Designing Future Ships for Significantly Lower Energy Consumption

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Abstract

The likelihood of both increases in, and volatility of, the cost of conventional fuel in the coming decades combined with more stringent emission regulations, means that ships in the future will have to be significantly more efficient and make use of alternative sources of energy. Considering the regulatory aspect, it has been claimed that, if the IMO were to reduce international shipping's carbon dioxide emissions to those consistent with limiting anthropogenic climate change to 2 degrees of warming, then ships in 2050 would have to reduce their carbon dioxide emissions by 75-90% compared to ships in 2012. To investigate what might be the appropriate mix of technologies and operational approaches for future ship designs the "Whole Ship Model" (WSM) was developed, which is a holistic ship design tool, primarily developed at UCL, that can generate many ship design options with different design, technology and fuel combinations. The Whole Ship model can be used to explore different arrangements and uses of energy efficiency measures on container ships, bulk carriers and tankers evaluating their performance over an operating profile. This paper will initially present some results from the Whole Ship Model, evaluating the potential performance of present day ships and technologies and will then compare this to technically feasible future ship designs that use contemporary or near-term technology to achieve very high reductions in carbon dioxide emissions and energy consumption.

1. Introduction

Although there is some agreement that oil will continue to be a part of the future energy mix for shipping beyond 2030, *Grahn et al. (2013), Smith et al. (2014)*, there is uncertainty as to future trends in several socio-economic factors that are pertinent to the design of ships, such as:

- oil price (as a recent, late 2014, drop in oil prices has demonstrated)
- freight rates
- environmental regulation (which is likely to increase)

1.1. Energy efficiency and Carbon Dioxide Emissions Regulation

The International Maritime Organisation (IMO) and the European Union (EU) are both taking steps to increase carbon dioxide emission regulations in shipping.

In July 2011, the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) became mandatory for new ships only (EEDI) and all ships (SEEMP). This came into force in January 2013, *IMO Press Briefing (2011)*. The EEDI is a metric related to the potential transport work of a ship and is calculated at an operational point of 75% of the main engine's Maximum Continuous Rating (MCR) *IMO MEPC.212(63) (2012)*. For compliance the calculated EEDI has to be smaller than the required EEDI from a reference line, which is an average index value for a defined group of ships based on data from HIS Fairplay *IMO MEPC.215(63) (2012)*. This required EEDI decreases over time, so demanding increased efficiency for future newbuild ships.

In November 2014, EU-wide rules for monitoring, reporting and verification of CO_2 emissions from ships were approved, *European Council (2014)*. From January 2018 all ships over 5000 gross tonnes calling at European Union (EU) ports will have to report actual fuel consumption for each voyage, *European Commission (2013)*. The rationale for this regulation is that a robust system for monitoring, reporting and verification of greenhouse gas emissions from maritime transport is a prerequisite for any market-based measure, whether applied at EU level or globally, *European Commission (2013)*. The IMO has taken its own steps towards an international mandatory system for collecting ships' fuel consumption data following MEPC 69 in April 2016, *IMO Press Briefing (2016)*. However, this is still lacking much of the detail that can be found in the EU-wide rules.

1.2. Defining an Emissions Target to limit the greenhouse gas impact to 2°C for 2050

Until any further technical and operational measures to control GHG emissions are progressed, the only effective regulation is the EEDI, which is a minimum efficiency standard for new ships, however the current EEDI trajectory does not have a future reduction rate as high as that which might be required to limit global greenhouse gas emissions to those consistent with a (maximum) 2°C global warming target.

By considering an appropriate global CO_2 emissions budget, *Traut et al. (2015)* used data from the Third IMO GHG Study, *Smith et al. (2014)*, to estimate what a limit of a 2°C increase in greenhouse gas emissions above pre-industrial levels would mean for the operational efficiency of ships.

Traut et al. (2015) examined the impact of three scenarios on the operational efficiency of ships, the scenario with the lowest required reduction in ship operational efficiency (a 75% reduction in carbon dioxide emissions compared to 2012) included a 10% decrease in operational speed per decade. For the purpose of this study, where we are considering operational speed, the most stringent scenario will be assumed; a 90% reduction in carbon dioxide emissions compared to a 2012 baseline.

2. Ship Owners and Operators in 2015

To determine a baseline of what energy efficiency technologies might currently be being used, a survey of ship owners was carried out by UCL in 2015, which was also submitted to the International Maritime Organisation's Marine Environmental Protection Committee, *Rehmatulla and Calleya (2016)*. The UCL survey can be found in, *Rehmatulla and Calleya (2016)*. This survey covered 275 ship owners and operators covering around 5,000 ships and examined the take up of technical efficiency measures. This survey indicated that there is little adoption of currently available technologies even those technologies that would deliver reductions in costs, as illustrated in Fig.1.

