitted with the BMS Mewis Duct®. At the design draught the power gain by the Mewis Duct® was found to be about 6.0% at 16 knots [Gougoulidis, G. and, Vasileiadis, 2015]. Model tests on a HSVA open hatch bulker found that the performance of a Mewis Duct® is not that dependent on speed or draught for a particular ship [Hollenback and Reinholz, 2011]. However, over 20 knots and to more slender hulls, the Mewis Duct® becomes inefficient as the duct tends to add drag in cleaner wake fields. [Gougoulidis and Vasileiadis, 2015].

For higher speeds, Becker Marine Systems – the company that sells the Mewis Duct® – has a device called Becker Twister Fin, which has fuel savings of up to 3% [Becker Marine Systems]. This is for improving the propeller inflow for faster ships, such as Container Vessels and all vessels faster than 18 kt [Mewis and Deichmann, 2013].

Grieg Shipping fitted a Mewis Duct® to their ship *Star Istind* and claimed a 6% reduction in fuel consumption after dry-docking [Greig Star, 2009]. A performance comparison between *Star Istind* and another Grieg Star ship, shown in Figure 4, appear to show that the Mewis Duct® is not that sensitive to operational speed. Note that in Figure 4, it is not known how shaft power was measured or calculated for these ships.

4.2 Modelling Assumptions and Implementation

The Mewis Duct® was scaled with Thrust Loading Coefficient as given by Mewis and Guiard [2011], but given that in some cases, particularly for container ships the savings were only around 3% a much more pessimistic curve was used, this also considered the comments from Lloyds Register.

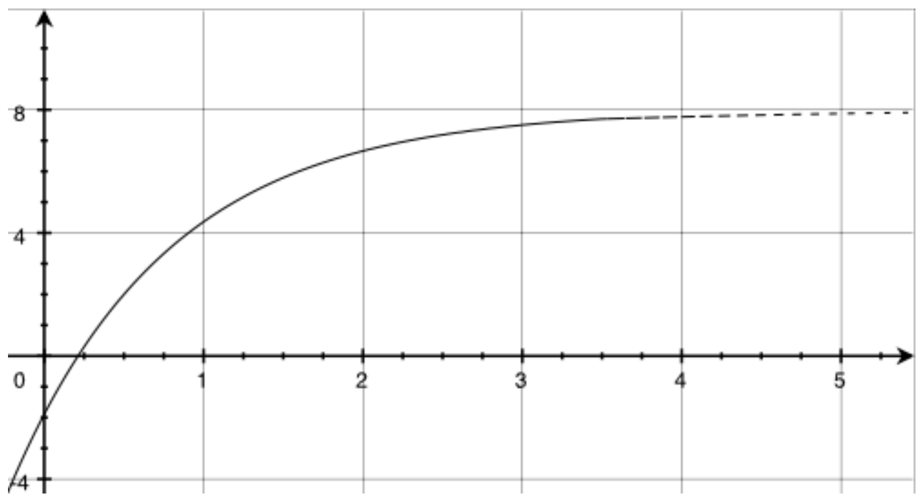

Figure 5: Scaling relationship used to find Mewis Duct® percentage reduction in propulsive efficiency on the y-axis against the thrust loading coefficient on the x-axis (note that negative values are ignored).

4.3 Costing Assumptions

The costs were adapted from the IMO document MEPC/Inf.7 [Russell et al., 2011]. The Mewis Duct® was assumed to cost the same as the price of an integrated propeller and rudder upgrade, assuming an annual effective discount rate of 5% from 2007.

4.4 Feedback from Lloyds Register

In our experience, the typical values for pre-ducts in full scale are below 3%. Also, PBCF's and wake adapted rudders don't give worst results than pre-ducts.

These kind of devices are quite sensitive to the ship draught and speed. The performance of the ship in ballast is usually worse with the device fitted than without the pre-duct.

Over an operative profile the % will be lower than the assumption of 4%-6%. It is also hard to believe that 8% is achieved at full scale for a single condition.

Model tests are not reliable for this technology. Due to the uncertainty from Reynolds Number differences between model and full scale (~10^6 in model scale and ~10^9 in full scale) model tests are not reliable and tend to predict higher improvements than in reality.

The same effect can be seen for other ESD's, see Rolls Royce information on Promass (http://www.rolls-royce.com/~/media/Files/R/Rolls-Royce/documents/customers/marine/promas.pdf).

4.5 Feedback from Danish Shipowners Association/Hans Otto Kristensen/Cartsen Manniche

There are several vessels built and delivered these days with a Mewis Duct from Newbuilding.

Agree with LR. Our experience with Mewis Duct is that it may have a positive contribution to the performance of the propeller especially for more full body vessels, but hardly higher than 5% and much lower – perhaps even a negative impact on the propeller performance - in ballast drafts. But it varies from design to design.

The Mewis Duct is in my world a "plaster" on a poor (aft body) design in the yard's strive to increase cargo capacity without increase the steel weight/vessels length.

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5 Trim Optimisation

Description: Trim optimisation is an operational measure of finding the lowest resistance by trimming a ship.

Fuel Consumption Reduction: The expected reduction in fuel consumption is between 2% and 5%. The WSM has been adapted to reflect this.

Included in Baseline Ship specification (that is in every ship run by Whole Ship Model): No.

Retrofitted to Existing Ships: Yes.

5.1 Mechanism for Energy Efficiency Improvement

Hochkirch and Volker [2010] quote a fuel consumption reduction of up to 5%. Reichel et al. [2014] quote 2% to 3% reduction in fuel consumption, this is measured from on-board software so might be a more accurate estimate.

Onboard systems to check for the correct trim can be based on mathematical models using hydrodynamic data. It is also possible to use sensors and, normally, have a user interface with a traffic light system [Bertram, 2014].

5.2 Modelling Assumptions and Implementation

The trim optimisation model calculates the impact on resistance for a number of trim angles between -5 and 5 degrees, in increments of 0.5 degrees. The change in resistance is calculated for each angle and the resistance of the ship is modified by the largest reduction in resistance.

Holtrop and Mennen [1982] model was used to model the impact of the forward draught term on correlation allowance. The forward and aft draft, can also be included in the bulbous bow and wake calculation, respectively. However modelling this proved to be complicated and potentially incompatible with other parts of the WSM so this was not done. When comparing to the literature review and feedback from Lloyds Register this was out by a factor of 5 so this correction was applied to the result. This is a large correction but it does link the forward trim to a regression method so that it could potentially be used to estimate the performance of trim optimisation on different ships. It is important to have in mind that it is possible that this method may not scale correctly with Froude number.

5.3 Costing Assumptions

Trim optimisation can pay back in several months [Bertram, 2014]. The costs were adapted from the IMO document MEPC/Inf.7 [Russell et al., 2011]. Assuming that the trim optimisation system that is used is based on existing tests, or a Computational Fluid Dynamics (CFD) study, trim optimisation was assumed to be half of autopilot adjustment cost, and also assuming an annual effective discount rate of 5% from 2007.

5.4 Feedback from Lloyds Register

Depends on the ship type.

As for the effect of the bulbous bow, the trim optimisation mostly affects the wave making component of the resistance.

For slow high block coefficient ships 2-3% is okay. For containerships this can go up to 7%.

Because of this the savings vary depending on the ship type and speed. For example, for a tanker wave making represents ~20% of the total drag and 1-3% is reasonable.

For containerships reasonable values can go up to 5-7%.

Regarding the proposed methodology, Holtrop-Mennen will not be an appropriate method for the estimation of the trim effect.

One option is based on tests or CFD; the other option is based upon monitoring of the ship. Towing tank trim or CFD data would be recommended.

I would say that there are two options for this:

1. Based on tests or CFD. So the costs are just the ones from a CFD study or the towing tests.
2. Based on monitoring of the ship: Some kind of installation and acquisition data system to be installed.

So for the first one the pay back can be indeed very short and in the second case longer.

5.5 Feedback from Danish Shipowners Association/Hans Otto Kristensen/Cartsen Manniche

Trim optimization is a very complex matter. The benefit is very speed sensitive, because the influence from the bulbous bow plays a very important role. Unfavorable flow around the bulbous bow at low speeds might change the situation completely compared to higher speeds. In some cases with forward trim at low draughts the upper part of the propeller is emerged which deteriorates the propulsion efficiency. The positive gain of up to 7 % as reported by LR is correct.

Regarding the proposed methodology, Holtrop-Mennen will not be an appropriate method for the estimation of the trim effect.

Again reference to SNAME 2009 Transactions by Cerup Simonsen and Jan de Kat et al. is recommended.

Our experience with trim tests and the use of SeaTrim shows a reduction of about 2-5% for a LPG (contract speed 16.5 knots). It is very much up to the crews to understand why trim optimization is necessary. Constant follow-ups by the operational department are needed in order to ensure that the crews are aware and use the trim tools. Let me suggest that the above-mentioned savings are relevant only if the trim optimizations are overviewed/monitored from shore.

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6 Vane Wheel

Description: A Vane Wheel consists of a number of blades that are freely rotating and coaxial to the ships propeller reducing rotational losses from the propeller.

Fuel Consumption Reduction: The fuel consumption reduction in the WSM is just below 3%.

Included in Baseline Ship specification (that is in every ship run by Whole Ship Model): No.

Retrofitted to Existing Ships: Yes.

6.1 Mechanism for Energy Efficiency Improvement

6.7m diameter grim/vane wheels were fitted aft of the propellers on the Queen Elizabeth 2 cruise liner during a refit, they were later removed and broke off during service [Lightbody, R., 2006].

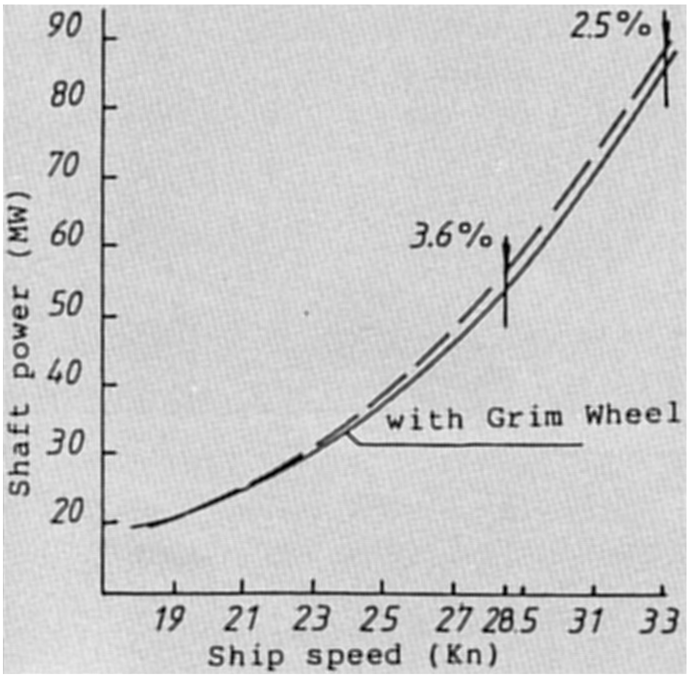

Figure 6: Performance of Grim Wheel fitted to Queen Elizabeth 2 [www.roblightbody.com].

More recently, a 4% energy saving has been quoted by manufacturers [Hochkirch and Volker, 2010].

6.2 Modelling Assumptions and Implementation

The grim vane wheel was modelled as a constant 3% change in propulsion efficiency because it is not clear how the performance scales with different ship characteristics.

6.3 Costing Assumptions

The costs were adapted from the IMO document MEPC/Inf.7 [Russell et al., 2011]. The Vane Wheel was assumed to be the same as the propeller upgrade cost, assuming an annual effective discount rate of 5% from 2007.

6.4 Feedback from Lloyds Register

Reference states that this is claimed by manufacturers for all devices that reduce rotational losses. I would use a 1% - 3% this device will be quite sensitive to the ship condition.

6.5 Feedback from Danish Shipowners Association/Hans Otto Kristensen/Cartsen Manniche

The Grim wheel is a complicated device and on QE II the blades broke off during service. The Grim Wheel has a larger diameter than a normal propeller. By increasing the diameter of the normal propeller to the same diameter as the Grim Wheel the normal propeller efficiency will be increased with nearly same percentage as for the Grim Wheel.

Can hardly see the benefit from a Grim wheel on a normal commercial trading vessel. Normally the propeller diameter is a limiting factor and introducing an even larger Grim wheel seems not to be beneficial.

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7 Contra Rotating Propeller

Description: A Contra Rotating Propeller is formed by two propellers on coaxial shafts rotating in opposite directions.

Fuel Consumption Reduction: The fuel consumption reduction in the WSM is just below 8%. Efficiency gains between 8% and 15% are quoted in literature, there is much uncertainty in the potential reduction in fuel consumption.

Included in Baseline Ship specification (that is in every ship run by Whole Ship Model): No

Retrofitted to Existing Ships: Yes

7.1 Mechanism for Energy Efficiency Improvement

Some large potential savings are quoted due to reducing circulation losses; care needs to be taken to ensure that the savings being quoted take into account the potential of other energy losses, such as the ones due to a complex gear system.

A numerical study by Laskos [2002] found improvements in hydrodynamic efficiency of 12% when installing a contra rotating propeller (CRP). Although some numerical studies show large gains these can be quite focused on hydrodynamic aspects.

Ishikawajima-Harima Heavy In-dustries Co., Ltd. (IHI) retrofitted a CRP system to a 37000 tonne deadweight bulk carrier, *Juno*, in 1989 and delivered another system in 1993. Since then, energy savings of 14%-15% were confirmed [SEA-Japan No.285].

The most in depth study of Contra Rotating Propellers, that considered a number of sources of information, quoted a fuel consumption saving of 8% for the Maersk EEE class [Hoorn et al., 2013].

As Laskos [2012] observes, despite the hydrodynamic advantages and the possible improvement of the propulsive efficiency that the CRP concept could offer, application to ships has been limited. A reasonable explanation can be given by considering the mechanical complexity, the increased installation cost and the high maintenance requirements.

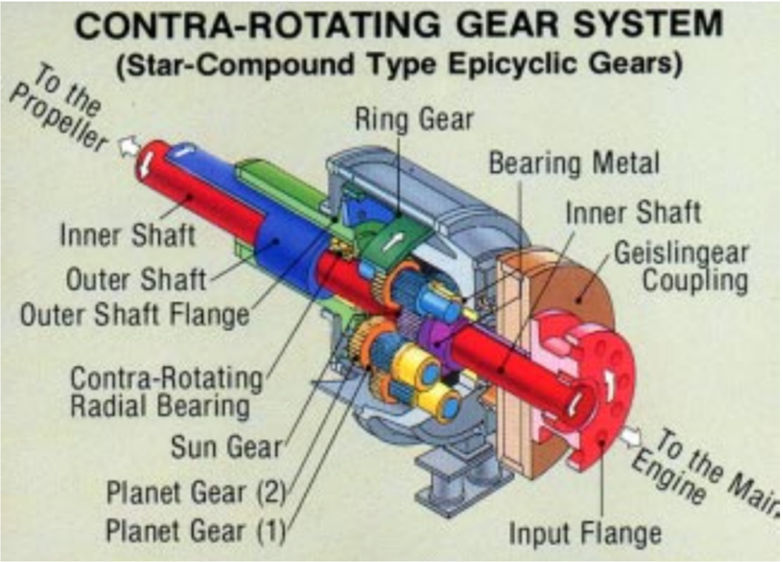

Figure 7: Gear system to support coaxial Contra Rotating Propellers [SEA-Japan No.285].

