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Ship impact model for technical assessment and selection of Carbon dioxide Reducing Technologies (CRTs)

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ABSTRACT

It is not unreasonable to imagine that the future may herald higher energy prices and greater regulation of shipping's Greenhouse Gas (GHG) emissions. With the introduction of the Energy Efficiency Design Index (EEDI) into MARPOL Annex VI, tools are needed to assist Naval Architects and Marine Engineers to select the best solutions to meet evolving requirements for reduced fuel consumption and associated carbon dioxide emissions. To that end, a concept design tool, the Ship Impact Model (SIM), has been developed for quickly calculating the technical performance of a vessel with one or more Carbon dioxide Reducing Technologies (CRTs) at an early design stage. The underlying basis for this model is the calculation of changes from known 'baseline ships'. The Ship Impact Model has been used in two projects to assess which selection (individual or combination) of Carbon dioxide Reducing Technologies (CRTs) have the most potential, in terms of cost-effectiveness and under other technical, operational and regulatory influences.

1. Background

Future Greenhouse Gas (GHG) emissions may be limited either due to regulation to reduce the risk of dangerous climate change or because the high prices of conventional GHG emitting energy products, such as fossil fuels, will lead to increases in energy efficiency and substitution by alternative energy sources. The credibility for such a future scenario is derived from energy scenarios, such as that derived by the International Energy Agency (International Energy Agency, 2010).

The efficiency increasing and energy options that are the most appealing are the options that reduce operating costs the most and have lower installation and purchase costs compared to conventional energy sources. Though it is important to consider that while an option can appear to be the most appealing on a basic cost and technical basis, as previous studies have shown (Eide et al., 2009; Det Norske Veritas, 2010), the technical considerations are part of a more complex shipping system (Calleya et al., 2012) and take-up of new technologies can be conservative. Ship owners are nervous about investing in new technology. Long-term contracting arrangements can be complex (Pirrong, 1993); for instance a combined owner and operator may have more incentive to invest in energy efficiency (Rehmatulla, 2011). There is uncertainty about the performance of new technologies and, in particular, the future of fuel prices and legislation. For fuel prices, the concern is not just over the absolute price of fuel but also the differential between different fuel types. Invest too soon and they could be uncompetitive compared to owners who delay, invest too late and they may not meet the legislation deadline. Choose the wrong technology and it could be redundant in ten years time when further legislation on, for example, black carbon is introduced. The proposal at the 65th meeting of the IMO's Marine Environmental Protection Committee (MEPC 65) to delay the introduction of Tier III from 2016 to 2021 (IMO, 2013) is an illustration of why ship owners are reluctant to be early adopters of technology.

The purpose of the Ship Impact Model (SIM) is to provide a tool for ship owners and operators to permit them to quickly explore various scenarios with different combinations of Carbon dioxide Reducing Technologies (CRTs) in an uncertain future. The SIM was developed as part of the RCUK (EPSRC) funded project "Low Carbon Shipping – A Systems Approach" (LCS) (Smith, 2010) and then applied to a Rolls-Royce led project, the Energy Technology Institute Heavy Duty Vehicle Energy programme (ETI, 2013). Running from 2010 to 2013, the aim of LCS was to use understanding of the many components of the shipping system to explore how the shipping industry might respond to the challenge of a GHG constrained future from a combination of the technological, economic, logistical, operational and infrastructure perspectives. The scope of the overall project is described in Smith et al. (2010). This paper focuses on a specific research area within the

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project – the development of ship design and evaluation procedures for the estimation of the technical specification of new build and retrofit ships over the next 40 years.

2. Definition of carbon dioxide reducing measures

Balland et al. (2010) work on air emission reduction methods, includes SO_x, and NO_x reducing measures in addition to Carbon dioxide (CO_2) and considers both operational and technological options as being air emission controls. The more generic term abatement options or abatement measures is often used by work submitted to the IMO's MEPC or published elsewhere (Buhaug et al., 2009; Det Norske Veritas and Lloyds Register, 2010; Committee on Climate Change, 2011). Buhaug et al. (2009) makes a clear distinction between operational and technological measures, and operational measures have been assessed as likely to have an effect quickly and technical measures as likely to take longer to show a significant impact (Det Norske Veritas and Lloyds Register, 2010). However, there has been no clear definition of terms, possibly due to CO_2 reduction being associated with efficiency improvement. Although interlinked, there are key differences between reducing CO_2 emissions, reducing fuel consumption, reducing costs and increasing efficiency.