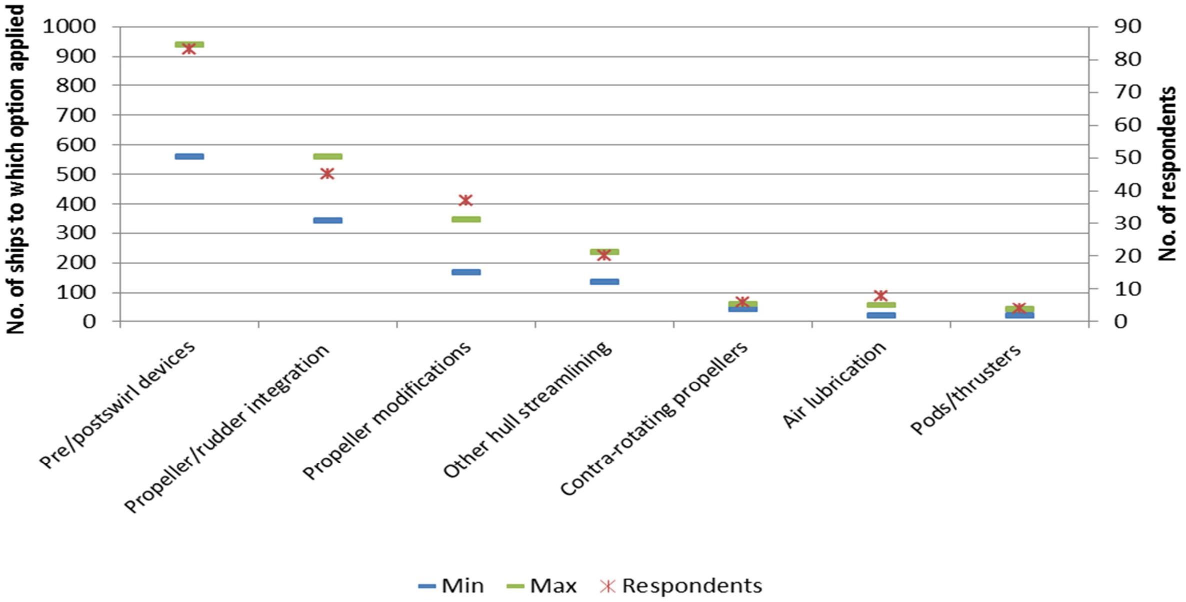

Fig.1: Adoption of ship hydrodynamic technical efficiency measures, *Rehmatulla and Calleya (2016)*

Rehmatulla and Calleya (2016) contain graphs showing the take-up of technical energy efficiency measures in design, hydrodynamic and machinery changes. It is very clear from the survey when there is little adoption of current technologies, as illustrated by Fig.1 where the most common technologies are still only applied to less than 20% of the fleet surveyed.

The technologies that were being used in 2015 and that are later considered in combination are:

- Bulbous Bow
- Rudder Bulb (this is combined with End Plated Propeller as in *Nielsen (2012)*)
- End Plated Propeller (this is combined with Rudder Bulb as in *Nielsen (2012)*)
- Energy saving lighting
- Engine Derating
- Speed control of pumps and fans
- Common Rail Engines (included as part of baseline ship)
- Efficient Boiler (included as part of baseline ship)

3. Whole Ship Model

The Whole Ship Model (WSM) was developed by UCL as part of the Shipping in Changing Climates (SCC) project, a multi-disciplinary project investigating likely future carbon emissions from shipping and the technical and operational methods available for their reduction. The WSM is a flexible and holistic ship design tool coded in Python that allows selecting or entering a description of a single ship or fleets, and is described in technical detail by *Calleya et al (2015b)*. Fig.2 shows an overview of the inputs that the WSM can utilise. Ship design and operational assumptions can be combined in order to examine how a ship performs over an operating profile at an early design stage. The WSM can compare technologies, different design variants of the same ship specification or examine the performance of shipping fleets, depending on the preference of the designer or decision-maker.