Another alternative arrangement is to have a pod behind the propulsor. This may be more costly due to having more equipment but could be a more reliable system due to having two separate propeller systems. Hochkirch and Volker [2010] quoted a saving of 13% for this.

7.2 Modelling Assumptions and Implementation

The contra rotating propeller was modelled as a constant 8% change in propulsion efficiency because it is not clear how the performance scales with different ship characteristics. The 8% was the lowest fuel reduction quoted in the literature, which means that there may be more potential for energy reductions than this.

7.3 Costing Assumptions

The costs were adapted from the IMO document MEPC/Inf.7 [Russell et al., 2011]. The CRP was assumed to be twice the cost of a propeller upgrade cost (due to additional gear system requirements), assuming an annual effective discount rate of 5% from 2007.

7.4 Feedback from Lloyds Register

Part of the price rise comes from the need of two concentric shafts rotating in opposite direction. As with other Hydrodynamic devices there is much uncertainty.

7.5 Feedback from Danish Shipowners Association/Hans Otto Kristensen/Cartsen Manniche

It is very often complicated to verify the better propulsion performance of a contra-rotating propeller, especially as a rotatable thruster version.

Figure 8: Redundant CONTAZ units are fitted with Contra Rotating Propellers

I believe it will be a part of a newbuilding specification due to its complexity as well as rather high investments.

Ref fixed propellers: I'm not so sure it will take place as retrofitting as it has an impact on the aft body design, stern tube, main engine settings as well as create space for the rather complicated planet gear.

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8 Stern Wedges

Description: Stern wedges on large ships reduce transom waves reducing resistance at higher Froude numbers.

Fuel Consumption Reduction: The fuel consumption reduction in the WSM is between 0% and 6%.

Included in Baseline Ship specification (that is in every ship run by Whole Ship Model): No

Retrofitted to Existing Ships: Yes

8.1 Mechanism for Energy Efficiency Improvement

The primary method of reducing resistance for large ships will be to reduce transom waves. At equivalent speed, stern wedges have the following effects on the transom flow: reduced height, slope, wave breaking, and amount of “white water” in the trailing waves [Gabor et al., 1999]. These devices can also act to increase waterline length and effect trim, especially on small boats with planing hulls, which can experience large changes in trim due to flaps [Gabor et al., 1999].

The most detailed available information on the performance of wedges and flaps is from a series of model tests and trials carried out for the Arleigh Burke class DDG-51 Destroyer funded by the U.S. Office of Naval Research [Gabor et al., 1999, Cusanelli, D., 2009].

For high speed ships in the commercial sector, particularly container ships and pure car carriers Kawasaki has a stern wedge with stern wave resistance and required propulsive power reducing by 3% to 7% [Kawasaki, 2016].

8.2 Modelling Assumptions and Implementation

A curve for this saving as a function of Froude number was written based on Gabor et al. [1999]. At a Froude number of 0.22 the stern flap starts to reduce resistance while at a Froude number of 0.4 the reduction in overall resistance is 6.5%. This should scale with wave-making resistance. A more pessimistic result was chosen to ensure that the wedge being used was not also benefiting from increasing the waterline length. Resistance can also increase up to around 0.5% below a Froude number of 0.22 as seen in Gabor et al. [1999]. This is likely due to the additional drag created not being overcome by the wave reducing benefit at lower speeds.

8.3 Costing Assumptions

The costs were adapted from the IMO document MEPC/Inf.7 [Russell et al., 2011]. Stern wedges were assumed to be seven times the cost of a propeller boss cap fin, assuming an annual effective discount rate of 5% from 2007.

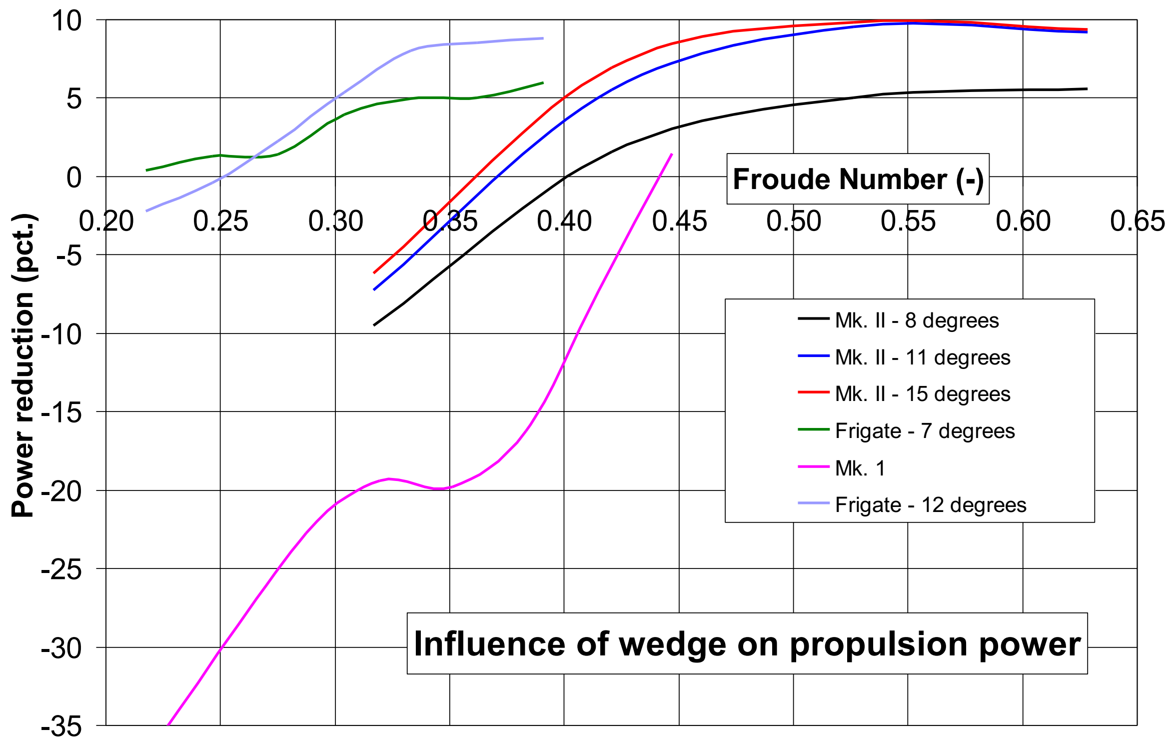
8.4 Feedback from Lloyds Register

This family of devices is attached to the stern at the level of the free surface. The working principle is based on the generation of additional lift to the hull which will produce an improvement of the transom waves and also a reduction of the wetted surface. The application is restricted to Fn above 0.2.

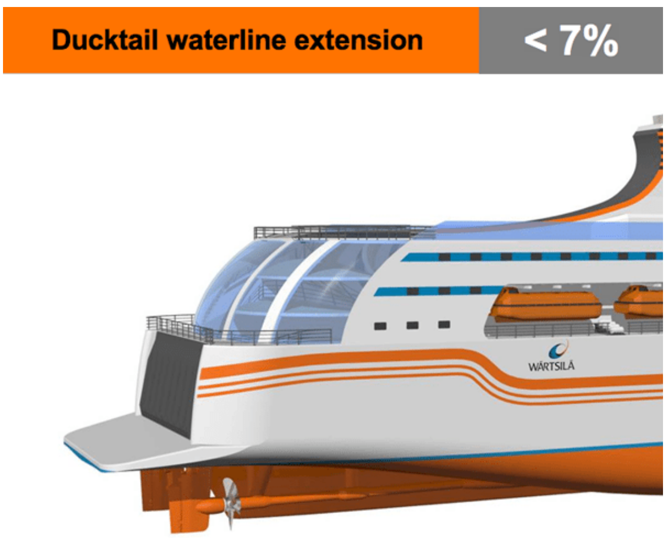
With the same cost as a cheaper hydrodynamic device (propeller bulb).

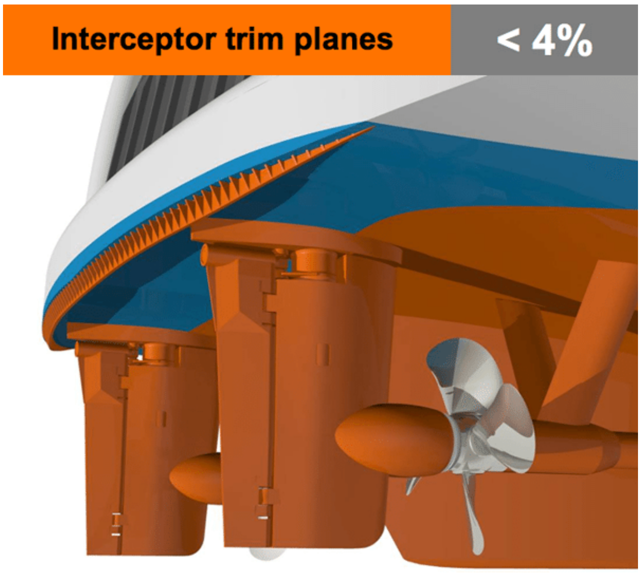
8.5 Feedback from Danish Shipowners Association/Hans Otto Kristensen/Cartsen Manniche

Stern wedges and stern flaps can reduce the power by up to appr. 10%. The same improvement can be obtained by using so-called interceptors. The improvement is mostly for the high end of the Froude Number as seen in the following figure.



Duck tails could well be a part of a newbuilding specification especially for faster vessels such as ROPAX, RORO, Cruise vessels etc. – see pictures. Only in few occasions on faster container carriers according to my knowledge.





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9 End Plated Propeller

Description: The propeller has end plates that reduce tip vortices and increase propeller efficiency; common variants are the Kappel propeller and the Contracted Loaded Tip (CLT) propeller.

Fuel Consumption Reduction: The fuel consumption reduction in the WSM is just below 2% possibly up to 5%, scaled with the propeller thrust loading coefficient.

Included in Baseline Ship specification (that is in every ship run by Whole Ship Model): No

Retrofitted to Existing Ships: Yes

9.1 Mechanism for Energy Efficiency Improvement

An end plated propeller (or tip loaded propeller) has end plates that reduce tip vortices and increase propeller efficiency. The mechanism for reducing tip vortices is well-known.

Currently two different types of tip propellers are available for ship propulsion; the Kappel propeller and the CLT propeller [Gennaro and Gonzalez-Adalid, 2012]. Upon inspection the Kappel propellers and CLT propellers appear very different. The tips of the CLT propeller blades are bent into end plates but the rest of the propeller appears more conventional compared to the Kappel propeller, which has a propeller blade with a more curved cross-section.

Only the propeller is modified so tip loaded propellers are potentially compatible with other propulsion efficiency improving devices. This is shown in a paper by MAN on their Kappel propeller [Nielsen, 2012].

9.2 Modelling Assumptions and Implementation

A paper and presentation given to SNAME 2012 by Gennaro and Gonzalez-Adalid [2012] contains a graph with the performance of CLT propellers against thrust loading coefficient. The pessimistic line in this graph was used to produce a straight line relationship that gives a saving between 3% and 9% based on the thrust loading coefficient (note that it is unlikely that 9% will be reached, Gennaro and Gonzalez-Adalid [2012] quote a maximum saving of 8%). Following feedback from Lloyds Register this model was adjusted to reduce the saving by 1%.

The percentage saving from the CLT propeller is also assumed to vary with ship operational speed, the thrust loading coefficient is calculated at each operational speed.

9.3 Costing Assumptions

The costs were adapted from the IMO document MEPC/Inf.7 [Russell et al., 2011]. Tip Loaded Propellers were assumed to be the same cost as a propeller and rudder upgrade, assuming an annual effective discount rate of 5% from 2007.

9.4 Feedback from Lloyds Register

End plated propellers (probably a better name for this) was requested by Lloyds, with a saving of up to 3% and a cost of $737k - $2596k (propeller and rudder upgrade cost).

9.5 Feedback from Danish Shipowners Association/Hans Otto Kristensen/Cartsen Manniche

Can very well be included in the newbuilding specification.

I'm sure that Maersk will be able to add some figures and experience to this subject as they have tested the CLT propellers some years ago real life. I believe that Norden tested the Kappel Propeller

about 10 years ago and I'm not sure if they have any of the Kappel propellers on their vessels today. The persons to contact at Maersk Maritime Technology could be Ole Bastholm Jørgensen/Troels Posborg.

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10 Flettner Rotors

Description: Flettner rotors are rotating cylinders that use the Magnus effect to produce thrust.

Fuel Consumption Reduction: Very approximately fuel consumption reductions between 10% at 20 knots and 30% at 10 knots were calculated.

Included in Baseline Ship specification (that is in every ship run by Whole Ship Model): No

Retrofitted to Existing Ships: Yes

10.1 Mechanism for Energy Efficiency Improvement

Flettner rotors are rotating cylinders that use the Magnus effect to produce lift, the resulting lift and drag can be used to produce thrust.

There is some additional explanation, diagram and some lift and drag coefficients in Borg et al. [1986].

With Flettner Rotors there is also the benefit that lift can be stopped by stopping the rotor from rotating.

10.2 Modelling Assumptions and Implementation

For this initial implementation the following simplified assumptions were made based on Traut et al. [2014]:

- Drag coefficient = 0.2.
- Lift coefficient = 12.5 (probably optimistic).
- Moment coefficient = 0.2 (this is used to calculate the power of the electric motor).
- Constant motor efficiency of 0.945 (this is not in on Traut et al. [2014]).

In addition to the assumption in Traut et al. [2014], it was assumed that the motor provided enough power to maintain a relative velocity (Flettner speed divided by wind speed) of 3.5. The lift and drag are calculated and resolved in the direction of the ship to give a thrust. For a cylinder the drag always acts head-on and the lift acts at 90 degrees. The direction of rotation of the Flettner was chosen to maximise thrust.

Table 1: Resistance and Flettner Motor Power of Flettner rotor on an 80000 tonne bulk carrier.