Two new specific terms, defined below, have arisen from the need for consistent use of language when modifying ships or ship operations with the prime objective of reducing Carbon dioxide (CO_2) emissions:

- A Carbon dioxide Reducing Measure (CRM) is any measure that reduces the Carbon dioxide (CO_2) emissions of a ship or a fleet of ships. A CRM can be categorised as an operational measure or a Carbon Dioxide Reducing Technology (CRT). An important operational measure (non-technological CRM) is reducing operational speed.
- A Carbon dioxide Reducing Technology (CRT) is any technology that can be incorporated into a ship (this could be either a retrofit or new build) that reduces the Carbon dioxide (CO_2) emissions of the ship compared to the original ship design (before modification). A CRT is one type of Carbon dioxide Reducing Measure (CRM) and can be categorised as reducing propulsion power, reducing auxiliary power, using fuel more efficiently (increasing energy/CO_2 emissions) or as using alternative fuels (e.g. Liquid Natural Gas (LNG) instead of Marine Diesel Oil (MDO)).

In this work the focus has been on CRTs that are currently available or are technically feasible today with little or no additional development cost. As ships have an expected service life of around 30 years, CRTs that are only applicable to new build ships will take much longer to widely implement (Calleya et al., 2012). Non-technological CRMs (such as trim optimisation and weather routing) do not interact with the ship in the same way as CRTs. Most non-technological CRMs are inherently cost-effective (often no physical changes to the ship are required) though the CO_2 reduction potential can be highly uncertain and may be dependent upon the incentive of the crew.

3. Development and description of the ship impact model (SIM)

The SIM has been developed as a concept design tool for quickly calculating the technical performance of a vessel with different CRTs. It is intended for use at the early stage of a new build or retrofit design process. The underlying basis for this model is the calculation of changes from known baseline ships. Although there is a wide range of ship types in the global fleet that can be described in the SIM, the current work has focused on four ship types: container ships, bulk carriers, oil tankers and LNG tankers. These four cargo ships were chosen as they represent the largest proportion of shipping CO_2 emissions and account for 89% of global gross tonnage (Buhaug et al., 2009).

Table 1 summarises the selected ship designs that were generated. Surveys of the Clarksons Research Shipping Database, carried out at the start of the LCS project in 2010 and 2011, indicated that many ships fall into size categories of similar displacements, partly due to port and canal size limits. In the LCS project, the focus was on ship types where there is the biggest potential for CO_2 emissions reduction; ship size categories that carry the most overall deadweight and in which there are a lot of similar ships (in terms of speed and size). Note that Liquid Natural Gas (LNG) tankers are a relatively small proportion of current international shipping, but they were included as they may represent an emerging market with increasing use of natural gas for power generation. Two types of LNG tankers were examined, Heavy Fuel Oil (HFO) powered 2-stroke diesel propulsion and LNG powered steam turbine propulsion. In 2007 the majority of LNG tankers were steam turbine driven, after 2007 the trend has been towards more diesel powered ships (Noble, 2007). However, this means there are many steam turbine propulsion ships currently at sea (these variants are not shown in Table 1).

The SIM uses a baseline data set of 36 full three-dimensional ship design models, these were produced using the ship design software Paramarine and are illustrated in Fig. 1. Each ship type was modelled at four sizes and two or three design speeds. These models were used to generate a virtual fleet of ships to populate the model. However, an operator or design house with their own fleet and design database could use this instead, so that the SIM could estimate the impact of CRTs on their vessels.

To include potential future changes in hullform design speed, ship models were made at one or two additional design speeds (depending on ship type). Slower (15 and 20 knot container ships and 10 knot oil tanker) hullforms were generated by manipulation of the extent of the parallel mid-body and bilge radius to achieve appropriate hull shape coefficients, such as prismatic coefficient and block coefficient. Hullforms with a larger block coefficient may have less CO_2 emissions per unit cargo carried due to an increase in cargo carrying capacity. This is in addition to ships operating at

Table 1
Selected ship types, sizes and speeds: C=Container Ship B=Bulk Carrier O=Oil Tanker L=LNG Tanker.