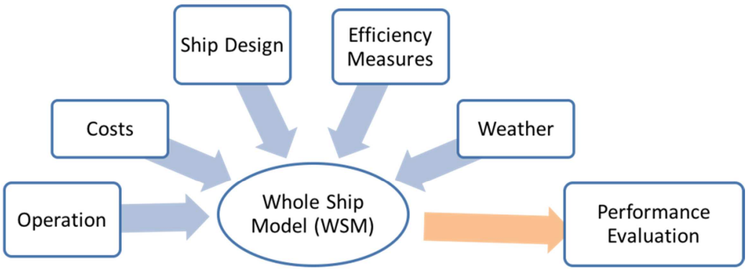

Fig.2: Overview of Whole Ship Model, *Calleya et al. (2016).*

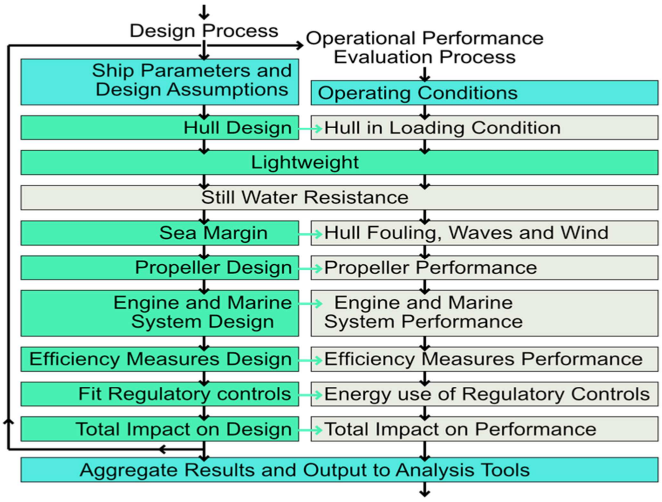

Fig.3: Overview of Whole Ship Model, *Calleya et al. (2016)*

The WSM runs in an iterative design process for both design and in service operating conditions, (see Fig.3, where the effects of different technologies, operational measures, fuel types, regulations, speeds and weather are incorporated in an iterative process leading to a numerically balanced design option). The design process establishes and fixes the main characteristics of the ship (e.g. capacity and installed power). The operational assessment process uses the ship specification created by the design process and calculates its performance at different ship speeds, weather conditions and in regulatory regions like for example in Emission Control Areas (ECA). It is important to note that the WSM calculates the ship performance in a series of steady-state conditions. The use of time-domain approaches is being considered for future development to allow full voyage modelling.

3.1. Hull Design and Still Water Resistance Estimation

The hullform modelled in the WSM has a fixed monohull topology that can be modified to represent different types and sizes of ships. The hullform generator was described in some detail in *Calleya et al. (2015b)*, and represents the hullform as a series of waterplanes constructed using straight lines and curves using hyperbolic functions. Although this method does not allow precise representation of certain features such as stern bulbs and tunnel sterns, it has the advantage of being adaptable to a wide variety of merchant ship types and sizes, without requiring excessive iteration or multiple model topologies. This model can generate a representative hullform from a limited set of inputs, some of which can either be entered by the user or based on programmed guidance (such as block coefficient varying with speed). This rapidly generated hullform is sufficient to allow the estimation of the hull lightweight, righting moment, resistance, and operational cargo load, and to give a rough general arrangement of the ship. Still water resistance is based on Holtrop and Mennen (1982) and some of the components from Holtrop (1984).

3.2. Propeller Design

The propeller model uses polynomial functions to describe the Wageningen B-Screw Series of propellers, *Oosterveld and Oossnan (1975)*. In the design process the propeller is sized to match the thrust required to drive of the ship at the specified design speed. For a fixed pitch propeller, the calculated propeller efficiency curve is fixed and then used to find the efficiency of the propeller in different operational conditions. When a controllable pitch propeller is selected the pitch of the propeller is varied for different propeller revolution speeds in order to find the highest operational efficiency.

3.3. Engine and Marine System Design

The engine model selects the main and auxiliary machinery required by the ship specification. The engine model is based on the MAN Diesel & Turbo project guides, *MAN Diesel & Turbo (2013)*. For the main propulsion machinery, the model selects from 18 two-stroke engines and 6 four-stroke Diesel engines with different cylinder numbers. In the case of the auxiliary machinery, it only considers seven different four-stroke Diesel engines with several cylinder numbers.

For the main engine, the model finds engines suitable for the maximum torque and propeller speed given by the hull and propeller design process (see Fig.4). It also takes into account engine and sea margin which are also designer defined. After finding all possible candidates, the engine model selects the most fuel efficient engine and returns to the main code information such as specific fuel oil consumption, physical characteristics, number of engines and emissions. In the case of the auxiliary machinery the engine model received from the ship definition the electrical power demand on board and then searches to find the most fuel efficient machinery option, considering and engine margin and redundancy. Embedded into the engine model is the fuel database which contains twelve different fuels and their physical properties (e.g. low calorific value). For this study only HFO has been considered since the objective is to focus on the potential impact of energy efficiency measures applied to this power train only, with respect to ship performance.

