LOW CARBON SHIPPING

A SYSTEMS APPROACH

FINAL REPORT 2014

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EXECUTIVE SUMMARY

INTRODUCTION & CONTEXT

In 2007 it was estimated that shipping accounted for 3.3% of global anthropogenic CO_2 emissions. The second International Maritime Organisation (IMO) Greenhouse Gas (GHG) study (Buhaug et al.., 2009) predicted that shipping would account for between 12 and 18% of global CO_2 emissions by 2050 if no action was taken to reduce its emissions. Carbon dioxide is not only the majority driver of shipping's contribution to radiative forcing, but also has the longest-lasting impact, which demonstrates that the challenge is not one of the instantaneous emissions in any one year, but the cumulative emissions over time.

In 2010, there was no holistic understanding of the shipping industry. Its drawn-out contractual, technological and financial evolution prevented access to both a top-down and a bottom-up system-level understanding of its sensitivities, and left many commercial habits ingrained and unchanged. The inescapable truths identified above around both the energy and carbon challenge have created expectations of high uncertainty in the forecast for both the drivers of growth in shipping and the designs and system configuration that will evolve over the next few decades.

The shipping industry in 2010 faced a daunting task: to develop a proportionate response to its responsibilities under the global commitment to avoid dangerous climate change (Copenhagen Accord), to minimise the risk of causing damage to the shipping industry and the global economic system that the industry serves, whilst lacking the toolset with which to evaluate the possible impacts and responses of the shipping system.

Recognising this as a significant challenge, the UK government, five UK universities and a number of shipping industry stakeholders formed a consortium to carry out a three-year research project: ***Low Carbon Shipping – A Systems Approach.*** The aims of the project were:

1. to develop knowledge and understanding of the shipping system, particularly the relationship between its principal components, transport logistics and ship designs, and clarify the many complex interfaces in the shipping industry (port operations, owner/operator relationships, contractual agreements and the links to other transport modes);
2. to deploy that understanding to explore future logistical and ship concepts and how they could achieve cost-effective reduction of carbon emissions; and
3. to develop projections for future trends in the demand for shipping, the impacts of technical and policy solutions and their associated implementation barriers, and the most just measurement and apportionment mechanisms.

As the majority of shipping emissions (75%) come from the freight shipping sector (particularly container ships, dry bulk and general cargo ships), wet bulk (crude, products and chemicals) and gas ships (LPG and LNG), these were the sectors chosen as the focus of the work.

Economic context

Following the global financial crisis of 2008, the shipping industry entered a new economic paradigm, of sustained high oil prices, progressive regulation on efficiency and emissions and low revenues. It is speculated that this is creating a "two-tier" fleet, with the older low-efficiency fleet losing out commercially to more efficient tonnage built since the beginning of this new paradigm. The performance claims of the "eco-ship" breed are still yet to be extensively verified in the public domain, and whilst some of the higher-end claims (30%) appear lacking in evidence and possibly overinflated, it is expected that this new tonnage will have some advantage over the existing fleet, and will therefore either command higher prices (e.g. time charter day rates), greater market share, or some combination of these parameters.

Policy Context

At the start of the project in 2010, the policy and regulatory backdrop to the CO_2 emissions of shipping was immature, complex and evolving. A number of proposals existed for regulation at several levels (UN, EU, UK), but there was uncertainty around the path and stringency that would become the final implementation. Over the course of the project, the shipping industry has progressed from being the subject of mounting pressure to curb its emissions, to becoming the first industry with international, legally binding commitments on efficiency increases.

Contents of This Report

The research effort was structured into six work packages, the key findings and references from each of which forms a section of this report. Outputs from all of the work packages contribute towards an understanding of what the possible future trajectories of the industry will mean to the shipping system and the ships that service future transport demand. This understanding then will allow policymakers to consider the foreseeable consequences of regulations in advance of their implementation, and firms within the shipping system to plan ahead with an informed strategy.