Ship size categories	Displacement range (to nearest thousand tonnes)	10 knots	15 knots	20 knots	25 knots
Feeder container ship	14,000		C	C	C
Handysize bulk	33,000–34,000	B	B		
Handymax bulk	42,000	B	B		
Panamax ships	71,000–73,000	B O	C B O	C	C
Aframax oil tanker	117,000	O	O L	L	
Medium-sized LNG	115,000				
Post-panamax container ship	122,000–123,000		C	C	C
Suezmax tanker	147,000–165,000	O	O L	L	
Q-Flex tanker	154,000–155,000				
Ultra large container ship (ULCC)	172,000–175,000		C	C	C
Cape bulk	186,000–188,000	B	B		
Very large crude carrier (VLCC)	305,000–343,000	O	O		

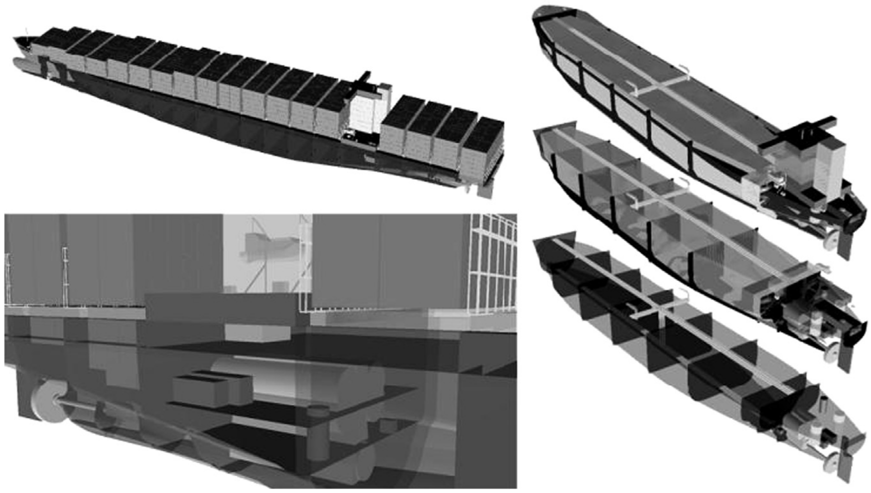

Fig. 1. Paramarine models of a container ship (left), showing the detail of the engine room, and an oil tanker (right), showing the complete ship, cargo systems and propulsion machinery.

a lower Froude number (longer ships for the same speed), where viscous resistance is a much larger proportion of the overall resistance, having a lower overall resistance due to a hullform with a higher block coefficient. To find the lowest CO_2 emissions per unit cargo carried, over an operating profile, there may be a trade-off between cargo carried and the resistance of the hullform. This is similar to the Maersk Triple-E that has a fuller hullform (with a larger block coefficient) compared to the Emma Maersk Class (RINA, 2011) and is designed to operate at a number of different speeds, with an average operating speed of around 16 knots (in line with current slow-steaming practices; IMarEST, 2013).

4. Assumptions

Generally, most ships that carry cargo have an aft engine and machinery space and superstructure above this and holds along the length with ballast tanks around the cargo holds in varying forms (such as double bottom tanks, wing tanks, or hopper and topside tanks). The topological similarity of most ships within a given ship type allowed the simplification of the modelling approach. The impact of the CRTs was defined as only affecting certain parts of the ship, with other areas, such as crew accommodation, remaining unchanged. This permitted a much simpler and quicker iterative ship design spiral to be used to balance the design, compared to a more conventional design spiral where the entirety of the design might be changed in each iteration (Watson, 1998).

In the design process of the model (shown in Fig. 2), it was assumed that the engine was selected to operate at 75% of the engine MCR (a Maximum Continuous Rating of 75% this means that there is a combined sea and engine margin of 25%). The operational performance is evaluated over an operating profile, in the specific example that is mentioned here an operating profile described by Maersk was used (Cerup-Simonsen et al., 2009), and a 12% addition to the ship's viscous resistance was assumed to allow for hull fouling. This 12% fouling allowance is an approximation assuming 6 months between dockings using Brown's (1976) observations from warships of 1/8th per cent per day. Using 3 months (91.25) as the average fouling time period at a 0.125% increase per day gives a 12% increase in the overall resistance due to fouling and this was applied to the ship as an increase in viscous resistance. Applying fouling as a change in viscous resistance allows for the correct integration of CRTs, which can sometimes be a function of the resistance of the ship and may have a different effect on the performance of the ship depending on the level of fouling. In practice the fouling could vary a lot with a specific ship, likely as a function of the speed of the ship and sea conditions (such as water temperature).

The SIM uses Holtrop and Mennen (1982), updated to include those components that were necessary from Holtrop (1984). The propeller model uses polynomials that describe the Wageningen B-Screw Series of propellers (Oosterveld and Oossnan, 1975). A limited amount of comparisons were made with model test data, particularly with a chemical tanker model test report, provided by Marintek, in order to check the accuracy of the resistance and propeller models and to select which regression formulae to use.