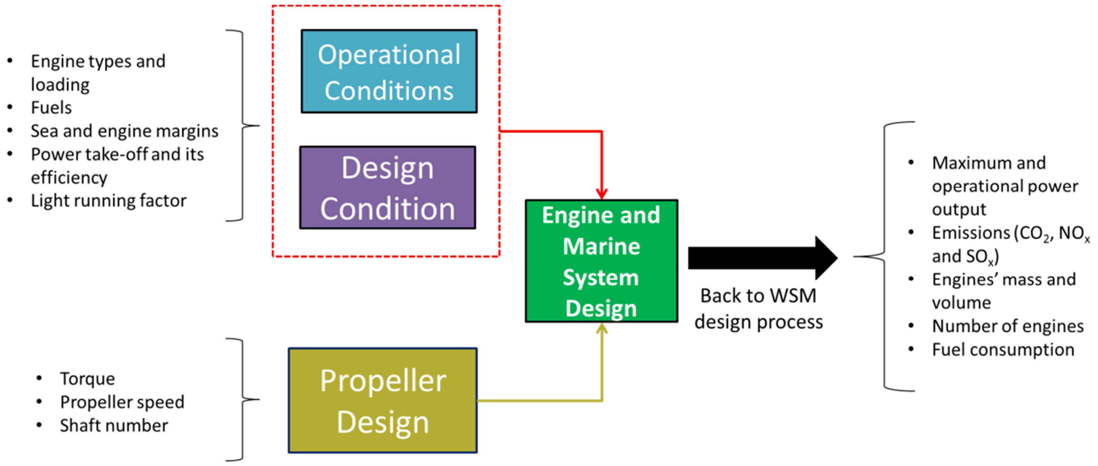

Fig.4: Relevant data flow to and from the engine and marine system model

3.4. Energy Efficiency Measure Models

Efficiency Measures are a group of technologies – hydrodynamic, mechanical or electrical – and operational choices – maintenance, routing and voyage optimisation – which, either individually or as a group, have an impact on the energy demand on board. Efficiency Measures are defined in files separate from the WSM, allowing different models to be used, different model sets have been used for different projects including those produced in the Low Carbon Shipping, *Smith et al. (2010)*, ETI project, *ETI News (2013)*, Shipping in Changing Climates and more recent projects. The Efficiency Measure model passes information to WSM via a set of parameters which modify the inputs of the different parts of WSM shown in Fig.3. A detailed list of parameters and that are passed between ships and technologies were described by *Calleya et al. (2015a)*.

The WSM has in its catalogue more than 32 different technological and operational measures which can be applied to the different ship specifications. It is possible to combine up to multiple technologies and assess the impact of each measure both on each other and the overall ship. If more measures need to be combined then it is possible to create a new efficiency measure file can be created where the impacts are modelled for that particular combination.

Each model is scaled according to the ship needs and limitations (e.g. it would not be possible for a container ship to have a set of large sails installed since there is not any space available on deck) and returns to WSM the efficiency measures' impacts such as volume, mass and energy requirements. The efficiency measures are sized and costed at the design condition while the WSM evaluates their performance separately at the operational conditions, including off-design conditions. The UCL ship performance models also consider operating ship speed as an independent input that can be varied rather than being treated as an energy efficiency measure, *Calleya et al. (2012,2015a)*.

3.5. Regulatory Controls

It is important to consider the implications of regulations on ship design. Technologies and operational measures introduced purely to comply with regulations are incorporated into the WSM in a similar way to the Efficiency Measures. The WSM considers regulatory controls for the ship such as for SO_x, NO_x and CO_2 emission or ballast water treatment. It adds the technology or group of technologies defined as being required to make the ship design comply with regulations that will be in force when launched.

4. Achieving 90% Reduction in Energy Usage in 2050

In order to find a high reduction in energy use a combination of technologies were considered that had a higher reduction in energy use than those being used by ship owners in 2015. Technologies were selected to improve upon the efficiency of ships, beyond what owners were doing in 2015. A brief explanation is given of the relevance of these technologies in this section

4.1 Resistance Reduction

The resistance of the hullform can be reduced by hydrodynamic means, such as adding (or removing) a bulbous bow or adding a stern flap, or by reducing the skin friction by air lubrication. 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 compared to an average hull form, as given in *Mäkiharju (2012).*

4.2. Improving Propulsive Efficiency

A Contra Rotating Propeller was considered as a possible future option instead of End Plated Propellers and Rudder Bulbs, which were being used in 2015. These can be implemented in several ways; by splitting the propulsion load between a conventional propeller and a pod immediately astern of it; by the use of contra-rotating gears; or by the use of hybrid electric propulsion systems. The Contra Rotating Propeller generally has a greater improvement in energy efficiency compared with other energy efficiency measures that improve propulsive efficiency (such as modifications to the propeller) but it is more mechanically complex and expensive due to the additional equipment. For a deep-sea cargo ship a system using contra-rotating gears may be the most desirable as it is relatively compact compared to some electric options and so was used in this study.