Ship speed (knots)	Percentage Thrust Requirement change due to Flettner rotors (%)	Flettner Motor Power (kW)
7.5	-40.9	95.3
10	-29.3	131.0
18.75	-14.0	332.5
20	-12.4	372.8
21.25	-10.9	416.3
23.75	-8.0	513.6
25	-7.0	567.7

An apparent wind direction and speed of -141 degrees and 14 knots was used to test the output, these are fairly favorable conditions with a lift and drag benefit. Each Flettner was assumed to have a

height of 13.5 m and a radius of 2.7 m (this is probably optimistic). This meant that for a 15 knots speed a single Flettner could produce a thrust of 460 kN.

The whole ship model was run with a test case, an 80000 tonne bulk carrier, in order to check the speed dependency (see Table 1).

10.3 Costing Assumptions

The costs were adapted from the IMO document MEPC/Inf.7 [Russell et al., 2011]. Air lubrication cost assumed, assuming an annual effective discount rate of 5% from 2007.

10.4 Feedback from Lloyds Register

Course keeping and stability issues need to be studied beforehand.

10.5 Feedback from Danish Shipowners Association/Hans Otto Kristensen/Cartsen Manniche

No comments for this technology.

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11 Sails

Description: Sails generate thrust from the wind, can be hard or soft and could also use different types of rig.

Fuel Consumption Reduction: very approximately between 10% and 50% reduction in emissions dependent on speed and conditions.

Included in Baseline Ship specification (that is in every ship run by Whole Ship Model): No

Retrofitted to Existing Ships: Yes

11.1 Mechanism for Energy Efficiency Improvement

Sails are rotated in order to maximize their resultant lift and drag in the direction of the ship.

Sails may only apply to certain routes. Bergeson and Greenwald [1985] have a reference to a 24% reduction in fuel consumption over 18 months in service. This is speed dependent and can be scaled to meet different cost requirements. A detailed analysis using model test data by Smith et al. [2013] found savings between 10% and 50%.

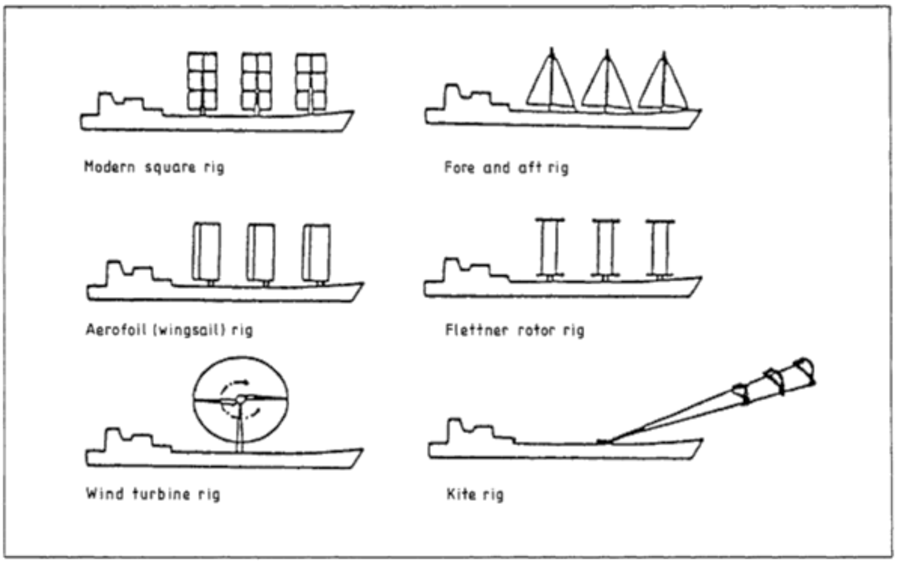

Figure 9: Different wind rigs for ships [Clayton, 1987].

Different types of rig have different lift and drag coefficients with different wind angles. This means that a particular rig may be better suited to a particular journey and a mixture of different types of sails on the same ship may potentially offer some advantage [Clayton, 1987]. The choice of rig also has an impact on cargo handling.

As with other wind assist devices, careful consideration to cargo handling and stability may be required. This could also be fitted as a new build.

11.2 Modelling Assumptions and Implementation

This model currently uses wing sails but it should be possible to change to different rigs by changing the lift and drag curve. The sail is rotated until the maximum possible thrust is found, at the moment the model runs with one wind direction.

Some wind data for a north Atlantic crossing was used [Gibbons-Neff and Miller, 2011] which defines force 4 (14 knots) wind in varying directions. The lift and drag coefficients for wing sails were taken from experimental data for wing sails [Bergeson and Greenwald, 1985].

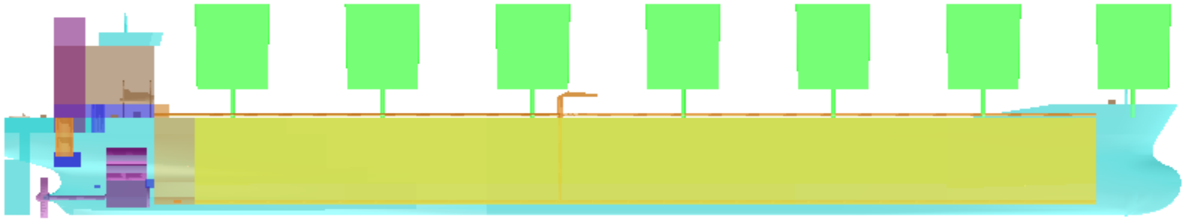

Figure 10: A Panamax Bulk Carrier fitted with 1607m^2 of sails [Calleya, 2014].

In order to examine how much sail area is available a bulk carrier was fitted with square rigs as shown in Figure 10, the relationship between available deck length was then used to size sails for different ship types.

Note that further consideration of stability and other rig types are required; currently sails are fitted equally to all ship types. Similar to Flettner rotors more assumptions need to be listed here.

11.3 Costing Assumptions

The costs were adapted from the IMO document MEPC/Inf.7 [Russell et al., 2011]. Air lubrication cost assumed, better to find a cost that scales with sail size, assuming an annual effective discount rate of 5% from 2007.

11.4 Feedback from Lloyds Register

Lloyds Register noted that sails could be part of a new ship specification. As for the previous case, stability and course keeping issues must be studied before the fitting to an actual vessel.

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12 Kites

Description: A kite is attached to the vessel's bow to use the available power coming from the wind supporting the propulsive power on board.

Fuel Consumption Reduction: A constant 5% reduction in the thrust requirement has been assumed.

Included in Baseline Ship specification (that is in every ship run by Whole Ship Model): No

Retrofitted to Existing Ships: Yes

12.1 Mechanism for Energy Efficiency Improvement

Saving from Naaijen et al. [2006] is around 5% to 10%. It is important to note that wind technologies could have expensive and cheap options as well.

12.2 Modelling Assumptions and Implementation

Due to the practicalities in, using kit, such as only taking time to deploy, the lower saving of a 5% reduction in overall resistance from Naaijen et al. [2006] was assumed.

The simplified kite model in Traut et al. [2014] could be use to improve this assumption and make this a function of speed.

12.3 Costing Assumptions

The costs were adapted from the IMO document MEPC/Inf.7 [Russell et al., 2011]. Air lubrication cost assumed, better to find a cost that scales with kite area, assuming an annual effective discount rate of 5% from 2007. Russell et al. [2011] may contain kite costs.

12.4 Feedback from Lloyds Register

No comments given for this technology.

12.5 Feedback from Danish Shipowners Association/Hans Otto Kristensen/Cartsen Manniche

With ref to kites the topic was quite hot some years ago and I believe the German company Beluga – now bankrupt – installed kites – SkySails – onboard some of their vessels. I wonder if the success was significant as there has been quiet around SkySails since the oil price dived.

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13 Air Lubrication

Description: Reduction in the frictional resistance by injecting air between the hull surface and seawater.

Fuel Consumption Reduction: Approximately around 3%.

Included in Baseline Ship specification (that is in every ship run by Whole Ship Model): No

Retrofitted to Existing Ships: Yes

13.1 Mechanism for Energy Efficiency Improvement

There are two main relevant systems available for purchase at the moment: Mitsubishi Air Lubrication System (MALS) and Silverstream System.

Shell reported on their website a saving of 4.3% and 3.8% for the vessel *MT Amalienborg* in ballast and laden conditions, respectively [Shell, 2015].

"The Silverstream System produces a thin layer of micro bubbles that creates a single 'air carpet' for the full flat of bottom of the ship. This reduces the frictional resistance between the water and hull and improves the vessel's operational efficiency, reducing fuel consumption and associated emissions" [Shell, 2015].

13.2 Modelling Assumptions and Implementation

Air Lubrication was implemented using the assumptions contained in Mäkiharju [2012], which allow for the calculation of the required air flow, for Air Layer Drag Reduction, and hence compressor power based on the air cavity. The air cavity was described as having a length of 80% of the waterline length and a width proportional to the block coefficient cubed. This allows the air cavity to be sized to fit different ships. The frictional resistance of the area of the air cavity is assumed to be reduced by 80% due to the air layer.

13.3 Costing Assumptions

The costs were adapted from the IMO document MEPC/Inf.7 [Russell et al., 2011]. Air lubrication cost assumed, assuming an annual effective discount rate of 5% from 2007.

13.4 Feedback from Lloyds Register

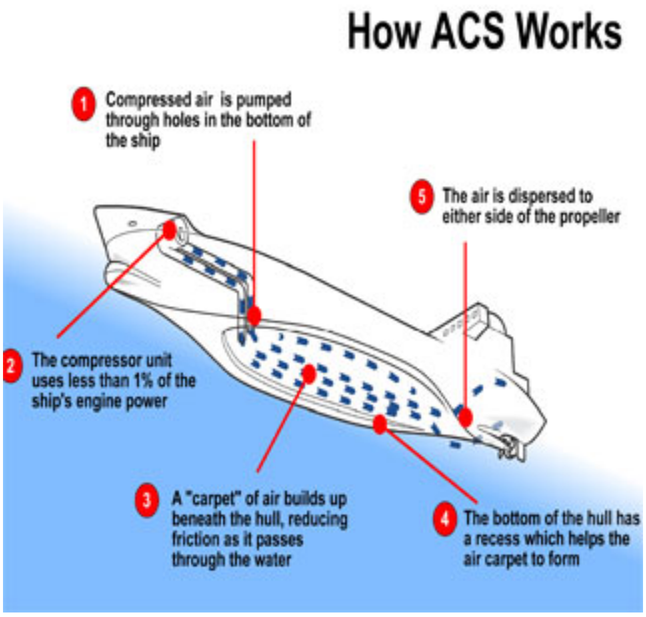
It will be dependent on the percentage of the drag due to friction.

Estimation must be carried out for the friction component in order to extrapolate the savings to different ship types/sizes.

13.5 Feedback from Danish Shipowners Association/Hans Otto Kristensen / Cartsen Manniche

Maersk did some testing years ago (2008) with air lubrication on one of their container vessels leading air through small holes in the shell. I do not know the result of the test, but I haven't seen it in big scale.

Dannebrog Group did a pilot installation using the Air Cavity System (ACS) approach on one of their 12,500 dwt multi-purpose newbuildings back in 2012 with expected savings of up to 10%. I understand that the claimed savings are about 3%. Installation cost is unknown but I would expect significant. I'm not sure if DK Group is still in the market as they have been quiet lately.



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Shell, Shell website, http://www.shell.com/business-customers/trading-and-supply/shell-shipping-and-maritime/shell-shipping-news-and-media-releases/silverstream-air-lubrication-technology.html, accessed August 2016, February 2015.

14 Silicone Hull Coating

Description: Silicone hull coating reduces frictional resistance compared to traditional silicone foul release coatings.

Fuel Consumption Reduction: A reduction of under 1%.

Included in Baseline Ship specification (that is in every ship run by Whole Ship Model): No

Retrofitted to Existing Ships: Yes

14.1 Mechanism for Energy Efficiency Improvement

Hull coatings act to reduce frictional resistance. This hull coating is assumed to the same as Hull Coating 1 in MEPC62/Inf.7 [Russell et al., 2011], which has fuel/CO_2 reductions that lie between 0.5% and 2%, compared to a conventional coating, and is available on the the market at the moment.

It has been assumed that the lower cost hull coating 1, is silicone based.

14.2 Modelling Assumptions and Implementation

This was assumed to be a 1% change in frictional resistance, this means that at the overall ship level the saving may vary depending on the frictional resistance relative to wave-making. This is represented as an average reduction in resistance.

14.3 Costing Assumptions

The costs were adapted from the IMO document MEPC62/Inf.7 [Russell et al., 2011]. The lower hull coating 1 cost was used, assuming an annual effective discount rate of 5% from 2007.

14.4 Feedback from Lloyds Register

No comments given for this technology.

14.5 Feedback from Danish Shipowners Association/Hans Otto Kristensen / Cartsen Manniche

The hull fouling is a very important issue and careful consideration must be given to hull cleaning between normal dry docking periods as quite large resistance reductions can be obtained, there is a paper from Propulsion Dynamics.

My experience with silicon coating is that it's normally quite difficult to apply and therefore expensive in application as well as in maintenance. Furthermore, the coating developed slime – not visible by eye – lowering the expected savings. As HOK states there is other products on the market, but I believe the current trend among makers are not in majority focusing on silicon based coating. But I may be wrong here.

References

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15 Polymer Hull Coating

Description: Polymer hull coating reduces frictional resistance compared to traditional silicone foul release coatings.

Fuel Consumption Reduction: A reduction of under 2%

Included in Baseline Ship specification: No

Retrofits: Yes, much care needs to be taken when interpreting savings in literature because hull cleaned if new coatings applied.

15.1 Mechanism for Energy Efficiency Improvement

Hull coatings act to reduce frictional resistance. This hull coating is assumed to the same as Hull Coating 1 in MEPC62/Inf.7 [Russell et al., 2011], which has fuel/CO_2 reductions that lie between 1% and 5%, compared to a conventional coating, and is available on the the market at the moment.

It has been assumed that the higher cost hull coating 2 is polymer based.

15.2 Modelling Assumptions and Implementation

This was assumed to be a 2% change in frictional resistance, this means that at the overall ship level the saving may vary depending on the frictional resistance relative to wave-making. This is represented as an average reduction in resistance.

15.3 Costing Assumptions

The costs were adapted from the IMO document MEPC/Inf.7 [Russell et al., 2011]. The higher hull coating 2 cost was used, assuming an annual effective discount rate of 5% from 2007, this means that at the overall ship level the saving may vary depending on the frictional resistance relative to wave-making.

15.4 Feedback from Lloyds Register

No comments given for this technology.

15.5 Feedback from Danish Shipowners Association/Hans Otto Kristensen / Cartsen Manniche

No comments given for this technology.

References

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16 Water-based Rankine cycle waste heat recovery system

Description: Waste heat recovery system based on a single-pressure water-based Rankine Cycle which produces electrical power to support the electrical demand on board.