Another assumption that permits significant reductions in the computational time required is to assume that any mass changes to the ship impact on cargo capacity at a fixed displacement. This is true for primary (ship impact directly from the CRTs) or secondary (such as changing the installed engine size due to having a lower power requirement) mass changes. This approach has also been adopted in the Life Cycle Performance Tool (LCPA) developed by the EC funded project “Breakthrough in European Ship and Shipbuilding Technologies (BESST)” (BESST, 2013), where the ship impact is measured in terms of passenger cabins gained or lost. The alternative approach of maintaining cargo capacity and varying the displacement may require a much more sophisticated model. The hullform may have to change shape to reflect the change in displacement and resistance, requiring a highly parameterised model and an automated method of controlling it. This could be computationally intensive, requiring multiple iterative processes to generate the new hullform while assessing the impact of the change in resistance and propulsive machinery on the hullform.

Having every CRT impact on the rated cargo capacity could reduce the accuracy of a CRT's performance calculation as cargo ships are not always full to capacity (particularly for container ships and when in ballast for other ship types). In order to mitigate this, the operational design condition and operational ballast condition cargo capacities from the input ship are described separately from design capacity and are used for calculating operational performance.

The SIM works by assuming changes from a baseline ship and does not contain any stability or structural checks as this is not required for the fitting of the majority of CRTs provided the baseline ship already meets regulations. Any additional changes that are needed to meet ship safety and regulatory requirements

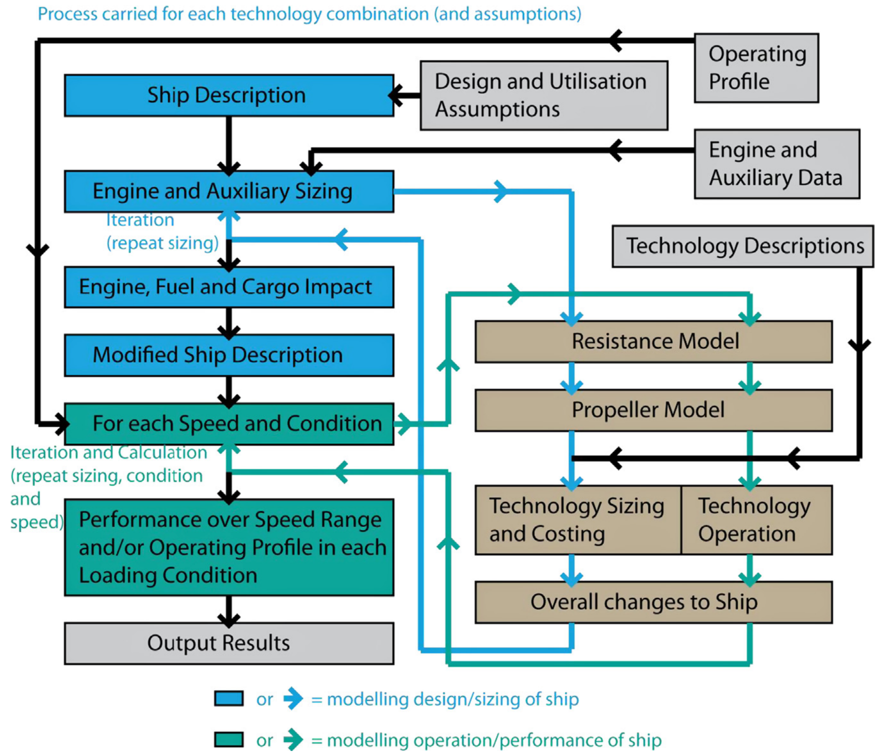

Fig. 2. Ship Impact Model process flow diagram.

are included in the technical assessment of the CRT. This means that specific stability and structural requirements, if required due to a CRT, such as sails, are represented in the file describing the CRT (described in Section 6) as a change in lightweight that is represented as an additional impact on cargo. Detailed three-dimensional models (as shown in Fig. 1) were used to create the input ship descriptions and were referred to in order to write the CRT files. For example, in order to correctly model the impact of adopting LNG, particularly the impact of the volume and the location of the LNG tanks, the detailed three-dimensional models that contained volume and stability calculations (as shown in Fig. 1) were needed in order to ensure that the simplified SIM correctly estimated the performance of LNG fuelled ships (Calleya et al., 2011). However, this does mean that if a large number of CRTs in combination cause a structural or stability change, this may not be modelled accurately.