Ishikawajima-Harima Heavy Industries Co., Ltd. (IHI) retrofitted such 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).*

4.3 Stern Flaps

A method of reducing resistance for large ships, particularly those at higher speeds, will be to reduce transom waves, *Gabor et al., 1999* and this can be achieved with stern flaps. 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*. The improvement is mainly found at the high end of the Froude Number range, which makes this more applicable to container ships.

4.4. Waste Heat Recovery Systems

Waste Heat Recovery System (WHRS) can be used to recover energy lost from the propulsion engine in several ways. Steam can be raised by a boiler heated by the main engine exhaust, driving turbo-alternators to generate electricity or directly providing heat to cargo etc. An Organic Rankine Cycle (ORC) WHRS can be also be used to extract energy from lower temperature sources such as cooling water. Mechanical methods such as turbo compounding can be used to extract energy from the exhaust, assumed to be parallel compounding for main engines and series compounding for auxiliary engines. Although the engine exhaust is the main source of waste energy, many (if not most) vessels already use this waste heat for cargo and domestic heating or electrical generation. Thus this practice was assumed to be part of the “baseline ship” and the additional options of ORC WHRC and turbo-compounding used as future developments. The WHRS models reflect the inability of these systems to extract power below certain main engine operating points, and additionally the effect of increased back-pressure on engine performance.

4.5. Wind Assistance (Flettner Rotors and Kites)

The lift, drag and input motor power of Flettner Rotors were calculated with reference to *Traut et al. (2014)*. The lift and drag are calculated and resolved to the direction of the ship to give a thrust. The direction of rotation of the Flettner Rotor was chosen to maximise thrust. Each Flettner Rotor was assumed to have a modest height of 13.5 m and a radius of 2.7 m. As an example of performance, with an apparent wind direction and speed of 141 degrees and 14 knots and a 15 knot ship speed a single Flettner Rotor can produce a thrust of 460 kN. The same constant wind speed and direction, which is optimistic, was used for all the calculations with Flettner Rotors in this paper.

Kites were included, but this model is under development and so were approximated as providing 5% of the thrust required for a given ship speed. This modest gain is offset by their limited impact on deadweight.

Both Flettner Rotors and Kites were assumed to be not applicable on a container ship due to limited deck space and stability. For all other ship types Flettner Rotors were placed on deck above the bulkheads and between the holds, which are normally around 30 m apart.

5. Technology Combinations for 2050 Evaluated by the Whole Ship Model

Surveying the generalised estimates of the potential of technologies to improve ship energy efficiency, those technologies with higher reduction in emissions were selected to try to achieve a 90% reduction in ship energy usage. The 2050 combination of technologies are:

- Bulbous Bow (if required)
- Contra Rotating Propeller
- Stern Flap
- Air Lubrication
- Main Engine Turbo Compounding Parallel
- Aux Turbo Compounding Series
- Organic Rankine Cycle WHRS
- Flettner Rotors
- Kites
- Engine Derating
- Speed Control of Pumps and Fans

The above technologies were evaluated by the Whole Ship Model (WSM). For comparison purposes a combination of the existing technologies used by ship owners in 2015 (given in Section 2) were also evaluated by the WSM.

Three different ship types were considered:

- 4999 TEU Container Ship with a design speed of 25.1 knots.
- 53541 dwt Panamax Bulk carrier with a design speed of of 15.3 knots
- 46249 dwt Tanker with a design speed of 14.8 knots

5.1. Variation in Fuel Consumption with Ship Speed

Figs.6 to 8 show how the fuel consumption (including auxiliary and boiler fuel use) of different loaded ship and technology combinations varies with speed. The impact of operational changes, such as reducing speed, can be assessed for given technological combinations from this data. It can be seen that the reduction in fuel consumption by combining technologies without wind produces maximum reductions in fuel consumption between 10 and 20%. This is equivalent to operating the ships approximately 2 knots slower.

Figs.6 and 8 show that the reduction in fuel consumption for combinations of 2050 Technologies (without wind technologies) is similar to the savings from using combinations of technologies that ship owners were using in 2015. This indicates some degree of flexibility in the choice of technology when combining technologies. It also illustrates that the major reductions in emissions required in the most stringent scenario (90%) are unlikely to be achieved without the use of wind assistance, speed reduction, alternative fuels, or some other high-impact approach.