Fuel Consumption Reduction: Around 3% – 4% of main engine fuel consumption.

Included in Baseline Ship specification: No

Retrofits: Yes

16.1 Mechanism for Energy Efficiency Improvement

Uses the available wasted energy from the exhaust gas to transform high-pressure water into steam to then be expanded to generate mechanical work. The expander's shaft is connected to an electrical generator which produces electrical power supplied to the vessel. By supplementing the electrical load the auxiliary engines can operate at reduced MCR and achieving a better fuel oil consumption.

16.2 Modelling Assumptions and Implementation

The Rankine cycle (RC) is the preferable thermodynamic cycle for heat sources found at temperatures above 500°C, but also it exhibits acceptable performances for lower heat temperatures such as the ones seen from marine [Feng et al. 2010; Wang et al. 2011; Quoilin et al. 2013; Cheang et al. 2015]. The typical RC waste heat recovery system (WHRS) options for marine systems are single- and double-pressure with the possibility of being coupled with a power turbine [Schmid 2004; MAN Diesel & Turbo 2012a]. The water-based RC WHRS can be scaled for small vessels (e.g. inland waterway vessels) or large container ships such as the 80 MW *Emma Mærsk* [Hultqvist 2008; Clean Thermodynamic Energy Conversion 2016].

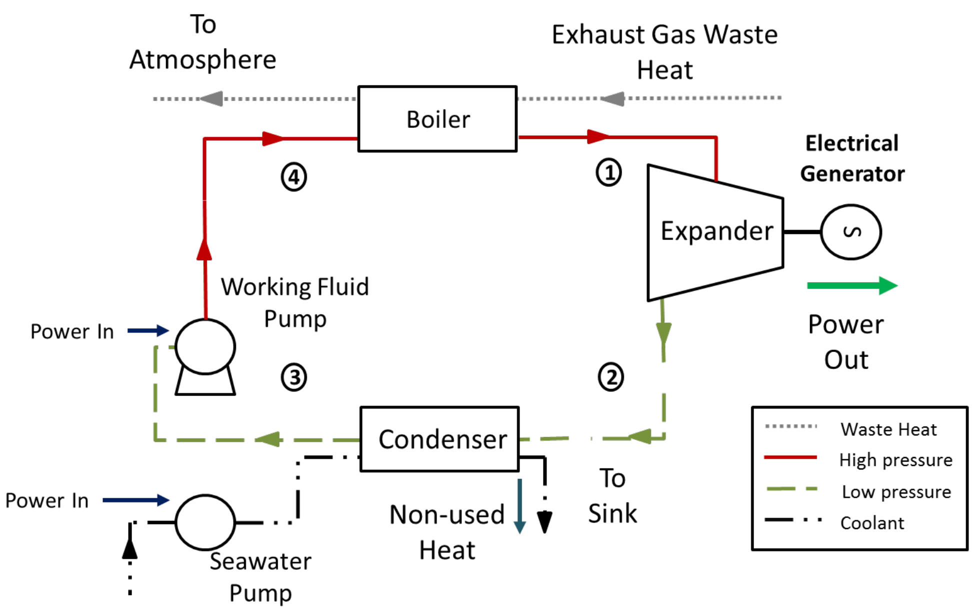

Figure 11: Waste heat recovery system layout assumed for its application in WSM. Here the boiler refers to the waste heat boiler discussed in Waste Heat Boiler section.

A single-pressure water-based RC WHRS[1] using the available waste heat from the exhaust gas – treated as air – is considered for WSM (see Figure 11). The advantages of such a system against a double-pressure are that they are simpler in design, lower capital cost and can operate with only one high-grade waste heat source (i.e. exhaust gas) [Theotokatos & Livanos 2012]. Furthermore, the benefit of a dual-pressure system is around two percentage points more of the engine power output – depending on the engine size [Shu et al. 2013]. For more details in regards to the power turbine please refer to the turbo-compounding technology review. The single-pressure is assumed to have a maximum thermal efficiency of 21% for all waste heat conditions when the WHRS can operate [Suárez de la Fuente & Greig 2015].

The WSM assumes that there is a waste heat boiler (WHB) which will be used as the WHRS boiler as seen in Figure 11. The introduction of a boiler in main engine's exhaust gas path increases the back pressure causing an increase of about 2 g/kWh in the specific fuel consumption (sfc) [MAN Diesel & Turbo 2012a]. However, this has been already considered by the WHB which is installed on all ships. The pinch point temperature difference[2] (ΔT_{pp}) of the heat exchangers is assumed to be 5˚C with a minimum approach temperature[3] (ΔT_{ap}) of 5˚C. This will guarantee an efficient heat transfer but at the expense of large heat exchangers [Li et al. 2012]. The power required to cool the thermodynamic cycle with seawater is consider. For the net power output the RC WHRS seawater temperature is assumed to be a constant 9˚C. For more detailed assumptions for this cycle please refer to Suárez de la Fuente and Greig [2015].

The exhaust gas temperature will be lowered until 164˚C which is the minimum temperature before sulphuric acid starts to condensate when the fuel sulphur content is 3% [Bahadori 2011]. The water-based RC WHRS will be able to operate from 50% MCR to 100% MCR if there is enough energy after the vessel's steam demand on board has been covered [Starcrest Consulting Group LLC 2013]. Lower engine loadings bring low benefits at the expense of damaging the WHRS equipment (e.g. droplet formation inside the expander due to low inlet temperatures).

Since the power produced by the RC WHRS is converted to electricity the electrical generator and switchboard efficiencies are considered. For the generator its efficiency is assumed to be a constant 97.0% and the switchboard about 99.8% [MAN Diesel & Turbo 2012b].

Due to limitations in WSM the effect of different ambient and seawater temperature, and fuel's sulphur content is not considered as recommended in Suárez de la Fuente [2016a]. The approach to this technology will be the use of a simple model which is capable of estimating the waste heat absorption (availability and temperature) from the exhaust gas system. This model is based on the results produced by Suárez de la Fuente and Greig [2015] Matlab® model for a marine WHRS. Also the model will take from the literature the engine efficiency at ISO conditions [4].

The water-based RC can be applied to any type and size of ship. Nuclear powered ships will not benefit from this technology since they operate already under the same thermodynamic cycle based on steam. The technology is scaled by its maximum mechanical power output which is dependent on the waste heat availability and quality coming from the exhaust gas. Since the waste heat availability

[1] Please refer to Suarez de la Fuente and Greig [Suárez de la Fuente & Greig 2015] for the operating pressure of the water-based RC.

[2] Refers to the temperature difference between the exhaust gas temperature and the water temperature at saturation point.

[3] Temperature difference seen by a counter-flow heat exchanger between the hot fluid entrance/exit and the cold fluid exit/entrance.

[4] For engine thermal efficiency, waste heat absorption and waste heat used to cover the heating demand on board please refer to the Appendix - WHB.

and quality are not given by WSM then some calculations – based on the results of Suárez de la Fuente and Greig [2015] – need to be added to this technology.

For the RC WHRS volume (V_{WHRS}) calculations are formed from the different volume footprint of different RC WHRS equipment [Aalborg Industries 2005; Siemens AG 2013; Thermal & Pressure Engineering 2013]. For the steam WHRS mass (m_{WHRS}) the data available in Nord and Bolland [2012] for a single pressure drum RC WHRS is taken.

In regards to the generator, this also scales in regards to the maximum power output received from the water-based WHRS [Lian et al. 2010], however the generator and switchboard mass and volume are assumed to be accounted in the WHRS mass and volume.

On the subject of WHRS being retrofittable the implications space limitation on existing ships and safety makes this technology less attractive. However, in recent years there has been a push by public entities in the United Kingdom to make WHRS an affordable and simpler to install option for existing fleets [Suárez de la Fuente, 2016b].

16.3 Costing Assumptions

Costs for the water-based RC come from Cunningham [2002], the electrical generator is taken from Lian et al. [2010] and the marine switchboard cost proportion to the electrical generator is taken from private conversations with the Energy Technologies Institute [2016]. Costing for the RC, generator and switchboard are dependent on the maximum power production ($\dot{W}_{e,max}$).

The annual through life cost (TLC) for the RC WHRS is an average from the costing values found in U.S. Energy Information Administration [2010] and Tarjanne and Kivistö [2008]. It is important to highlight that TLC costs were not found for marine applications but they are assumed to be close to land-based systems. To quantify the TLC costs it is assumed that the vessels are in operation 65% of the time in a year of which 70% of that time the marine WHRS will be in operation (i.e. 4000 hours per year). It was assumed that the TLC costs are calculated using the RC power output at its design point ($\dot{W}_{e,design}$) since it is where normally will be operating.

16.4 Feedback from Lloyds Register

No comments for this technology.

16.5 Feedback from Danish Shipowners Association/Hans Otto Kristensen / Cartsen Manniche

Are you sure it's retrofit? I see this part as a bit complicated for retrofit – but perhaps few tankers have been retrofitted during the expensive fuel oil days some years back??

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17 Organic Rankine cycle waste heat recovery system

Description: Waste heat recovery system based Rankine Cycle and using an organic fluid (i.e. that contains carbon molecules in its structure) to produce electrical power to support the electrical demand on board.

Fuel Consumption Reduction: Around 2% – 4% of main engine fuel consumption.

Included in Baseline Ship specification: No

Retrofits: Yes

17.1 Mechanism for Energy Efficiency Improvement

Uses the available wasted energy in the scavenge air system to transform the high-pressure organic fluid into vapour to then be expanded to generate mechanical work. The expander's shaft is connected to an electrical generator which produces electrical power supplied to the vessel. By supplementing the electrical load the auxiliary engines can operate at reduced MCR and achieving a better fuel oil consumption.

17.2 Modelling Assumptions and Implementation

The organic Rankine cycle (ORC) uses the same cycle proposed by Rankine for the water-based RC. The main difference between RC and ORC is the working fluid used which will basically affect the thermodynamic behaviour of the system, plant layout and equipment required. The ORC uses organic fluids which must contain any carbon compound, whether it has a biological origin or not such as in the case of benzene or R123 [Balmer 2011]. One of the strongest points of an ORC is its large working fluid catalogue which is formed from pure fluids or a mixture thereof. The ample range of organic fluids permits the creation of tailored thermodynamic designs to match any heat source.

For these reasons, it was decided that refrigerants (e.g. R245fa) would be more suitable for the ship application. However, refrigerants tend to have a lower decomposition temperature which limits their use for extracting the waste heat from the exhaust gas [Suárez de la Fuente 2016a]. It was assumed that the ORC WHRS will be operating using the available waste heat from the scavenge air system and producing electrical power through a generator (see Figure 12). After air is compressed via the power extracted by the turbine, the fluid increases considerably its temperature. In order to increase the air density, hence having better combustion for the main engine, the temperature must be reduced [Woud & Stapersma 2012]. Normally, an intercooler is used to reduce the compressed air's temperature to about 30˚C to 40˚C when the ambient temperature is assumed to be 25˚C (see MAN Diesel & Turbo [2016e] for example). It is assumed that the ORC will be in operation above 40% MCR – when there is enough waste heat to produce useful electrical power – and will cool down the air to the required inlet temperature. Below this engine loading the bypass will direct the hot compress air to the heat exchanger. The pressure drop for the ORC boiler is assumed to be the same as for a typical scavenge air intercooler, hence no extra losses are consider. Due to limitations in WSM, the effects of different ambient and seawater temperature are not considered. Instead ISO conditions are assumed to be always present.

A recuperative[5] ORC is a common plant layout for dry and isentropic fluids – meaning that after expansion the fluid will be still in its superheated vapour state – which uses the available heat after expansion to increase the working fluid's temperature on the cold side [Branchini et al. 2013].

[5] Refers to the use of a recuperator which is a heat exchanger that transfers heat from the working fluid's hot side to the cold one without having mass transfer.

Since the power produced by the ORC WHRS is converted to electricity the electrical generator and switchboard efficiencies are considered. For the generator its efficiency is assumed to be a constant 97.0% and the switchboard about 99.8% [MAN Diesel & Turbo 2012a].

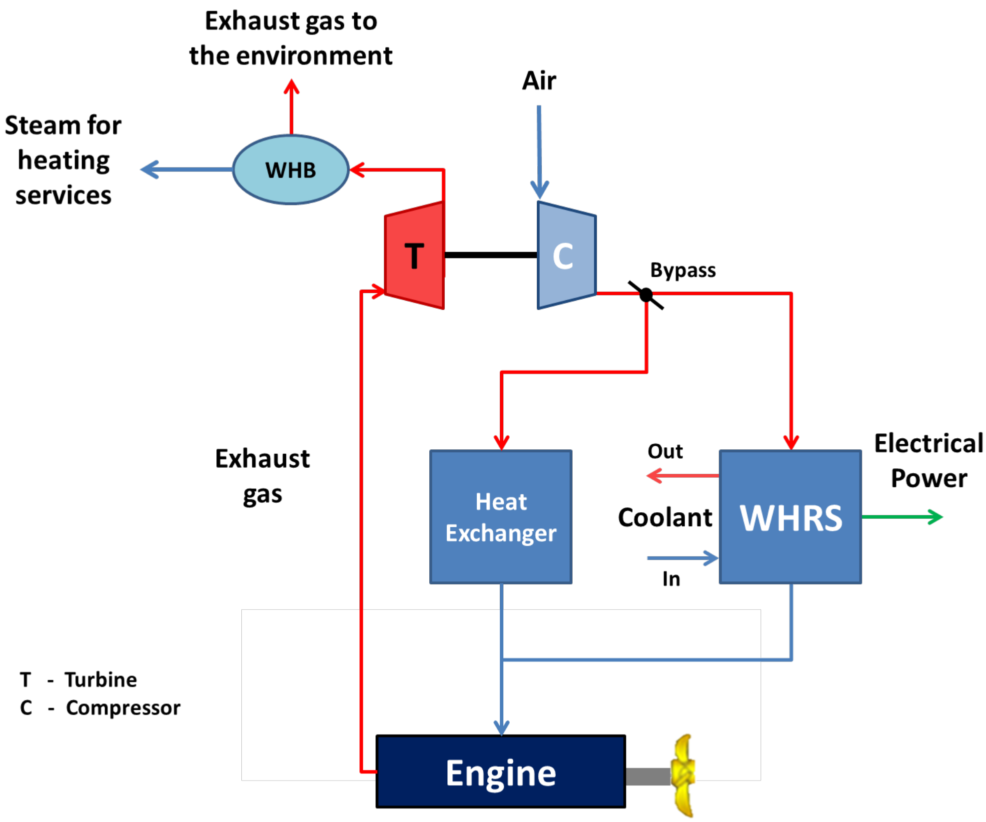

Figure 12: Location of the marine ORC on board the ship. A bypass valve is used to divert the compressed air to the respective cooling device before entering the engine.