Some assumptions contain a lot of uncertainty, particularly those relating to operational aspects, such as operational profile, auxiliary power utilisation (for example, the power requirement for refrigerated and chilled containers), displacement and cargo load when the ship is in operation (this is likely to vary between voyages). To evaluate the impact of uncertainty, the user can calculate the performance of the ship over up to two ranges of varying design and/or operational parameters (such as design speed, deadweight, design engine rating and additional resistance due to fouling). This means that the ship design process is automatically carried out again for each combination of design and/or operational parameters that are varied.

5. Model process overview

Fig. 2 illustrates the process used in the SIM. This is carried out for the baseline ship and is then repeated for each technology or combination of technologies, as required. The first step is to size the baseline ship and select the installed power and support equipment. The SIM calculates secondary impacts, for example, if installing a CRT makes the engine more efficient, or reduces the energy requirement, then a smaller engine might be selected from the engine list. The SIM then carries out the same iterative process at each operational speed considering the off-design case where applicable. The propeller model is an example of this, for a fixed pitch propeller the pitch of the propeller is determined in the design stage and the same efficiency curve is used at all speeds to calculate the off-design performance of the propeller. This process is carried out both for the baseline ship and the ships with CRT(s) fitted. Modelling both the baseline and variants in the SIM – rather than comparing a SIM generated variant with a separate model – allows for a direct comparison of the results.

As mentioned in Section 4, it is possible to vary the inputs and assumptions, such as design speed, deadweight and endurance, repeating the analysis of the baseline ship and CRT(s) for each design speed, cargo capacity, endurance, fouling allowance or assumed auxiliary power requirement (power for crew and cargo). When a range of assumptions are explored that have an impact on the ship hullform parameters and cargo capacity (such as design speed or deadweight) the SIM estimates the new ship characteristics (including lightweight and hullform parameters) based upon curves fitted to the parameters of the available ships in the virtual fleet (described in Section 3). The type of curve fitter to each ship characteristic is fixed, and they were selected based on accuracy. This allows the model to represent a wide range of ships. Relationships such as that between wetted surface area, block coefficient, prismatic coefficient and displacement are not checked for consistency in the SIM and are instead derived from the input data. This avoids making additional assumptions, such as estimating wetted surface area, in the SIM and makes the SIM insensitive with regards to the source of the ship database.

As well as ship descriptions, technology descriptions and supporting data (engine list and associated fuels, boilers, description of fuels and LNG tanks, etc.) are also required. The correct supporting equipment is selected automatically depending on the technology description and allows secondary ship impacts to be calculated. For example, an LNG fuel demand will cause the required fuel to be calculated and LNG tanks sized to meet this capacity.

6. Selection and description of Carbon dioxide Reducing Technologies (CRTs)

The technologies themselves are described as changes in up to 19 characteristics of the baseline ship. The changes to the baseline ship can be described in three categories, for different types of effect on the ship. The effects on the ship and how they are recorded are listed in Table 2.

The ship impact model technology interface must be flexible enough to deal with different technology architectures. To aid in the development of the interface, a reduced set of technologies was used to provide examples of the interface parameters required. The list in Table 2 was found to work well as an interface between the potential different CRT and ship combinations that could be considered. Most individual CRTs can be described by as few as three or four parameters from Table 2. This list was developed with input from subject matter experts on the CRTs. This was a two way process to ensure the right information is available from the ship and the ship represents the CRT in the correct way.

The CRT files (implemented as MATLAB functions) can access the following information about the ship and operating condition, as shown in Table 3. This means that the outputs from the CRT described in Table 2 can be described as functions of the inputs from the ship in Table 3.

A CRT file could be as simple as an engine improvement that reduces the specific fuel consumption by X%, this would not require any reference to the input list described above, in Table 3. A CRT file can also be a much more complex function of the inputs. Though a detailed customisable model could be described in a CRT file, this was only done in one instance. In some cases it was found to be more effective to look at a complex CRT, such as a waste heat recovery system, by pre-calculating a look-up table of different operational conditions that can be referred to by the SIM. The look-up table can be generated by the CRT file itself on the first iteration of the model or it can be generated in different software entirely and included inside the CRT file. This had the advantages that it was possible to interface with different software packages, such as the engine simulation software GT-Power for the ETI HDVE project, and that the run-time can be decreased by having pre-calculated results where full simulation is not required.

The power from a waste heat recovery system is likely to be based on the specification of the host engine and could be described, in Eq. (1), as:

$$power_{waste\ \ heat} \propto \frac{OutputPower_{hostengine}}{RatedPower_{hostengine}} \quad (1)$$

There is also a choice as to whether the power$_{waste\ heat}$ is used for main propulsion power or hotel/auxiliary power. The waste heat recovery function is referred to each time the model looks at a different condition or ship speed to calculate power$_{waste\ heat}$ at the calculated Output Power$_{host\ engine}$.