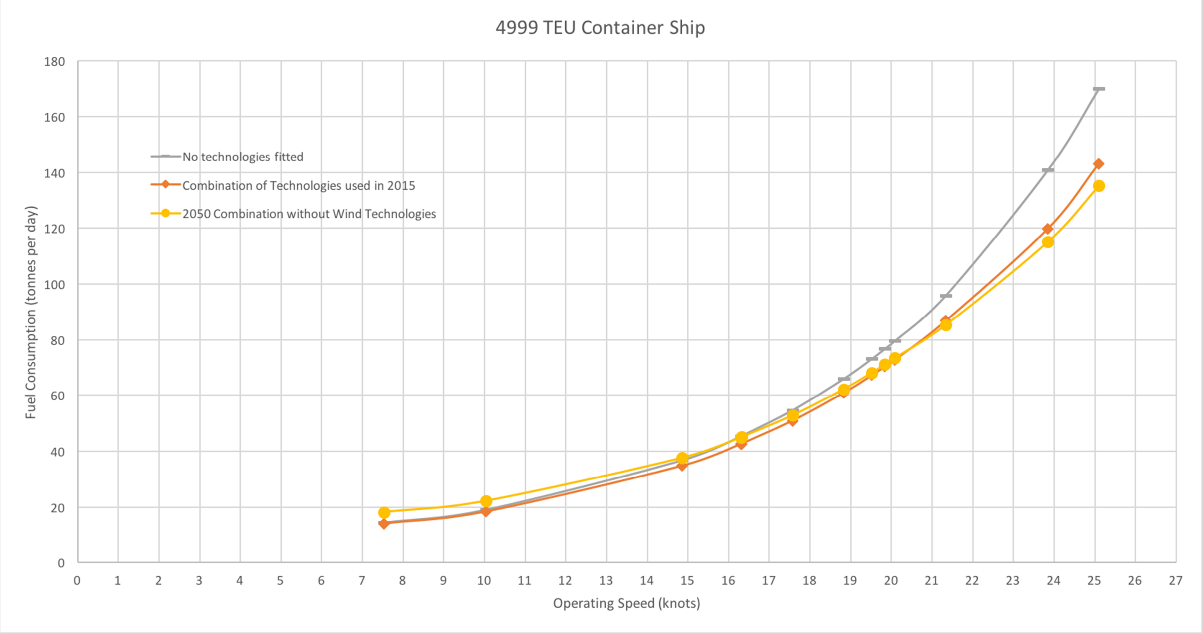

Fig.6: Fuel Consumption against speed for a 4999 TEU Container Ship fitted with different technology combinations

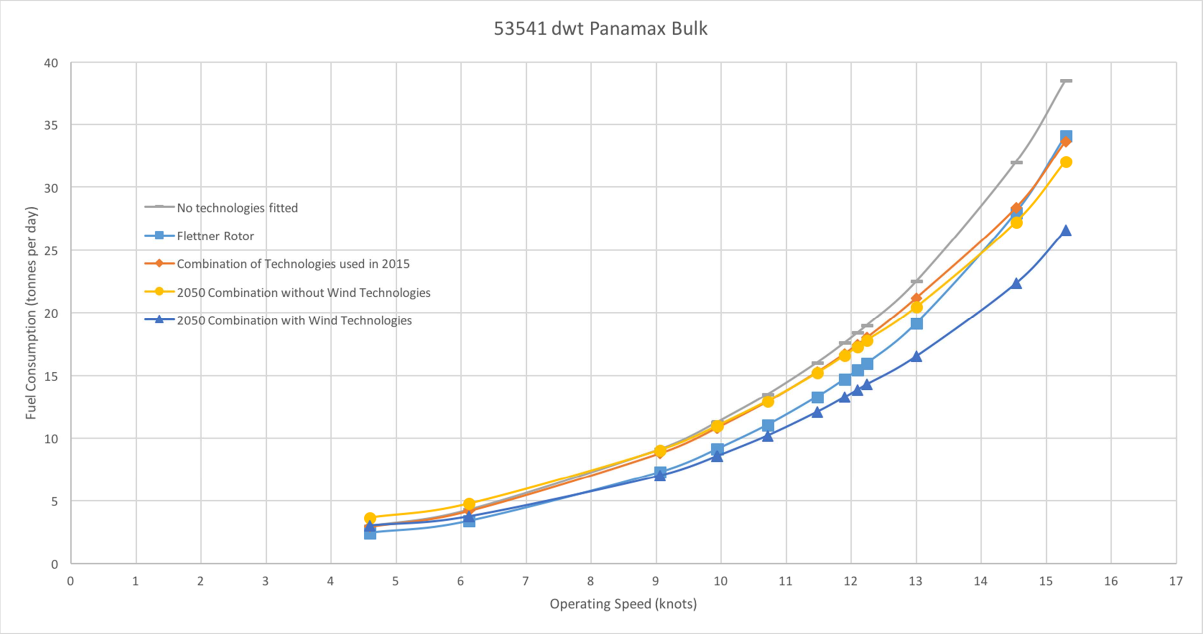

Fig.7: Fuel Consumption against speed for a 53541 dwt Panamax Bulk fitted with different technology combinations