Due to limitations in WSM the effect of different ambient and seawater temperature, and fuel's sulphur content is not considered as recommended in Suarez de la Fuente [2016].

The approach to this technology will be the use of a simple model which is capable of estimating the waste heat absorption (availability and temperature) from the scavenge air cooling system. The model will take from the literature the engine efficiency at ISO conditions[6].

Figure 13 shows the proportion of waste heat availability to the total fuel power. Low thermal efficiency does not mean larger waste heat availability at the scavenge air system as shown for engine 5G40ME. This engine has a thermal efficiency of around 49% at the 75% MCR but its proportion of waste heat available from the scavenge air is around 16% and the lowest of the sample used. Further, it is seen that as the engine loading increases the waste heat availability also does. This pattern is seen in all the engines sampled.

It was decided that two different groups will be used to characterise the waste heat availability in the scavenge air system: A) engines which maximum power output is lower than 15000 kW have a lower waste heat availability from the scavenge air – except for the case of engine 6S60ME treated as an outlier, and B) engines with a maximum power output larger than 15000 kW. Each of these two

[6] For engine thermal efficiency please refer to the WHB section.

groups were averaged at each operating point to then find a logarithmic curve fit which can represent the waste heat availability for the model.

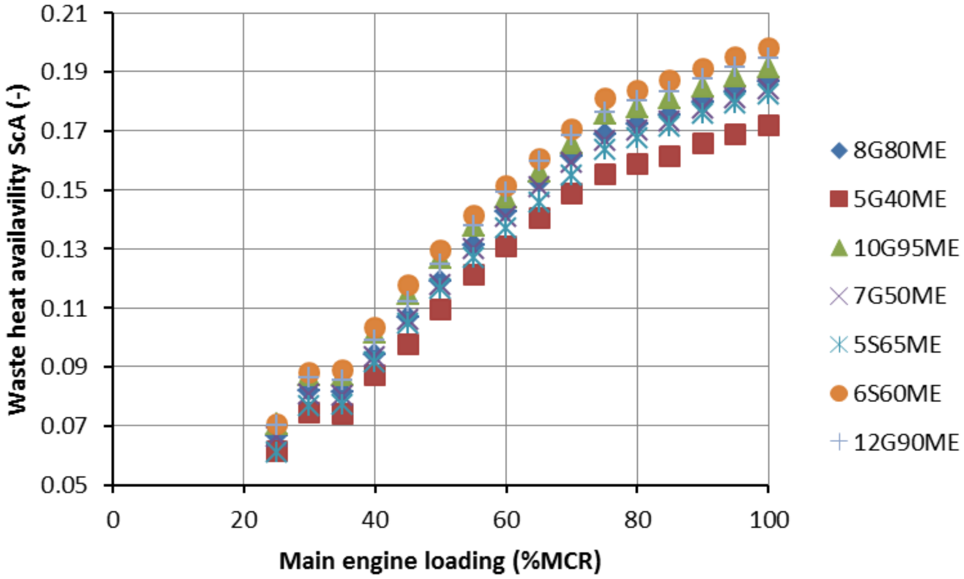

Figure 13: Waste heat availability at the scavenge air (ScA) system as given by the MAN Diesel and Turbo catalogue at ISO conditions.

Since this technology is absorbing waste heat from a lower grade source and also there is less available energy to be used than in the exhaust gas system it is expected that the fuel saving of this technology will be around 2% to 4%. Opcon Energy Systems AB [2012a] using the available waste heat from excess steam and jacket cooling water on board the general cargo *MV Figaro* could achieve fuel savings of around 4% to 6%. However, this savings come from two different waste heat recovery systems being acceptable to assume that each one of the system is bringing around 2% to 3% in fuel savings.

For the ORC WHRS volume and mass calculations are taken from Opcon Energy Systems AB [2012b]. In regards to the generator, this also scales in regards to the maximum power output received from the water-based WHRS [Lian et al. 2010], however its volume plus the switch board are assumed to be integrated within the ORC mass and volume.

On the subject of ORC WHRS being retrofittable and as mentioned previously, Opcon Energy Systems AB [2012a] retrofitted its ORC WHRS system into the *MV Figaro*. As discussed with the steam WHRS, the Energy Technologies Institute has been calling for WHRS manufacturers to come with a WHRS prototype which can be easy to install and affordable for existing vessels [Suárez de la Fuente, 2016b].

17.3 Costing Assumptions

Specific costs for the ORC ($SC_{ORCWHRS}$) are assumed to have a similar trend as given in Quoilin et al. [2013] for waste heat applications and using a power fit in order to use it for this model. Quoilin et al. [2013] give the installation cost in euros, hence an average annual exchange rate of $1.11/€ is used [European Central Bank 2016]. The electrical generator is taken from Lian et al. [2010] and the marine switchboard cost proportion to the electrical generator is taken from private conversations with the Energy Technologies Institute [2016]. The initial costs are taken from the maximum power output delivered by the WHRS ($\dot{W}_{e,max}$) which happens when the waste heat availability is at its maximum (i.e. at the maximum continuous rating).

The annual through life cost (TLC) for the ORC WHRS is taken from Saavedra et al. [2010] and Suárez de la Fuente [2016a]. It is important to highlight that TLC costs were not found for marine applications but they are assumed to be close to land-based systems. To quantify the TLC costs it is assumed that the vessels are in operation 65% of the time in a year of which 70% of that time the marine WHRS will be in operation (i.e. 4000 hours per year). It was assumed that the TLC costs are calculated using the ORC power output at its design point ($\dot{W}_{e,design}$) since it is where normally will be operating.

17.4 Feedback from Lloyds Register

No comments for this technology.

17.5 Feedback from Danish Shipowners Association/Hans Otto Kristensen / Cartsen Manniche

No comments for this technology.

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18 Turbo-compounding in series

Description: Waste energy recovery system that uses part of the energy available from the high-pressure high-speed exhaust gas to produce electricity via an electric generator. For engines below 2 MW in installed power.

Fuel Consumption Reduction: Around 2% – 4% of main engine fuel consumption.

Included in Baseline Ship specification: No

Retrofits: Yes

18.1 Mechanism for Energy Efficiency Improvement

A turbine is used to extract part of the available energy from the high-pressure high-speed exhaust gases after it has exited the turbocharger. After the process the exhaust gas leaves at a lower pressure and slower speed. The turbine shaft is connected to an electric generator which will supplement the electricity production on board.

18.2 Modelling Assumptions and Implementation

A turbo-compound system is treated here as a waste energy recovery system producing electrical work from the exhaust gas system after it has passed the turbine from the turbocharger. This solution tends to favour small engines – up to 2 MW – which are commonly seen for small vessels or auxiliary engines. Series turbo-compounding can effectively handle any after treatment technology, however it is recommended that the turbo-compound is installed after the after treatment technology, reducing the backpressure negative effect [Aghaali & Ångström 2015].

An important negative aspect of using turbo-compounding in series with the turbocharger on a Diesel engine is that it creates high back-pressure in the exhaust gas system which means that the engine needs to increase its pumping work to expel the exhaust gas from the combustion chamber. The extra work required by the engine will increase the specific fuel oil consumption (sfoc) but also this technology could delay combustion inside the cylinder which will further reduce the engine's efficiency [Ismail et al. 2012]. An increase of 2.5% in the auxiliary engine sfoc will be added when this technology is installed [Aghaali & Ångström 2014].

For the turbine efficiency is modelled as a polynomial of second degree which achieves a maximum efficiency of 78% at the engines design point. It is assumed that a maximum 10% of the available wasted energy can be extracted for power production

The generator efficiency is assumed to be a constant 97.0% and the switchboard efficiency is assumed to be at about 99.8% [MAN Diesel & Turbo 2012a]. The waste energy recovery system will be operating above 65% MCR were there is enough pressure and mass flow rate to spin the power turbine. At lower engine loadings the power turbine will be able to operate but under a low turbine efficiency which by counting the backpressure effect, it will not bring any fuel saving.

In regards to the mass Weerasinghe et al. [2010] found that a 60 kg turbocompound system – not counting the compressor and clutch – was able to produce extra 1.54 kW_e for a truck. This reference is the only one found in regards to the turbocompound system mass and it is deem as a good enough approximation for this study. For the switchboard mass, the data available from Power Electronics [2016] for a 1000 kW_e system was used. The switchboard has a mass of 2.5 tonnes, giving a specific mass of 2.5×10^{-3} t/kW_e. In case of multiple turbogenerators, due to multiple auxiliary engines, only the mass impact of the turbogenerator will be multiplied by the number of auxiliary engines installed (N_{AE}) with the turbocompound system while it is assumed that the same switchboard can handle all the turbogenerators.

For the turbocompound footprint it will be used the stand alone turbogenerator solution from Bowman Power Group for all engines below 2 MW plus the power electronics required to operate it [Bowman Power Group 2016a].

18.3 Costing Assumptions

For the series turbocompound solution a purchase cost of \$865/kW_e is used which will be defined using the maximum power output of the turbocompound system [Perez-Osses 2015]. A fixed through life cost (*TLC*) of \$0.6/h will be used for an equipment of capable of generating 60 kW_e [Bowman Power Group 2016b] giving \$0.01/kWh.

In the particular case of auxiliary engines, the Initial cost (*IC*) and *TLC* cost is multiplied by the number of auxiliary engines installed, which is assumed to be three. To quantify the TLC costs it is assumed that the vessels are in operation 65% of the time in a year of which 60% of that time the marine WHRS will be in operation (i.e. 3400 hours per year). Both costs are scaled using the maximum power delivered.

18.4 Feedback from Lloyds Register

Change description from heat to energy.

18.5 Feedback from Danish Shipowners Association/Hans Otto Kristensen / Cartsen Manniche

No comments for this technology.

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19 Turbo-compounding Parallel

Description: Waste energy recovery system that uses part of the energy available from the high-pressure high-speed exhaust gas to produce electricity via an electric generator. For engines above 2 MW installed power.

Fuel Consumption Reduction: Around 2% – 3% of auxiliary engine fuel consumption.

Included in Baseline Ship specification: No

Retrofits: Yes

19.1 Mechanism for Energy Efficiency Improvement

A turbine is used to extract part of the available energy from the high-pressure high-speed exhaust gases. After the process the exhaust gas leaves at a lower pressure and slower speed. The turbine is feed with a small part of the pre-turbocharger exhaust gas via a bypass. A shaft is connected to an electric generator which will supplement the electricity production on board.

19.2 Modelling Assumptions and Implementation

A power turbine uses, as with the turbocompound system, the available energy in the exhaust gas but instead of working in series with the turbocharger – full exhaust gas mass flow rate – it works in parallel. The power turbine uses a portion of the exhaust gas via a bypass system in the exhaust manifold to produce electrical power via a generator. This option is commonly recommended for medium and large diesel engines [MAN Diesel & Turbo 2012b]. The bypass will send 10% of the energy available in the exhaust gas as defined in the waste heat boiler section. In power turbine systems the power falls off at lower loads due to smaller mass flow rates, hence its operation will happen after the 50% MCR.

It is assumed that the exhaust gas has enters the turbine at a temperature of 490˚C which is 10˚C lower than the maximum allowed by MAN Diesel and Turbo for two-stroke engines and it exhaust at the temperature given by the engine data at ISO conditions [MAN Diesel & Turbo 2016]. The specific heat is set to a constant of 1065 kJ/(kg-K), and the exhaust gas mass flow rate is 10% of the given by the literature. As it is set now, the change in the power output will depend solely in the exhaust gas mass flow rate at any given engine loading condition between 50% MCR and 100% MCR.

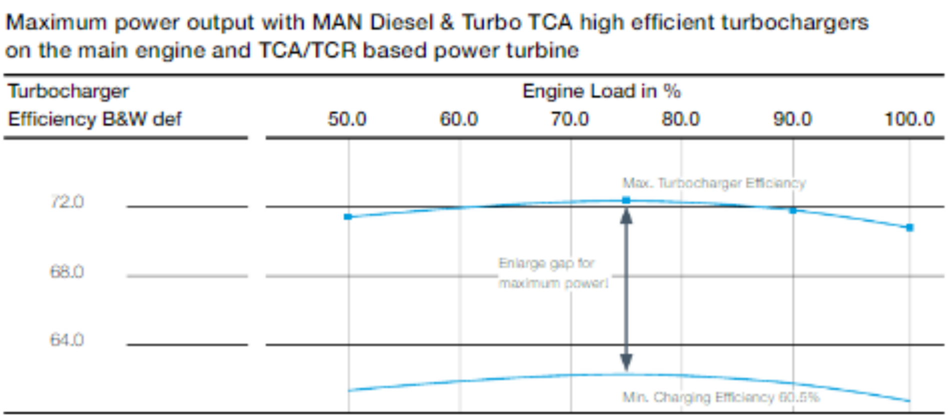

Figure 14: Power turbine conversion efficiency as the engine loading changes.

The turbine efficiency is assumed to behave as it is shown in Figure 14 with the maximum efficiency at 68% [MAN Diesel & Turbo 2011]. It is important to mention that the thermal efficiency calculation

assumes that the same exhaust gas pressure is delivered to the power turbine which in reality will not be the case. Due to limitations in the information generated in WSM pressure levels, exhaust mass flow rates are not given, hence it is assumed as good enough approximation. In case of parallel operation the exhaust manifold bypass valve will be close in case there is not enough energy to operate the power turbine.

For the generator its efficiency is assumed to be a constant 97.0% and the switchboard about 99.8% [MAN Diesel & Turbo 2012a]. The auxiliary power will be sized as if the power turbine is not installed since its operation depends in the main engine power production and not in the auxiliary engines.

For the parallel operation the sizing of the power turbine comes from the separate parts that form it: turbine and generator. The turbine mass and volume is taken from TCR produced by MAN Diesel and Turbo [MAN Diesel & Turbo 2014].

For the generator, the mass per electric power produced for wind turbine synchronous generators is around 0.023 t/kW$_e$ [Binder & Schneider 2005]. Being used in slow speed shaft speed will require heavier electrical generators. On the other side of the spectrum, are the gas turbines for electric power production which their generator will have a lower mass per power produced – around 0.002 to 0.005 t/kW$_e$ [General Electric Aviation 2016]. The average between these extreme is taken for the exhaust gas power turbine. It is assumed that the on board power electronics are capable of handling the extra load coming from the exhaust gas power turbine.

19.3 Costing Assumptions

For the parallel operation the cost of the power turbine comes from the separate parts that form it: turbine and generator. The cost of the turbine is taken as per the cost of a turbocharger for 4000 kW four-stroke diesel engine [Environmental Protection Agency 1998]. This is not an ideal reference since it is for a whole turbocharger and for a relatively small engine, but was the only one found that discussed about the cost of a turbocharger, this issue was also highlighted in the work of Shu et al. [2013].