MODELLING THE SHIPPING SYSTEM

GloTraM

A key output of the project, GloTraM, is a tool used to quantify how the many components of the shipping system interact and explore potential scenarios for the future of the shipping industry. Technologies, alternative fuels and operational interventions are all characterised by their impacts on a ship's performance and economics. The model selects configurations and changes both for the existing fleet and new-builds through the application of profit maximisation at a firm level (ship owners and operators). Unlike the existing literature, which is dominated by Marginal Abatement Cost Curve approaches, this produces insights into how the operational efficiency and technical efficiency interact. The model also analyses how the decarbonisation potential is reduced by the diminishing efficiency increase through compounding of multiple technologies and technical incompatibilities. The model's outputs include quantifications of emissions and the evolution of the shipping industry's fleet sizes, costs and revenues, as well as identification of the market share of different technologies and the future demand for a range of different marine fuels.

Take-back

Take-back in this instance refers to the diminution of energy efficiency gains through an unintended consequence. Informed through the modelling tools, including GloTraM, the occurrence of a take-back phenomenon was found to have the potential to disrupt the sector's decarbonisation ambitions. The results of the analysis showed that maximum profit occurs at a different speed and for a different level of technology uptake in each fuel price/freight rate combination. The results also showed that for any given level of technology uptake in each scenario, the speed at which profits are maximised is higher as the ship becomes increasingly technically energy efficient (the cost of speed increase is proportionately lower and the higher capital costs of a more efficient ship incentivise a higher operating speed). This speed increase represents a decrease in operational energy efficiency, which can offset a large proportion of the energy savings achieved through the implementation of technology.

Slow Steaming

The relationship between the speed of a ship and the power required to propel it presents a substantial opportunity for increased energy efficiency. The investigation into the existing fleet in this era of 'slow steaming' estimated that in 2011, relative to 2007, average operating speeds were 10-15% lower for many of the bulk fleets (tankers, dry bulk), and approximately 25% lower for container ships. The consequence of these observed differences in speed is a significant reduction in fuel consumption, by as much as 30 to 40% for many of the bulk fleets and by 50% and above for some container ship fleets, relative to the estimates presented in the IMO 2nd GHG study. Ultimately the speed reduction, which in turn reduces transport work, absorbs some of the impact of the main engine fuel consumption on energy efficiency, so that the improvement in operational efficiency is approximately 10% (relative to the IMO 2nd GHG study estimates of overall efficiency for many of the bulk fleets), rising to 30% for some of the container fleets.

One observation made by some commentators is that lower ship speeds necessitate the construction of more ships and that the GHG emissions associated with the manufacturing processes can offset the benefits of reduced speed. To test this claim, a formulation of the "total CO_2" was developed and applied to sample ship specifications. For the examples considered the relationship shows a minimum occurs between 2 knots and 5 knots depending on the specific ship type. At lower speeds, the embodied emissions dominate the relationship (i.e. the emissions from the additional ships required outweigh the operational emissions benefits of lower speed), while above the minimum speed the operational emissions dominate. In practice there are also commercial drivers for speed and safety issues, which need to be considered, and these are applied in GloTraM when evaluating future scenarios for the industry.

TECHNOLOGIES & SHIP DESIGN

This part of the research effort was divided into three tasks. The first addressed technical solutions related to improvements in ship and propulsor hydrodynamics; the second looked at technical solutions related to marine engineering systems including main and auxiliary engines and fuels; and the third task developed a ship impact model that could be used to identify the impact of technologies on the ship design in a holistic sense, and act as an interface between the technology assessments and the global shipping model. The ship impact model was developed for each of the ship types considered in the LCS project as a whole, and represents the interactions between design parameters, enabling the development of a full understanding of how the ship design is affected by incorporation of technologies – for example not just reflecting impact on hull resistance, or engine efficiency, but also on stability, lightship and capacity.

The detailed parametric whole ship model was used to correctly size technologies. Each ship size and type are modelled with enough accuracy and detail to ensure they realistically reflect the overall impact of the implementation of efficiency technologies on cargo capacity and cost.