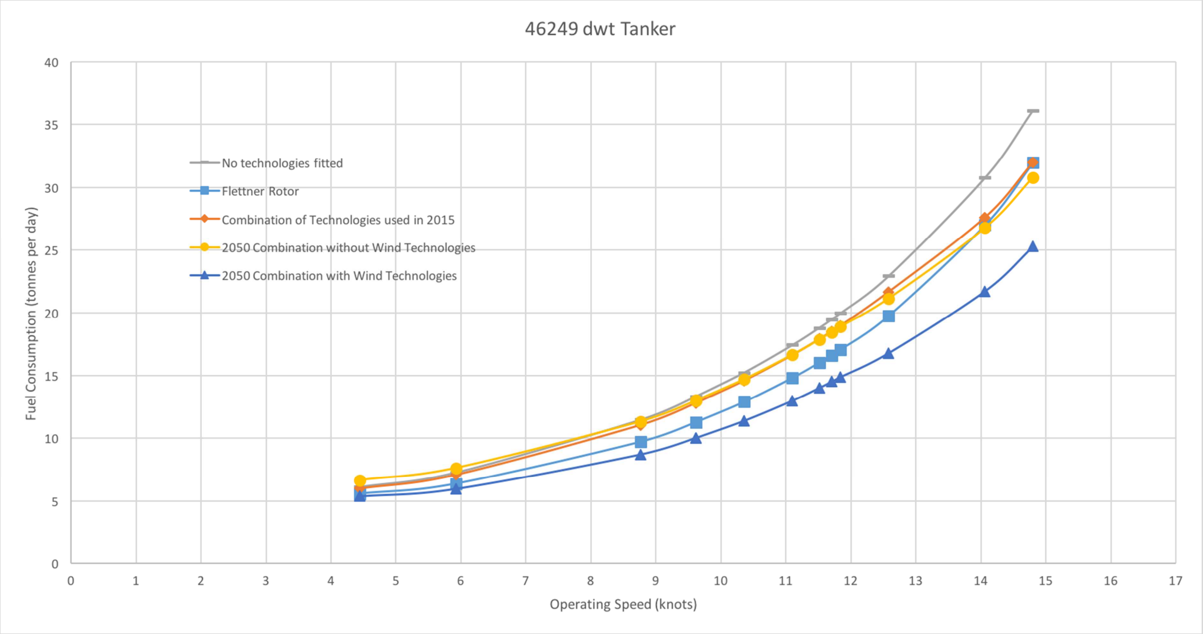

Fig.8: Fuel Consumption against speed for a 46249 dwt Tanker fitted with different technology combinations.

It can be seen that the 2050 combination of Technologies has a higher fuel consumption compared to the 2015 combination at lower speeds. This is in some part due to the increase in auxiliary engine specific fuel consumption due to back pressure from turbo compounding of the auxiliary engine. This increase in auxiliary fuel consumption is also exacerbated by:

- The container ship, **Error! Reference source not found.**, having more installed auxiliary power then the tanker, **Error! Reference source not found.**.
- Additional installed auxiliary power for air lubrication (and Flettner Rotors when installed).
- Turbo compounding in series being effective below 65% of the rated auxiliary power.

At higher speeds the increase in recovered waste heat due to turbo compounding in series complements the additional power required for air lubrication (and Flettner Rotors when installed). Note that the last bullet point here is actually an artefact of the way the technologies have been described in the WSM, the auxiliary engines can be sized better in the WSM by considering the combination of technologies that the ship will use, the WSM can also quickly run multiple versions of the same technology.

Figs.7 and 8 include the fuel consumption reduction from wind technologies, Flettner rotors were also plotted separately due to their large contribution to reducing fuel consumption. Even though the fuel consumption from wind technologies could vary considerably based on operational conditions, the calculated fuel consumption from using Flettner rotors on the slower bulk carrier and tanker is roughly comparable to that achieved by all the other technologies combined. Note that the findings here are subject to the assumptions used and the way their performance is modelled.

5.2. Ship Energy Efficiency Operational Indicator (EEOI) based on ship activity in 2010

The Ship Energy Efficiency Operational Indicator (EEOI) was calculated based on the average weighted operational speed of ships in 2010, from the 3rd IMO Greenhouse Gas study, *Smith et al. (2014)*, and ship utilisation information that was submitted to the IMO, *Smith et al. (2015)*.