The operational cost for the parallel power turbine with its generator will be assumed as with the series operation at $0.6/h. It is assumed that the vessels are in operation 65% of the time in a year of which 60% of that time the marine WHRS will be in operation (i.e. 3400 hours per year).

19.4 Feedback from Lloyds Register

Change description from heat to energy.

19.5 Feedback from Danish Shipowners Association/Hans Otto Kristensen / Cartsen Manniche

Are you sure it's on the main engine? I would believe the savings is on the hotel load taken from the aux engines only and not main engine?

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20 Solar Power

Description: Usage of photovoltaic cells to convert solar radiation into electrical power using the available space on deck.

Fuel Consumption Reduction: Around 0.1% – 3.0% of auxiliary engine fuel consumption.

Included in Baseline Ship specification: No

Retrofits: Yes

20.1 Mechanism for Energy Efficiency Improvement

Solar panels produce electricity using the photoelectric effect, where certain materials produce an electric current when exposed to light. Solar panels are formed of several sets cells composed of the photoelectric material connected in series and parallel to produce the desired voltage and current.

20.2 Modelling Assumptions and Implementation

Solar photovoltaic panels is a system that generates electrical power obtained from the available energy found in solar radiation using the photoelectric effect.

Solar radiation changes during the day, geographical position and season of the year, hence the importance of the route for the correct calculation of the power input of this technology to the ship. Since the route information is not available for WSM an average of 3.943 kWh/m^2 per day is assumed taken from the monthly average seen in Figure 15 [National Aeronautics and Space Administration 2016]. It is assumed that the vessels are in operation 65% of the time in a year giving a total of operation reducing the Insolation Incident on a horizontal surface to 2.563 kWh/m^2. Assuming an hour in operation the available power per surface area is 2.563 kW/m^2. This is the available solar power per surface area covered by the photovoltaic panels and it considers the whole day operation throughout the year.

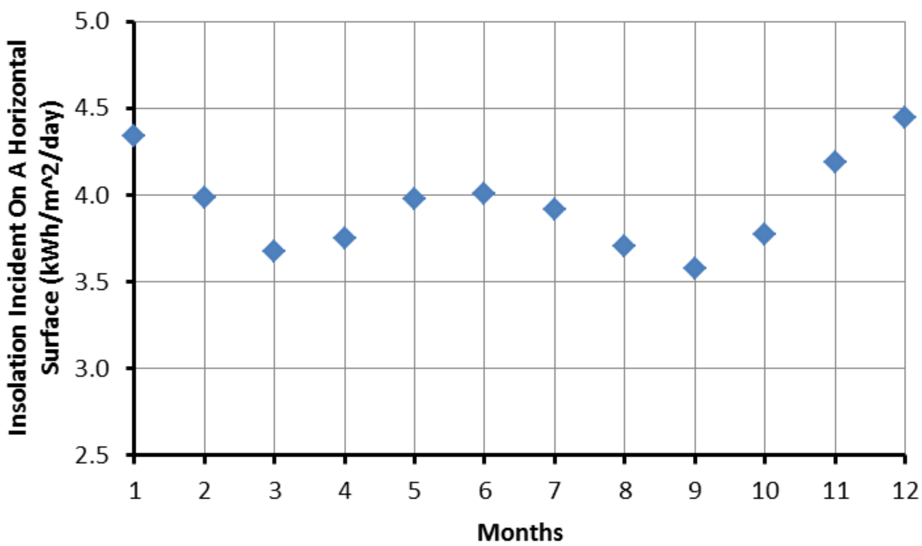

Figure 15: Monthly average potential power available for extraction for a horizontal surface.

Power output is directly linked to available deck and superstructure area. Ships with large “free” deck area (e.g. tankers) will be able to deploy extensively this technology. On the other hand, container ships do not have deck space to install solar panels – probably available space on the superstructure

roof – hence this technology will only use the available area in the superstructure. It is assumed that only 50% of the available space on deck and superstructure would be use for the installation of the system, this assumption is in line with the assumptions made for naval ships and much higher than the one seen for the *Auriga Leader* [Kirkpatrick 2013].

It is assumed that the active area of each panel is about 1 m^2 with an added 10% area for the base structure of the solar panel and they will be laid down horizontally. The efficiency of a module varies depending on the manufacturer, materials and location. Gerbinet et al. [2014] gives values between 6% to 16%, Kirkpatrick [2013] experimentally got a maximum efficiency of 13% while theecoexperts.co.uk [2016] gives a large catalogue of commercial solar panel with efficiencies that range from 14% to 21%. The efficiency of the solar panel changes according to the hour of the day, or in other words with the inclination of the light arriving to the solar panel. An average of 13.5% could be used as efficiency for this technology, however an 11.0% will be used to reflect not ideal conditions as happens with maritime operation (e.g. sea breeze).

For the mass of the system is given by a sample of 11 different solar panel vendors found in ENF Ltd. [2016] giving 7.4 t/kW_e while for the volume it was assumed that the depth of each panel to be 0.05 m while the volume of the mounting based in not considered since there is a large range of options, costs, mass and volume.

20.3 Costing Assumptions

The initial cost for the solar panel is taken from the same sample used for the installation mass [ENF Ltd. 2016] plus installation costs assumed to be $1500/kW taken from what is shown in theecoexperts.co.uk [2016]. For the total through life cost is taken from Open Energy Information [2016] which gives a range between $7.56/kW to $110.00/kW and a median of $30.00/kW. The last value is taken for this study.

20.4 Feedback from Lloyds Register

No comments for this technology.

20.5 Feedback from Danish Shipowners Association/Hans Otto Kristensen / Cartsen Manniche

Are you sure it’s on the main engine? I would believe the savings is on the hotel load taken from the aux engines only and not main engine?

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21 Superstructure mass reduction

Description: Superstructure mass reduction using composite materials which are lighter than steel.

Fuel Consumption Reduction: Around 0.2% – 1.0% of main engine fuel consumption.

Included in Baseline Ship specification: No

Retrofits: No

21.1 Mechanism for Energy Efficiency Improvement

Lower ship mass requires less power to move. From other point of view reducing the ship mass will allow to carry more cargo for the same propulsive power, which is also an increment in ship efficiency.

21.2 Modelling Assumptions and Implementation

The use of lightweight materials can reduce significantly the propulsion power need or increase the cargo capacity of any given ship. The energy efficiency mechanism is to switch the normally marine grade steel for lightweight materials such as aluminium and composite materials. For example, stainless steel has a density of about 7800 kg/m^3 while for aluminium is about 2600 kg/m^3. A plate with an area of 1 m^2 and thickness of 0.07 m will have a mass of 546 kg when using steel and 182 kg when using aluminium, this is a mass reduction of about 67%. This technology will look only into mass reduction coming from the ship superstructure which as an extra benefit it produces an improvement on stability since the centre of mass is lowered [Molland 2008].

The benefit of the change of material will be greater as the superstructure mass has a larger proportion in the total ship mass as is the case of passenger ferries and cruise ships where 40% of the total mass comes from the superstructure [Molland 2008]. In the case of the commercial ships studied by WSM the expected benefit will be lower since the superstructure proportion is smaller, however the investment could be higher since the overall size of the superstructure is larger.

The new superstructure material which will be used is a sandwich construction material consisting of two fibre-reinforced polymer (FRP) laminate on each side of a core of lightweight polyvinyl chloride (PVC) foam as described in Hertzberg [2009]. The density of FRP-PVC is given by the composition of its materials and size of the plates, where a 52 mm FRP plate can substitute a 7 mm A32 marine grade steel. Combining the densities of each material used in the composite material, assuming that the sheet surface area is 1 m^2, gives a combine density of 334 kg/m^3. A fire retardant material (FRP) is added to the composite panel, taken to be a fire resisting division 60 minutes (FRD 60) which is a Safety of Life at Sea (SOLAS) A-Class material [Morgan Thermal Ceramics 2013]. The total density of the composite material is about 162 kg/m^3. Table 2 show the properties of the composite material including the fire retardant materials.

Table 2: Composite material which will substitute the superstructure steel.

Material	Density (kg/m^3)	Laminate Thickness (m)	Quantity
FRP	2000	0.002	2
PVC	200	0.050	1
FRD 60	69	0.100 (0.075+0.025)	1

It is important to have in mind that by substituting the materials the volume of the superstructure will increase since a 254 mm plate will substitute the typical 7 mm steel plate of the superstructure. Then the relationship between material masses assuming a surface area of 1 m^2 is given by a relationship of about 0.46 as shown in Table 3. A 16% is added to the superstructure composite mass due to

adhesive and bonds [Hertzberg 2009] which modifies the mass change proportion to 0.534. This is about a mass saving of about 47% which is in range of what has been found for different ships using the same methodology [Hertzberg 2009].

Table 3: Mass comparison between the two optional materials for the ship's superstructure.

Material	Density (kg/m^3)	Surface Area (m^2)	Thickness (m)	Mass (kg)
Steel	7800	1	0.007	54.6
Composite	162		0.154	24.9

To calculate the superstructure mass the methodology suggested by Watson and Gilfillan [1977] will be used. In this method the calculation of Numeral *E* is found from the hull and superstructure. The WSM assumes, for all ships types and sizes, that the superstructure of any given ship is an average of four decks – except for container ship which has seven – with a height of 2.8 m each. This gives a total superstructure height (hss) of 11.2 m – or 19.6 m for container ships.

Due to an increase on the plate thickness, there will be a volume impact on the superstructure when using composite materials. In order to approximate this impact it is assumed that the volume of 17.5 m^3 – single room with dimensions of 2.8 m height, and 2.5 m for the width and depth – is formed using 7 mm steel. When switching to composite material the plate thickness increases by 147 mm. Assuming that the internal room volume stays the same the new volume including the composite plates changes to 20.6 m^3 an increase of 18%.

21.3 Costing Assumptions

The source of costs and the scaling relationship is important. Hellbratt [2008] shows that the initial costs when using composites for a ferry are around €79.4 million compared to €69.0 million using marine steel. Taking the mass assumption of 47% less mass when using composites then the cost per tonne of composite is around 215% more expensive than a tonne of steel. This proportion is used for the costing of the lightweight construction. An specific cost of about $670/t is assumed for the marine steel A32 taken from four different vendors and then it was averaged [Alibaba.com 2015].

Hellbratt [2008] also shows that the maintenance and operation costs for a composite ferry is about 27.8% lower than when using steel, this is mainly to do with no issues with corrosion. However this number also includes the fuel consumption of the ship which is reduced thanks to the mass reduction. TBE International Limited [2014] showed that the cost in maintenance related to corrosion and fatigue was reduced by about 60% on an Airbus A350. It was not possible to detect either the cost of superstructure maintenance using steel or a direct comparison with composites, hence it will be assumed that the through life costs are the same.

21.4 Feedback from Lloyds Register

No comments for this technology.

21.5 Feedback from Danish Shipowners Association/Hans Otto Kristensen / Cartsen Manniche

Seems to be correct according to a new study by DTU by, PRADS 2016 paper different researchers.

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22 Superstructure Aerodynamic Design

Description: Superstructure aerodynamic improvements for the reduction of the wind added resistance.

Fuel Consumption Reduction: Up to 1.0% of main engine fuel consumption.

Included in Baseline Ship specification: No

Retrofits: No

22.1 Mechanism for Energy Efficiency Improvement

Reduction of the air drag, hence reduction on the ship's added resistance due to the wind, via aerodynamic improvement on the superstructure which will reduce the power requirement at any given speed.

22.2 Modelling Assumptions and Implementation

Wind resistance can contribute up to roughly one-third of the total added resistance from wind and waves. Modern ships have a still air resistance – ship going forward – of about 2% - 3% of the total resistance of the ship. Empirical methods developed by Isherwood [1973], Blendermann [1994] and Oil Companies International Marine Forum (OCIMF) [2007] are available for estimating the added resistance from wind. These formulas will be used to calculate the added resistance of the superstructure.

The benefit of having a more aerodynamic is a reduction of in the added resistance from wind arriving to the superstructure external surface area. Benefits of a more aerodynamic superstructure for commercial ships is scarce and are dependent on the shape of the superstructure, loading condition, cargo, wind direction and speed. Kim et al. [2015] found that the air drag coefficient for a fully loaded container vessel reduced between 1% and 27% depending in the aerodynamic technology and wind direction. An average reduction value of about 5% is assumed for yearly operations for all ships.

Further study needs to be done for this technology, the work is ongoing.

No relevant mass and volume impact was identified for this technology.

22.3 Costing Assumptions

The source of costs came from Lloyds Register own experience citing a cost between $730k to $2600k. The cost will be spread by the size of the superstructure.

22.4 Feedback from Lloyds Register

Added by recommendation from Lloyds Register, cost was also recommended by Lloyds Register.

22.5 Feedback from Danish Shipowners Association/Hans Otto Kristensen / Cartsen Manniche

In my world the total contribution from still air resistance to the total resistance for a vessel is about 2% for a slower vessel and up to 10% for a faster vessel. And there seems to be a more or less direct relationship between RT and the fuel consumption – perhaps HOK can add to this.

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23 Energy saving lighting

Description: Change of lighting equipment from incandescent to LED which will lower the electricity demand on board.

Fuel Consumption Reduction: Up to 0.5% of main engine fuel consumption.

Included in Baseline Ship specification: No

Retrofits: No

23.1 Mechanism for Energy Efficiency Improvement

Reduction in the electrical demand on board due to a change in the lighting technology used. Incandescent lighting systems are much more inefficient that LED lightning.

23.2 Modelling Assumptions and Implementation

The use of efficient Light Emitting Diode (LED) lighting in place of conventional incandescent lamps and tube lights on board, contributes to a lower power demand which will improve the vessel energy efficiency. Another benefit of LED lighting system is that they have a longer life-span which reduces the maintenance costs.

The WSM code does not have any provisions for lighting requirement or space layout inside the hull and superstructure, hence it is required to make some assumptions. Also the volume of the hull is not given hence it will be calculated as the cuboid formed by the ship's length, beam and depth multiplied by the ship's block coefficient at 80% [Molland 2008], of this it will be assumed that between 20% and 30% will be illuminated.

The American Bureau of Shipping [2012] splits the ship spaces in five different type of spaces: crew accommodations, navigation and control, service spaces, operating and maintenance spaces, and red or low-level white illuminance. For this work the navigation and control space will be assigned totally to the superstructure volume (V_{ss}) while the other will occupy space in the hull ($V_{l,hull}$). The distribution of spaces is as shown in Table 4 given in percentage of $V_{l,hull}$. The same table shows the average illuminance requirement in three different categories (Low, Medium and High) for each space as given by the American Bureau of Shipping [2012]. This distribution has been assumed for all type of ships.