There is a lot of freedom to describe a range of CRTs. As shown in Table 3, the CRT can also be sized directly from the input ship description, which will not change between different ship operating conditions. For example, a Mewis duct, improving flow into a propeller, could be sized by referring to the propeller diameter in the ship description.

A separate fuel list is required to isolate fuel incompatibilities when looking at different CRT options and is needed to associate costs with the fuel(s) that the ship is using. Estimating cost is computationally more straightforward than calculating performance. The cost is important in deciding which technologies to pick over others and, in the case where a CRT can be implemented

Table 2
Possible inputs from CRT to Ship.

Type of parameter	Parameter	Units
Resistance parameters	Change in Viscous Resistance	%
	Change in Wetted Surface Area	± m^2
	Change in Propulsive Coefficient	%
	Change in Overall Resistance	± kN
Engine and fuel parameters	Change in Main Engine Specific Fuel Consumption	%
	Change in Auxiliary Engine Specific Fuel Consumption	%
	Change in Engine Shaft Speed	%
	Main Engine Fuel Selector	none
	Auxiliary Engine Fuel Selector	none
	Heat Boiler Fuel Selector	none
Service parameters	Change in main engine power	± kW
	Change in auxiliary engine power	± kW
	Change in shaft generator power	± kW
	Change in heat energy	± kW
	Deck space impact	± m^2
	Change in mass due to technology/cargo impact	± te
	Can technology be retrofitted?	Yes/No
Cost parameters	Unit purchase cost of technology	± $
	Through Life cost of technology	± $

Table 3
Possible outputs from ship to CRT (if required).

Type of Parameter	Parameter	Units
Ship characteristics (51 items taken directly from full description of ship for a specific ship design speed and deadweight)	Cargo density	te/m^3
	Available deck space	m^2
	Waterline length	m
	Beam	m
	Wetted surface area	m^2
	etc.	
Utilisation parameters (for particular speed and condition)	Operating speed	knots
	Demanded main engine power	kW
	Demanded auxiliary engine power	kW
	Demanded heat power (could be boiler power)	kW
	Demanded propeller torque	Nm
	Demanded retrofit?	Yes/No
Design parameters (set by design condition)	Design speed	knots
	Installed main engine power	kW
	Installed auxiliary engine power	kW
	Installed shaft generator power	kW

to a varying extent, how much of a CRT should be used, such as when considering using different numbers of standardised rigid sails.

7. Output format and utilisation of the ship impact model

The ship impact model has had two main objectives; to advise, as part of the LCS project (Calleya et al., 2012; Smith et al., 2010), on what carbon dioxide emission reductions are possible for shipping and how best to regulate shipping to achieve this; and to act as an early stage design tool, as part of the Rolls-Royce led ETI HDVE project, to select which technologies to develop further.

The initial technical output from the ship impact model is saved to a spreadsheet in the format depicted in Fig. 3. This output format was developed to allow post processing of the SIM outputs to provide a simplified description of the ship impacts of CRTs that could be used in a model of the wider shipping system without requiring run-time execution of the SIM to generate each of thousands of ships in the global fleet, this is described in Calleya et al. (Calleya et al., 2012). This output structure also allows subject matter experts to assess the performance and impact of their CRT on the ship.

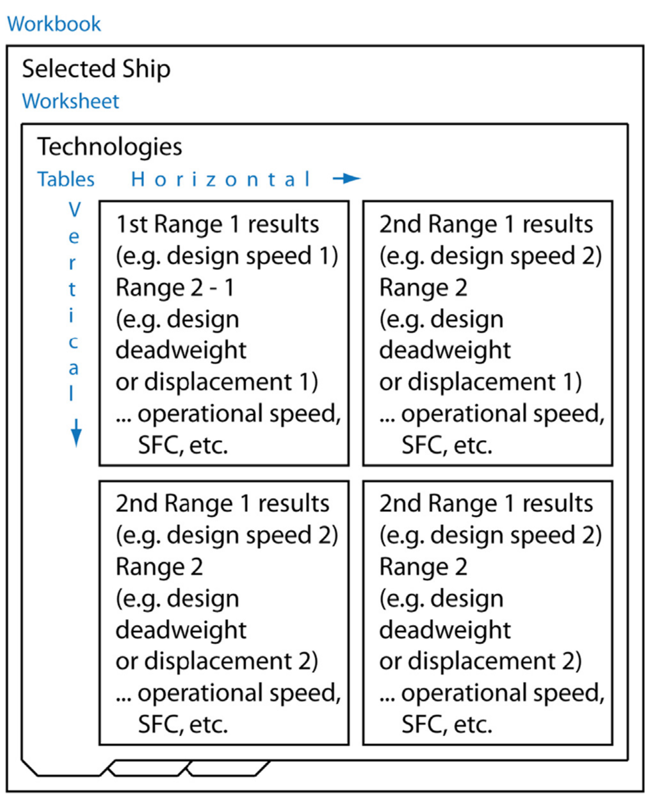

Fig. 3. Format of the Ship Impact Model (SIM) output spreadsheet.