The EEOI, as defined in *IMO MEPC Circ.684 (2009)*, is a measure of the cargo carrying efficiency of a ship, in terms of CO_2 emissions (Fuel Consumption × Carbon Factor) per cargo (m_{cargo}) × distance (D) travelled for each fuel (j) over a number of voyages (i):

$$Average\ EEOI = \frac{\sum_i \sum_j \left(FC_{ij} \times CF_j\right)}{\sum_i \left(m_{cargo,i} \times D_i\right)}$$

The average annual EEOI for a 4999 TEU container ship in 2010 shown in Table I was calculated based upon being 68% full for a loaded voyage with an average annual speed of 16.2 knots. For a 53541 dwt Panamax Bulk, shown in Table II, this is 90% full with a 11.9 knot average annual speed and for a 46249 dwt Tanker, shown in Table III, this is 81% full with a 11.7 knot average annual speed. The carbon factor of Heavy Fuel Oil from *IMO MEPC Circ.684 (2009)*.

Table I: 4999 TEU Container Ship EEOI in 2010 based on 68% utilisation

Technologies	Median EEOI for 16.3 knots (in 2010) Percentage change	EEOI if 25.1 knot Design Speed is used Percentage change
none fitted	0.0	0.0
Combination of Technologies used in 2015	-6.2	-15.8
2050 Combination without Wind	-1.0	-20.5

Table II: 53541 dwt Panamax Bulk EEOI in 2010, based on 90% utilisation

Technologies	Median EEOI 11.9 knots (in 2010) Percentage change	EEOI if 15.3 knot Design Speed is used Percentage change
none fitted	0	0
Flettner Rotors	-16.5	-11.5
Combination of Technologies used in 2015	-5.1	-12.7
2050 Combination without Wind	-5.9	-16.8
2050 Combination with Wind	-24.8	-31.0

Table III: 46249 dwt Tanker dwt Panamax Bulk EEOI in 2010, based on 81% utilisation

Technologies	Median EEOI 11.7 knots (in 2010) Percentage change	EEOI if 14.8 knot Design Speed is used Percentage change
none fitted	0	0
Flettner Rotors	-14.6	-11.5
Combination of Technologies used in 2015	-4.9	-11.4
2050 Combination without Wind	-5.1	-14.7
2050 Combination with Wind	-25.4	-30.0

The percentage change in calculated average annual EEOI will vary in the same way as fuel consumption. Tables I to III are useful to see what the reduction in EEOI would be from technologies in operation. In Table I, due to the 2050 technologies having an increasing fuel consumption at lower speeds and that a container ship in 2010 operated well below its design speed the combination of 2050 technologies is worse than the 2015 combination. For the Panamax Bulk in Table II they are about the same. At the lower speeds that Panamax Bulk ships operated at in 2010 the reduction in EEOI due to Flettner Rotors is approximately three times the percentage reduction in EEOI from the other three technologies. At the design speed of the Panamax Bulk ship they are similar.

6. Conclusions

This paper has summarised the Whole Ship Model (WSM), a holistic and extensible model developed by UCL for the Shipping in Changing Climates (SCC) project. The WSM allows the assessment of the performance and ship impact of a range of technologies over a range of ship types, design specifications and operational conditions. In this study, a limited set of technologies have been evaluated against a projected, highly stringent, requirement to reduce the emissions from international shipping by 90% as part of a co-ordinated attempt to limit anthropogenic climate change to 2^0C of warming.

6.1 Emissions Reduction

It was found that by combining technologies without wind and speed reduction, fuel consumption may be reduced by between 10 to 20%, although this requires multiple technologies to be adopted, in contrast to the current practice where few of the presently available technologies for efficiency improvement are being widely used. Wind assistance can provide further reductions in fuel consumption, but still far short of 90%. Meeting this challenging requirement will require a combination of technologies, speed reductions and fuel decarbonisation. Given the potentially higher costs of alternative fuels and the economic impacts of changing operational speeds, technologies that are currently seen as unattractive may become more widely adopted to help offset these issues. This has been considered in the application of energy saving technologies to warships (*Pawling et al, 2016*) where even unlikely technologies such as wind assistance were found to be justifiable considering the higher cost of naval fuels and fixed operational speeds.

6.2 Future Work

In this study, technologies and ships have been combined without optimisation, but the WSM allows individual technologies and ships to be quickly designed to work better together, by changing the technology models to represent different optimisation strategies. For example, WHRS could be optimised to perform at lower engine powers to reflect reduced ship speeds or “flexible steaming”. Such optimisation may be significant for technologies such as wind assistance, where the selection and sizing of Flettner Rotors or kites has thus far been assumed to be generic, rather than optimised for the ship size and operating profile. Simple line graphs were used here as relatively few technologies and ships were examined, but the WSM can generate large datasets containing many options and *Calleya et al. (2016)* presented a web-based approach for exploring these more expansive results.

6.2 Implications for Future Regulation

This work also has important implications for the EEDI discussion ongoing at the IMO assessing the potential energy saving from technologies allows for a path for future technologies and fuels to be developed. Having smaller savings from technologies does not mean regulation needs to be reduced.

Acknowledgements

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