Ship & Propulsor Hydrodynamics

The study examined incremental improvements through refinements in conventional hull forms, as well as the opportunities for radical changes based on new operational procedures relating to ballast loading and trim. Improvements will be assessed across the entire mission profile, including both loaded and ballast conditions, and in a range of expected sea-states.

A significant reduction in CO_2 of the order of 16% is possible, however in order to achieve these changes a substantial change in the overall dimensions of the ship is required. This does mean that these improvements may not be practical when more realistic constructional, operational and financial constraints are imposed, but they are indicative of what may be achieved given a blank canvas.

A set of devices suitable for retrofitting on existing ships (as well as new build) was examined in order to assess the likely gains in ship performance. Device manufacturers often promise substantial performance gains in terms of reduction in fuel consumption and, eventually, carbon emissions. In all cases, the level of savings achieved by using these technologies was lower than that published in the literature, and in many cases substantially so.

There are two possible explanations for this discrepancy. Firstly, many previous studies were based either on model-scale physical tests or simplified Computational Fluid Dynamics (CFD) models; it is possible that either the method or metric (or both) adopted in these studies was not appropriate for predicting the performance of these devices at full scale. Secondly, it might be argued that the devices in the present study did not deliver the expected savings because the designs in this study were not suitably optimised. In this case, it must then be considered that if these devices must be optimised for a given ship in specific operational conditions, it is unclear how the devices behave when the vessel is operating in off-design conditions.

The results of the study into the design of propulsors for in-service conditions were found to depend strongly on ship type and operating profile. For ships that are subject to large weather forces, such as container ships, improvements in efficiency over the basic propeller were found to be as much as 1.5%. Efficiency improvements for ships for which weather loading is less significant, such as fully-laden VLCCs, may be of the order of 0.5%.

Wind Assist

Preliminary analysis was undertaken to assess the performance of wind assistance devices. The results did not imply strong potential for cost-effective implementation, however the analysis methods used required many simplifications. Varying speed and course during the voyage to incorporate the variability of the resource (wind) in the operation of the ship could create differences in the fuel savings achieved, as could the design of bespoke installations or optimised hull/rig combinations. Flettner rotors appear to offer improved performance over conventional sails or kites, but most data are based on relatively small scale or computational studies, and the technical issues related to the energy consumption and the durability of the rotor drive system may not be completely resolved.

Internal combustion technology and electrical propulsion

Marine engineering propulsion systems are developing and the technology is improving with future machines offering efficiency gains over existing technologies. The two-stroke diesel engine propulsion system is likely to improve in efficiency over time through a combination of factors rather than a specific step change in technology. A slow-speed long-stroke diesel engine operating on LNG fuel with digital electronic control to optimise injection, exhaust valve and turbo-charger (scavenge) performance, together with waste heat recovery system, can be expected within a few years. In the long term, however, it is difficult to see what else can be done to further improve slow speed diesel engine efficiency performance beyond 2020.

Electrical technologies are developing rapidly, offering advanced systems that are flexible and more efficient than was previously the case. Advanced motor technologies are now available, whilst the next generation of power electronic drives is on the horizon. Superconductivity is too far away and too immature to enable us to make a significant projection as to its performance.

Alternative Fuels

Unlike many other studies of this nature, this research considered the total carbon footprint of different fuel types used in the full range of marine engine types on a “well-to-hull” basis (or “field-to-hull” basis in the case of biofuels). This therefore included the up-stream carbon cost of fuel production and transportation to the vessel. On this basis, there is strong indication that existing residual and distillate marine fuels are actually already relatively “carbon-effective” choices. A wide variety of biofuels was considered. Under some conditions these can offer a net reduction in carbon cost, but many do not if considered on a “field-to-hull” basis owing to the carbon-intensive production processes (including fertilisers, farming methods, etc.). Given the competition between biofuel and food production, there is also a limit on how much biofuel could actually be used for fuelling shipping transportation and, in some cases, the use of biofuels can increase the emission of species aside from carbon dioxide. The best performers in terms of carbon-footprint were blends with existing fossil fuels. (L)NG as a fuel also can provide carbon (and other) emission reduction benefits against traditional marine fuels, however, again, the picture is not as clear as might be supposed due to the highly carbon-intensive production cost of fossil fuel LNG. Using hydrogen as a fuel was also considered, but under existing production methods this too can be carbon-intensive. If renewable energy sources can be used for hydrogen production then this provides a realistic possibility for a net reduction in carbon footprint.