8. Multiple Carbon dioxide Reducing Technologies (CRTs)

Each individual technology is described using the interface as described in Section 6. The same characteristics, shown in Table 2, are used to combine the effects of different CRTs together. At the level of detail shown in Table 2 most of the individual characteristics of each CRT can be added or multiplied together, the overall effect of this on the whole ship is much more complex.

In order to demonstrate the SIM using combinations of CRTs four CRTs were selected. These were; Propeller Boss Cap Fin (PBCF), changing fuel to Liquid Natural Gas (LNG), photovoltaic solar cells for auxiliary power, and thrust from wing sails. The effect of the individual CRTs and combinations are shown in Table 4 and Fig. 4. The ship selected for this analysis was a 25 knot Panamax Container ship, with a design deadweight of 35032 t (4584 TEU) and 294.2 m in length, with an endurance of 35 days and an operating profile described by Maersk (Cerup-Simonsen et al., 2009), as mentioned in Section 4. The time in design condition and ballast condition was assumed to be 68% and 12%, respectively, the remaining 20% of time was in port. The CRTs themselves were picked from independent studies done for both LCS (Calleya et al., 2012; Smith et al., 2010) and ETI projects, with the help of subject matter experts.

In the specific example, shown in Table 4, solar cells and wing sails achieve only a small beneficial effect due to the described ship having a very small amount of available deck space and a high design speed. The wing sail assumed a north Atlantic crossing, with wind speeds around force four, based on a north Atlantic pilot chart (Gibbons-Neff and Miller, 2011). Wind power to provide thrust can have a much more significant impact at lower speeds and in ships with more space and stability available to fit them,

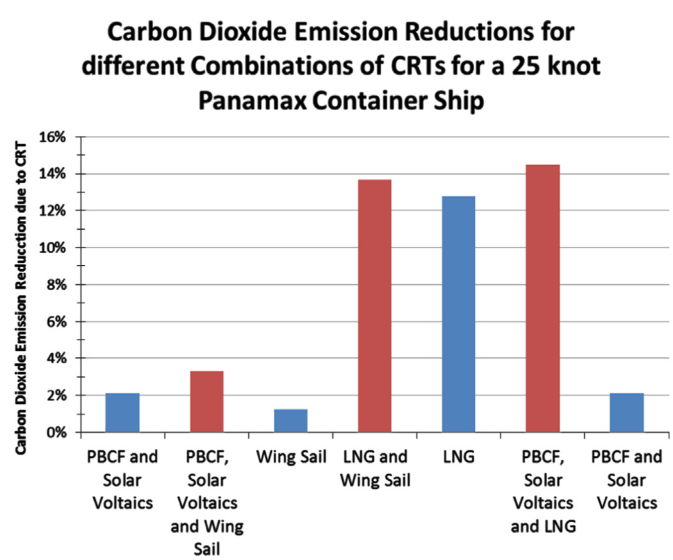

Fig. 4. CO_2 emission reduction of different CRTs. Combinations of CRTs are shown in between single CRTs (with the exception of PBCF and Solar Voltaics).

Table 4
Some outputs for a 25 knot Panamax container ship with an endurance of 35 days.

CRT	Baseline	PBCF	solar cells	LNG	wing sails	PBCF, solar cells, LNG and wing sails
CO_2 (tonnes/day)	272.4	266.6	272.4	237.6	269.0	229.9
% reduction	0.0%	2.1%	< 0.1%	12.8%	1.2%	15.6%
CO_2/design cargo	0.0078	0.0076	0.0078	0.0097	0.0077	0.0094
% reduction	0.0%	2.1%	< 0.1%	−24.8%	1.2%	−20.8%
EEDI (gCO_2/t nm)	43.0	42.7	43.0	53.4	42.9	53.0
% reduction	0.0%	0.6%	< 0.1%	−24.2%	0.1%	−23.3%

such as on a bulk carrier. These differences between ship types are captured in both the CRT files and the ship descriptions, which give the amount of available deck space for fitting CRTs that have to go on deck.