Table 4: Space distribution and its assumed illuminance requirements. In parenthesis under the illuminance column shows the proportion of the volume that needs to be under the different level of illuminance.

Space type	Volume Proportion (% of $V_{l,hull}$)	Illuminance (Lux)		
		Low	Medium	High
Crew Accommodation	9	127 (30%)	460 (52%)	810 (18%)
Service	11	178 (16%)	444 (58%)	750 (26%)
Operating and Maintenance	80	130 (53%)	330 (39%)	1630 (8%)
Low-level	1	25		
Navigation and Control	90 (V_{ss})	180 (20%)	420 (73%)	810 (7%)

The ship total volume will be split in volumes of 17.5 m^3 which will be called room units which have 6.25 m^2 as surface area with a constant 2.8 m height. When the number of rooms is not exact and the left volume is above 17.5 m^3 but less than 40% then it will be increased to that of the single room

reaching a maximum of 24.5 m^3. In case of having a higher proportion than 40% then it will assumed as another single room with a maximum volume of 10.6 m^3. The excess volume will be assigned to the operating and maintenance room with a medium illuminance.

It is assumed that the LED lamps will not have an impact on mass and volume. For mass the difference is negligible since an LED has a mass of about 75 g while for the incandescent is around 37 g [Screwfix Direct Ltd 2016; Ledbulbs.co.uk 2016]. In the case of volume, it is possible to find LED lamps that occupy the same space as their counterparts.

23.3 Costing Assumptions

The initial cost for LED lamps (IC_{LED}) is simply the lamp unit cost per kilowatt (SC_{LED}) installed multiplied by the power installed. A small sample taken from internet gives a SC_{LED} of \$859.9/kW_e for LED lamps while for incandescent lamps the specific cost (SC_I) is just \$21.2/kW_e.

Table 5: Proportion of time in the year that the different spaces will be illuminated by the lamps. Also shows when the lamps will need to be changed for both technologies.

Space Type	Proportion of Time (%)	Operating Hours in a Year (h)	Time Until Incandescent Replacement (years)	Time Until LED Replacement (years)
Crew Accommodation	50	4380	0.23	11.42
Service	45	3942	0.25	12.68
Operating and Maintenance	65	5694	0.18	8.78
Low-level	5	438	2.28	+40
Navigation and Control	40	3504	0.29	14.27

For the through life cost for LED (TLC_{LED}) and incandescent (TLC_I) bulbs it is assumed that a bulb can last for about 50000 hours while for the incandescent bulb is about 1000 hours [Lim et al. 2013]. The life span of each lamp technology will be assumed for all illuminance scenarios. In each of the space groups it will be assumed a percentage of time of the year which the lighting will be turn on (see Table 5). This assumption will apply to all illuminance groups.

23.4 Feedback from Lloyds Register

No comment for this technology.

23.5 Feedback from Danish Shipowners Association/Hans Otto Kristensen Cartsen Manniche

Normally the saving is on the aux engine consumption. We have LED lightning on some of our vessels and it seems that we can save up to 10% on the aux engine consumption/hotel load in total 0.25 MT/day => 1% on main engine.

Pls note that installing LED in engine may be limited as the LED socket/console has a upper temperature limit of 45°C; several sockets have failed on our vessel.

References

American Bureau of Shipping, 2012. Crew Habitability on Ships, New York.

Ledbulbs.co.uk, 2016. 6W Incanda-LED Classic Dimming. MEGAMAN, p.1.

Lim, S.-R., Kang, D., Ogunseitan, O.A. & Schoenung, J.M., 2013. Potential Environmental Impacts from the Metals in Incandescent, Compact Fluorescent Lamp (CFL), and Light-Emitting Diode (LED) Bulbs. Environmental Science & Technology, 47(2), pp.1040–1047.

Molland, A., 2008. The maritime engineering reference book: a guide to ship design, construction and operation 1st ed. A. F. Molland, ed., Oxford: Butterworth-Heinemann.

Screwfix Direct Ltd, 2016. Sylvania GLS Incandescent Vintage Lamp ES 60W | Light Bulbs | Screwfix.com. Light Bulbs, p.1. Available at: http://www.screwfix.com/p/sylvania-gls-incandescent-vintage-lamp-es-60w/3753g [Accessed August 11, 2016].

24 Engine derating

Description: It is the operation of an engine at its normal maximum pressure as set at its design point but having a lower brake mean effective pressure and shaft speed. This produces a reduction in the engine's specific fuel oil consumption.

Fuel Consumption Reduction: 2% specific fuel consumption reduction.

Included in Baseline Ship specification: No

Retrofits: Yes

24.1 Mechanism for Energy Efficiency Improvement

By altering the fuel injection timing to adjust the mean and maximum pressure relationship, the result brings a reduction in Specific Fuel Oil Consumption (SFOC). For a fixed pitch propeller matched engine the relationship between power, propeller and ship speed is fixed to a particular propeller curve. A move in this curve is down to the amount of fuel combusted in the engine. Hence, de-rating an engine achieves a better fuel consumption for lower than normal propeller speeds.

In case that the propeller is not changed, de-rating will cause a reduction in design speed which leads to a lower propulsion demand. In this case the main engine is optimised for the new operating conditions, hence a lower SFOC [Pérez Osses & Bucknall n.d.].

24.2 Modelling Assumptions and Implementation

A de-rated engine operates at a lower Brake Mean Effective Pressure (BMEP) and shaft speed while keeping maximum constant power [Wettstein & Brown 2008]. The engine is optimised to run at a lower SFOC for the desired operative condition. As shown in Figure 16, point 1 is the MCR point while point R is a potential possible new MCR point of the de-rated engine with decreased engine power and engine speed but higher propulsion efficiency.

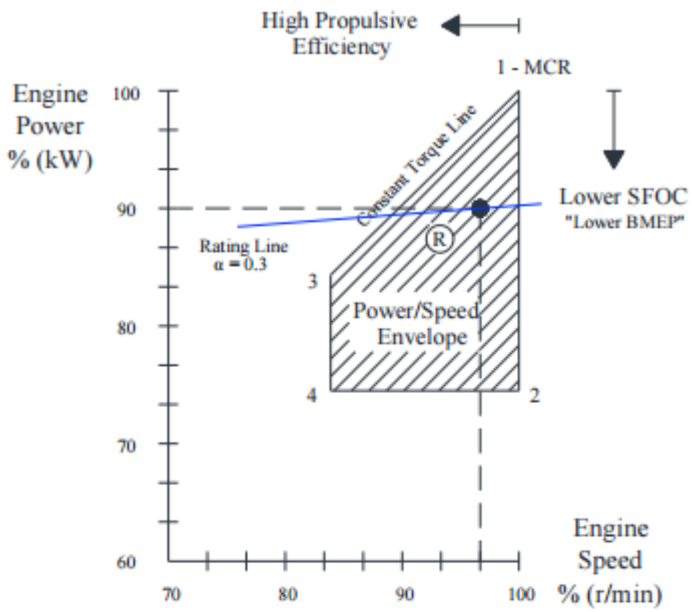

Figure 16: Engine power/speed diagram [Wettstein & Brown 2008].

24.2.1 De-rating an existing ship

De-rating the main engine and propeller can lead to up to 15% fuel saving if a ship's operational speed is generally lower than the one originally designed for [MAN Diesel & Turbo 2015]. The whole

de-rating project includes designing of a new propeller, re-matching the turbocharger, etc. If the ship is designed for a relatively higher speed, e.g. 18 knots, but it often sails at 15 knots, then de-rating may be an effective method to improve efficiency. In the case that the ship is equipped with a fix pitch propeller and a new propeller is not fitted then the result of derating will be a lower navigational speed [Woodyard 2009].

24.2.2 Derating engines for new ships

When de-rating is used for new ships, the de-rated engine power is that which will drive the ship at a given design speed with a propeller selected – probably with a larger diameter – for the desired power at a lower shaft speed [Woodyard 2009]. This approach is the one followed for this work, since WSM studies the effect of different design speeds for the same ship. This data is sent to Glotram to calculate the benefits and side effects of reducing operating and design speeds.

24.3 Costing Assumptions

The costs were adapted from the IMO document MEPC/Inf.7 [IMO 2011]. Reduced speed leads to reduced propulsion demands, further less fuel consumption. The impacts to SFOC and propeller efficiency are not considered in the initial estimation stage.

24.4 Feedback from Lloyds Register

Minimum power requirement for bad weather or traversing the barred speed range should be considered.

24.5 Feedback from Danish Shipowners Association/Hans Otto Kristensen / Cartsen Manniche

A de-rated engine works at a lower mean effective pressure (BMEP) and according to MAN Diesel this will decrease the SFOC by appr. 4 pct.

Re-optimising the engine by selecting a lower power with a lower RPP and a larger propeller is what I will call slow steaming where the fuel reduction per cargo unit per nautical mile can be reduced as follows:

75000 DWT Bulk carrier:
5 % speed reduction reduces the energy demand per transport unit by 14 %
10 % speed reduction reduces the energy demand per transport unit by 24 %

9000 TEU Container ship:
5 % speed reduction reduces the energy demand per transport unit by 15 %
10 % speed reduction reduces the energy demand per transport unit by 26 %

References

IMO. (2011). Reduction of GHG emissions from ships - MEPC 62/INF.7. Retrieved from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Technical and Operational Measures/Marginal abatement cost.pdf

Wettstein, R., & Brown, D. (2008). Derating: a solution for high fuel savings and lower emissions. *Switzerland, Wärtsilä*.

Pérez Osses, J. R., & Bucknall, R. W. G. (n.d.). On the impact of marine engineering efficiency with de-rated engines: A study using VLCCs.

MAN. (2015). Derating - Change of Engine SMCR. Retrieved from

http://primeserv.man.eu/docs/librariesprovider5/primeserv-documents/de-rating.pdf?sfvrsn=2

Woodyard, D., 2009. *Pounder's Marine Diesel Engines and Gas Turbines* 9th ed., Oxford: Butterworth-Heinemann.

25 Energy storage system

Description: Energy Storage Systems (ESS) can be used to store energy from regeneration (i.e. from a waste recovery system) to optimise engine loading conditions, or to provide propulsion and auxiliary power, etc.

Fuel Consumption Reduction: Depends on the system configuration and device types.

Included in Baseline Ship specification: No

Retrofits: Yes

25.1 Mechanism for Energy Efficiency Improvement

In electric/hybrid vehicles, ESS can be used to store energy from regeneration, to optimise engine loading conditions, to provide direct propulsion, etc. Batteries and ultra-capacitors have been used by land-based electric vehicles and have been developing rapidly over the past decade [Khaligh & Li 2010]. ESS are essential when fuel cells (FC) are used– ESS can function as a buffer to compensate the transient loads to optimise the FC load conditions. Given its fundamental advantages, Lithium-ion batteries will probably continue to dominate portable electrochemical energy storage including portable electronics, power tools, and hybrid/full electric vehicles for many years to come [Nitta et al. 2015].

In this project, ESS is assumed to be used together with the auxiliary power system to optimise the engine load conditions to achieve a lower SFC. For example, when the engine load is extremely low, e.g. below 25% MCR, which is an unfavourable running area for most marine diesel engines, ESS can be an alternative power source to provide auxiliary power. Depending on the operating profile and system configuration, the savings could vary from ship to ship. Also, such technology is limited by the availability of charging facilities on shore unless the system is configured with the ability to charge the energy storage device when there is redundant power from the auxiliary power system.

25.2 Modelling Assumptions and Implementation

It is assumed that Lithium-ion batteries are used for the ESS media – the volumetric energy density is 350 kWh/m^3; the specific energy density is 280 kWh/t. Both charge and discharge efficiency are set to 0.9. The specific energy cost is $773/kWh while the specific power cost is $309/kW.

It is assumed for this technology that there are three auxiliary engines installed, and the ESS can deliver power equal to one generator; the batteries can discharge at rated power for 15 mins.

The efficiencies of DC/AC convertor, main switchboard, transformer, AC/AC converter are 0.99, 0.998, 0.99, 0.985 respectively.

It is assumed that ESS supplies power when the auxiliary engine load is less than 25% MCR.

25.3 Costing Assumptions

The model calculates the costs based on specific energy cost and specific cost first – the higher cost of the two will be the unit purchase cost.

25.4 Feedback from Lloyds Register

1. Electric power storage, peak shaving, Combined Diesel Electric and Diesel.

ESS is only modelled to provide auxiliary power.

25.5 Feedback from Danish Shipowners Association/Hans Otto Kristensen / Cartsen Manniche

No comment for this technology.

References

Khaligh, A., & Li, Z. (2010). Battery, Ultracapacitor, Fuel Cell, and Hybrid Energy Storage Systems for Electric, Hybrid Electric, Fuel Cell, and Plug-In Hybrid Electric Vehicles: State of the Art. IEEE Transactions on Vehicular Technology, 59(6), 2806–2814. http://doi.org/10.1109/TVT.2010.2047877

Nitta, N., Wu, F., Lee, J. T., & Yushin, G. (2015). Li-ion battery materials: present and future. *Materials Today*, *18*(5), 252–264. http://doi.org/http://dx.doi.org/10.1016/j.mattod.2014.10.040

26 Common rail

Description: Optimise the engine over different operating fields. Electronically controlled injection systems can deliver multiple fuel injections at variable injection timing with very high rail pressure.

Fuel Consumption Reduction: 0.1% - 0.5% [IMO 2011].

Included in Baseline Ship specification: No

Retrofits: Yes

26.1 Mechanism for Energy Efficiency Improvement

On a conventional engine, fuel is injected at a fixed rate by a pump, and the pump is adjusted for a particular engine loading condition, which means the injection for other engine loading conditions are not optimised. In a common system, the injectors are connected to a common rail which reserves high pressure fuel supplied by the fuel supply pump. The fuel pressure is maintained by a fuel supply pump and pressure limiter. The Engine Control Unit is responsible of controling the fuel pressure in the common rail system depending on the engine loading condition. Very high rail pressure (up to 3000 bar) together with multi-stage injection leads to very fine fuel droplets, which improves the engine efficiency and reduces NO_x emissions. With the common rail system, a diesel can be optimised over the different operating fields.

Electronically controlled injection systems can provide multiple injections within a working cycle with optimised timing and amount. A small amount of fuel is injected into the cylinder as pre-injection to warm up the combustion chamber, and then more fuel is injected into the cylinder in the main-injection period. After the main-injection, post-injection maintains a relatively higher temperature during expansion stroke. The peak pressure and peak combustion temperature are reduced, so the NO_x and PM emissions are reduced as well as noise.

Multiple injections also contribute to the improvement of fuel efficiency since the injected fuel is better mixed with the air.