It has been assumed that all CRT and ship combinations are designed to the same endurance of 35 days, as large cargo ships tend to have a large bunker capacity. For the purpose of this study the same endurance was used for LNG as for HFO fuelled ships.

The final column of Table 4 shows the effect of combining all four CRTs on a single ship, a total of 15.6% reduction in CO_2 emissions is achieved. This clearly demonstrates that simple addition of the individual contributions from CRTs (this gives 16.1%) over estimates the net reduction from a suite of CRTs. A better estimate is found by calculating the combined effect of a suite of CRTs by representing individual CRTs (*A*, *B* and *C*) in terms of the percentage CO_2 reduction (CO_2%reduction) as:

$$CO_2\%\text{reduction}_{A+B+\ldots} = 1-(1-CO_2\%\text{reduction}_A) \times (1-CO_2\%\text{reduction}_B) \times \ldots \quad (2)$$

Using Equation (2) produces a value of 15.7%, this still does not give exactly the same result as that calculated by the SIM, over estimating the net reduction from a suite of CRTs.

9. Discussion

Published CO_2 and fuel savings, particularly from CRT manufacturers, can be given in isolation of their ship application context. Performance estimates can vary greatly depending on the assumptions made and the performance measure that is being used.

Table 4 shows that for LNG while the overall CO_2 emissions of the ship have decreased, a reduction in cargo capacity has meant that the CO_2 emissions per unit cargo has increased. The large increase in CO_2 emissions per unit cargo is due to the cargo space taken up by using a less dense fuel (compared to HFO/MDO) that has to be contained in pressurised tanks while maintaining the large bunker capacity used for a fast (25 knot) Panamax Container Ship with an endurance of 35 days. Table 4 also shows that this results in a reduced EEDI compared to the baseline ship despite using LNG that has a lower carbon factor than HFO/MDO. It may be necessary to re-consider the large bunker capacities of existing ships when switching to less dense fuels, especially fuels that require additional containment, compared to HFO/MDO.

Table 4 also shows that the percentage reduction in terms of the Energy Efficiency Design Index (EEDI) is much higher than the percentage reduction in CO_2 emissions.

The Ship Impact Model allows design decisions to be made based on an operating profile, though accurately considering the operational characteristics can be difficult due to the lack of available operational data and its uncertainty.

10. Limitations of the ship impact model (SIM)

Some CRTs, such as sails, are effected by environmental conditions (wind and waves). Even when not considering the sea conditions, it is unclear whether hydrodynamic and propulsor related CRTs can be scaled accurately (to different ship types, sizes and speeds) and it may not be possible to calculate some combinations of hydrodynamic and propulsor related CRTs from independent performance information because they interact with each other directly (for example, flow control devices before and after a propeller) and have to be modelled or tested together.

Only three ship loading conditions were considered; a design condition, a ballast condition and a port condition. It may be necessary to consider more operating conditions to better calculate the CO_2 emissions of a ship or to examine the potential change in CO_2 emissions due to varying design and operational assumptions.

This paper has focused on the CO_2 emissions from CRTs, however it is the task of the ship designer to evaluate the options considering both cost and operational performance; there are two different ways of doing this; net present value and required Freight Rate (Stopford, 2009).

11. Future work

Future work should aim to better understand some of the uncertainties in the modelling of CRMs, particularly those aspects that are difficult to model, such as environmental and operational conditions. In particular, more emphasis is needed on:

- The affect of different design and operational assumptions on CO_2 emissions. A sensitivity analysis can be used to explore changes in the design and operational assumptions.
- Operational states, in terms of energy usage. More operational states should be included to allow for a better estimate of the fuel consumption. In particular, more hull fouling conditions should be examined because hull fouling may have a large affect on the resistance of a ship and a high degree of uncertainty. Considering some aspects of the ship in the time domain, such as hull fouling or energy storage, may allow a better estimation of the performance of a ship and CRMs.
- Alternative modelling methods to increase flexibility and accuracy. For example, having an alternative regression method for resistance that can be used instead of Holtrop-Mennen.
- Modelling and designing systems to represent synergistic combinations of CRMs.

Designing for operational flexibility considering both operational data and the environment may allow some ships to operate with lower CO_2 emissions and may allow a better estimate of sea and engine margins.

It is also necessary to consider net present value or required freight rate and regulation (particularly on SO_x and NO_x emissions) as incentives to the adoption of CRMs.

There may also be the potential to explore the trade-off between cargo capacity and resistance in terms of the CO_2 emissions per cargo carried by changing the hull shape.

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