26.2 Modelling Assumptions and Implementation

It is assumed that a common rail engine's mass and volume are the same as an ordinary engine. The savings are achieved by a lower SFC, i.e. 0.995 of the original SFC [IMO 2011].

26.3 Costing Assumptions

The costs were adapted from the IMO document MEPC/Inf.7 [IMO 2011].

26.4 Feedback from Lloyds Register

No comments for this technology.

26.5 Feedback from Danish Shipowners Association/Hans Otto Kristensen / Cartsen Manniche

No comment given for this technology.

References

IMO. (2011). Reduction of GHG emissions from ships - MEPC 62/INF.7. Retrieved from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Technical and Operational Measures/Marginal abatement cost.pdf

27 Engine tuning

Description: Optimise the engine for the most commonly used load ranges.

Fuel Consumption Reduction: 0.1% - 0.8 % [IMO 2011].

Included in Baseline Ship specification: No

Retrofits: Yes

27.1 Mechanism for Energy Efficiency Improvement

The main engine should be optimised for the most commonly used load ranges by either changing the cam profiles and fuel injection timing. For a specific operating point, the SFC might be higher than the original condition. However, the overall fuel consumption should be lower than the original condition.

27.2 Modelling Assumptions and Implementation

It is assumed the tuning does not affect the engine's mass and volume.

The savings are achieved by a lower overall SFC, i.e. both 0.992 of original for both main and auxiliary engines.

27.3 Costing Assumptions

The costs were adapted from the IMO document MEPC/Inf.7 [IMO 2011].

27.4 Feedback from Lloyds Register

No comments for this technology.

27.5 Feedback from Danish Shipowners Association/Hans Otto Kristensen / Cartsen Manniche

No comment for this technology.

References

IMO. (2011). Reduction of GHG emissions from ships - MEPC 62/INF.7. Retrieved from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Technical and Operational Measures/Marginal abatement cost.pdf

28 Variable speed control of pumps and fans

Description: Control the usage of pumps and fans at a variable speed according to the actual need.

Fuel Consumption Reduction: 1% reduction in fuel consumption was found from the WSM.

Included in Baseline Ship specification: No

Retrofits: Yes

28.1 Mechanism for Energy Efficiency Improvement

Pumps and fans are controlled at a variable speed according to their need, giving a better operating efficiency.

28.2 Modelling Assumptions and Implementation

The implementation of variable speed control of pumps and fans was modelled as 1% reduction in shaft power and auxiliary power.

28.3 Costing Assumptions

The costs were adapted from MEPC/Inf.7 [Russell et al., 2011], assuming an annual effective discount rate of 5% from 2007.

28.4 Feedback from Lloyds Register

No comments for this technology.

28.5 Feedback from Danish Shipowners Association/Hans Otto Kristensen / Cartsen Manniche

No comment for this technology.

References

Russell, B.A., Bruce, St Amand, D., Faber, J., Wang, H. and Nelissen, D. Marginal Abatement Costs and Cost Effectiveness of Energy-Efficiency Measures, SNAME, International Maritime Organisation, MEPC62/Inf.7, 2011.

29 Hybrid turbocharging

Description: A hybrid turbocharger integrated with a generator uses exhaust-gas energy at the turbocharger inlet to generate electricity [ONO et al. 2012].

Fuel Consumption Reduction: ~3% when the main engine load is higher than 60% MCR [ONO et al. 2012].

Included in Baseline Ship specification: No

Retrofits: Yes

29.1 Mechanism for Energy Efficiency Improvement

Re-matching of a variable geometry turbine to the compressor will provide a better availability in the exhaust system to extract more energy by using variable speed generator/motor fitted to the turbocharger shaft to generate electricity. The generator output will reduce the power demand to auxiliary gensets. Also electric power can be supplied to the hybrid turbocharger to accelerate the compressor and generate boost pressure rapidly to improve transient response. This is particularly useful during manoeuvring, in bad weather, and for rapid traversing the barred speed range.

29.2 Modelling Assumptions and Implementation

It is assumed that the hybrid turbocharging system generates electricity only when the engine load is higher than 60% MCR [ONO et al. 2012]. The model assumptions are taken from MET83MAG-Hybrid V/G Turbocharger.

Voltage convertors and harmonic filters are required for the hybrid turbocharger variable speed motor/generator.

The mass increase due to the integration of hybrid turbocharging is that of the electric motor/generator together with the associated electrical systems for a voltage converter, harmonic filters and electrical cables.

29.3 Costing Assumptions

It is assumed that additional equipment price is the same as diesel genset, i.e. $280/kW.

29.4 Feedback from Lloyds Register

Preliminary engine cycle simulations results with a hybrid turbocharger concept matched to a 2-stroke marine diesel engine confirm the 3% energy saving claim relative to the baseline engine at the MCR condition.

29.5 Feedback from Danish Shipowners Association/Hans Otto Kristensen / Cartsen Manniche

No comment for this technology.

References

ONO, Y., SHIRAISHI, K., & Yamashita, Y. (2012). Application of a large hybrid turbocharger for marine electric-power generation. Mitsubishi Heavy Industries Technical Review, 49(1), 29.

30 Block coefficient reduction

Description: Block coefficient reduction reduces resistance, making the ship more slender, whilst maintaining the same waterline length, but comes at the expense of a higher purchase cost.

Fuel Consumption Reduction: A reduction in the resistance in operation between 8% and 13% (for ships with a block coefficient above 0.6)

Included in Baseline Ship specification: No

Retrofits: No

30.1 Mechanism for Energy Efficiency Improvement

The selection of the block coefficient of ship is a complicated balance between purchase cost, cargo capacity and the though water resistance. This can be further complicated by changing dimensions and considering dimensional constraints (such as port requirements), stability and seakeeping. Ship builders can design blockier and easier to fabricate ships with worse through water performance in order to reduce purchase cost.

30.2 Modelling Assumptions and Implementation

In order to investigate the impact of changing block coefficient two ships were examined by calculating the recommended block coefficient for the design speed of existing ships, as calculated by referring to a block coefficient by Ayre in Schneekluth and Volker [1998], which underestimates the block coefficient compared to most ships, as some ship types are primarily for reducing ship build cost. This aspect of the calculation is pessimistic.

The block coefficient of two ships was reduced by increments of 0.05 from the block coefficient calculated by the WSM. It was found that the impact on wave making resistance was a large part of the calculated impact; this can be seen in Table 6 and Table 7. The length and beam of the ships were kept the same and the WSM calculated the corresponding draught in its design process.

Table 6: Varying the block coefficient of a bulk carrier with a design speed of 15 knots, deadweight of 50038 tonnes and Beam of 31.2m.

Block Coefficient	Operation Speed (kt)	Design Draught (m)	Lightweight (t)	Wave Resistance (kN)		Total Resistance (kN)	
0.75	15	15.3	11440.3	148.0	0.0%	839.6	0.0%
0.70	15	16.6	12471.2	85.1	-42.5%	765.0	-8.9%
0.65	15	18.2	13696.2	61.9	-58.2%	747.1	-11.0%
0.60	15	20.0	15173.2	40.8	-72.4%	720.8	-14.1%

Table 7: Varying the block coefficient of a container ship with a design speed of 20 knots, deadweight of 95162 and beam of 31.4m.

Block Coefficient	Operation Speed (kt)	Design Draught (m)	Lightweight (t)	Wave Resistance (kN)		Total Resistance (kN)	
0.68	20	9.7	11188.3	289.7	0.0%	1256.3	0.0%
0.63	20	10.5	12382.9	193.6	-33.2%	1084.1	-13.7%

In some cases, particularly for ships with a higher Froude number, increasing the waterline length (whilst reducing block coefficient) lowers resistance more than an increase in draught would.

Reducing draught may be a stringent assumption but this can be more readily applied to different ships reducing stability concerns and berthing costs.

Note that very slow speeds may benefit from a higher block coefficient if it leads to a decrease in wetted surface area. Holtrop-Mennen [1982] was used in the resistance model in the WSM, which can have limitations beyond the ship characteristics that are used in the resistance model.

The WSM also calculates the new lightweight and engine and propeller requirements.

In order to capture the findings in a technology file it was assumed that the wave-making resistance was reduced by 35% and the frictional resistance by 5%.

This is a general saving but this is likely to vary substantially between ships due to practical, seakeeping and stability requirements.

30.3 Costing Assumptions

The costs were adapted from the IMO document MEPC/Inf.7 [Russell et al., 2011]. Block coefficient reduction was assumed to be the same as the propeller upgrade cost, assuming an annual effective discount rate of 5% from 2007.

30.4 Feedback from Lloyds Register

Agree that Holtrop-Mennen is the right technology for this.

30.5 Feedback from Danish Shipowners Association/Hans Otto Kristensen / Cartsen Manniche

This was added following feedback from Carsten to include more operational measures and consider the optimisation of future ships (the latter is considering in block coefficient reduction).

Why keeping the same length? In some bulkcarrier cases or special purpose vessels it might the case keeping the length the same, but most of the vessels can be longer. One of reason why the length is not changed is because is a part of the yards price key -> greater length -> more steel -> higher newbuilding price. But vessels should be built longer in order to increase the efficiency. Don't keep the length fixed and only vary the draft.

References

Holtrop, J. and Mennen, G., “An Approximate Power Prediction Method” International Shipbuilding Progress, 29, pages 166-170, 1982. Holtrop-Mennen [1982].

Russell, B.A., Bruce, St Amand, D., Faber, J., Wang, H. and Nelissen, D. Marginal Abatement Costs and Cost Effectiveness of Energy-Efficiency Measures, SNAME, International Maritime Organisation, MEPC62/Inf.7, 2011.

H. Schneekluth and V. Bertram Ship Design for Efficiency and Economy, page, Butterworth-Heinemann, second edition, 1998, page 26.

31 Hull cleaning

Description: Reduction in frictional resistance due to choice of hull cleaning strategy.

Fuel Consumption Reduction: 5%

Included in Baseline Ship specification: No

Retrofits: Yes, assuming this can be combined with coatings

31.1 Mechanism for Energy Efficiency Improvement

Buhaug et al. [2009] stated that the appropriate choice of hull coating and hull maintenance can amount to a 5% difference in energy requirement.

31.2 Modelling Assumptions and Implementation

This is modelled as a 5% reduction in frictional resistance, for the purposes of this work it is assumed that this can be combined with different hull coating

31.3 Costing Assumptions

31.4 The costs were adapted from the IMO document MEPC/Inf.7 [Russell et al., 2011]. The lower hull coating cost was used, assuming an annual effective discount rate of 5% from 2007. Russell et al. [2011] may contain kite costs.

31.5 Feedback from Lloyds Register

No comments for this technology.

31.6 Feedback from Danish Shipowners Association/Hans Otto Kristensen / Cartsen Manniche

This was added following feedback from Carsten to include more operational measures and consider the optimisation of future ships.

References

Buhaug, Ø., Corbett, J., Endresen, Ø., Eyring, V., Faber, J., Hanayama, S., Lee, D., Lee, D., Lindstad, H., Markowska, A., Mjelde, A., Nelissen, D., Nilsen, J., Pa ̊lsson, C., Winebrake, J., Wu, W., and Yoshida, K. (2009). Second IMO GHG Study 2009 (MEPC 59/INF.10). Marine Environment Protection Committee - 59th session, International Maritime Organisation.

Russell, B.A., Bruce, St Amand, D., Faber, J., Wang, H. and Nelissen, D. Marginal Abatement Costs and Cost Effectiveness of Energy-Efficiency Measures, SNAME, International Maritime Organisation, MEPC62/Inf.7, 2011.

32 Future hull coating

Description: Future hull coating is a hull coating that benefits from new technology, possibly from hydrophobic technology.

Fuel Consumption Reduction: 10% reduction in frictional resistance (available in the future)

Included in Baseline Ship specification: No

Retrofits: No

32.1 Mechanism for Energy Efficiency Improvement

This is a notional future hull coating that reduces frictional resistance by 10% on average, which is will be available from 2030. The cost is also high compared to other hull coatings.

Although there are potentially some developments in non-stick services that could be of benefit. The development of this hull coating is unclear because developing a coating to reduce resistance, fouling and last a long-time is a difficult task.

It is assumed that this future technology will be compatible with hull coating. However, when keeping the same hull cleaning time interval it is expected that its benefit to the ship will be lower than with other hull coatings.

32.2 Modelling Assumptions and Implementation

A 10% reduction in frictional resistance was assumed.

32.3 Costing Assumptions

The costs were adapted from the IMO document MEPC/Inf.7 [Russell et al., 2011]. Three times the cost of the higher hull coating cost was used, assuming an annual effective discount rate of 5% from 2007. Russell et al. [2011] may contain kite costs.

32.4 Feedback from Lloyds Register

No comments for this technology.

32.5 Feedback from Danish Shipowners Association/Hans Otto Kristensen / Cartsen Manniche

No comment for this technology.

References

Nothing yet.

33 Autopilot upgrade

Description: Autopilot upgrade is an improvement to the autopilot that improves weather routing.

Fuel Consumption Reduction: A 1% reduction on overall resistance

Included in Baseline Ship specification: No

Retrofits: No

33.1 Mechanism for Energy Efficiency Improvement

In practice, this reduces added resistance due to waves; it may also involve a mathematical model of a ship.

33.2 Modelling Assumptions and Implementation

Voyage and heading optimisation is important as the shortest distance over water does not necessarily give the lowest fuel consumption or shortest voyage time. This is an area that already has had the financial incentive to be developed because autopilots are fairly inexpensive compared to most other fuel-reducing measures, not requiring any changes to the ship. Trials have shown a 1% reduction in CO_2 emissions from a bulk carrier from a Japan based marine navigation company [Sustainable Shipping, 2010]. A well optimised autopilot function can remove the need for unnecessary changes in heading; reduce the energy loss in the rudder as well as reducing the distance sailed off-track.

33.3 Costing Assumptions

The costs were adapted from the IMO document MEPC/Inf.7 [Russell et al., 2011]. Autopilot upgrade was assumed to be half of autopilot adjustment cost, and also assuming an annual effective discount rate of 5% from 2007.

33.4 Feedback from Lloyds Register

No comments for this technology.

33.5 Feedback from Danish Shipowners Association/Hans Otto Kristensen / Cartsen Manniche

This was added following feedback from Carsten to include more operational measures and consider the optimisation of future ships.

References

Russell, B.A., Bruce, St Amand, D., Faber, J., Wang, H. and Nelissen, D. Marginal Abatement Costs and Cost Effectiveness of Energy-Efficiency Measures, SNAME, International Maritime Organisation, MEPC62/Inf.7, 2011.

[Sustainable Shipping, 2010] Sustainable Shipping (2010). Ship control unit reduces carbon emissions. Sustainable Shipping website, Available from: http://www. sustainableshipping.com/news/i96981.print [Accessed July 2013].