Fuel Cells

The volume and weight of a Fuel Cell system are higher than those of a combustion engine with the same power output. The fuel cell system can be assumed to be to weigh10% more than an internal combustion engine generator for the same power level, and the system volume and projected area will be approximately 10 and 15 times higher respectively. About 85% of this volume corresponds to the ancillary systems of the fuel cells system. The thermal recuperators, air and fuel heaters, and power converter units, boost converters and DC/AC inverters, each represent about 30% of the whole volume of the ancillary systems.

When compared to a conventional marine diesel generator, a fuel cell system provides higher efficiency. This is translated into lower fuel consumption and also lower carbon emissions per energy unit. Fuel cell systems have a 50% efficiency, based on the fuel low heating value, and also taking into account the parasitic losses exerted by the ancillary systems. In a fuel cell system, there is no internal fuel combustion associated with the power output, and so the SOx , NOx and CO emissions are reduced to a negligible level. Currently, fuel cell systems present a higher initial cost than traditional combustion engine technology, though its maintenance costs are drastically lower once established.

Solar

The limited area available on a realistic commercial vessel means that solar is unviable for main propulsion. Using solar for auxiliary power could achieve a reduction in CO_2 emissions of up to 10%. Installing solar panels leads to the same size generators being used, as power reductions are not large enough to facilitate the installation of a smaller auxiliary power plant. There is, therefore, no difference between a retrofit and new build.

PORTS AND LOGISTICS

Shipping is a derived demand: it exists not for itself but in response to demand from consignors for the transport of freight to consignees. Transport logistics systems, of which shipping is a key component, respond to trade demands and ‘lubricate’ the global economy by providing nodes and links (ports, distribution centres, transport services, etc.) to fulfil demand for product movement. Transportation, and shipping in particular, is therefore one of the key enablers of globalisation. In fact recent research reported in UNCTAD’s Review of Maritime Transport 2013 suggests that containerisation has been a stronger driver of globalisation than trade liberalization has. In order to understand the role and activity of shipping it is necessary to consider its place in the wider transport system, and in turn to understand what drives the demand for international freight transport, which occurs within ‘end-to-end’ supply chains linking sources of production with the ultimate consumer. Shipping and ports are important links and nodes within many supply chains, both in terms of their costs and their performance. When seeking to mitigate the (growing) CO_2 footprint associated with shipping activity, we need to understand the fit between shipping and the wider supply chains and logistics systems within which shipping operates.

This research largely adopted a bottom-up approach to investigating the logistics aspects of low carbon shipping, including: by examining the role of transhipment activity; by detailing emissions for individual shipping movements; and by mapping the role and impact of shipping within individual supply chains. The starting point for the analysis was to profile the maritime freight traffic flowing into and out of the UK. We then catalogued port-related sustainability initiatives and analysed and estimated port-related CO_2 emissions. These analyses indicated that emissions generated by ships during their voyages between ports are of a far greater magnitude than those generated by the port activities. Thus, while reducing the emissions of ports themselves is worthwhile, the results suggest that ports might have more impact through focusing their efforts on helping / facilitating the reduction of shipping emissions. The work around ports, in terms of the various initiatives and calculation of their carbon emissions, is the first comprehensive review of port-related sustainability issues in the UK and should be of interest to all stakeholders.

The next phase of the work involved estimating the CO_2 emissions associated with UK-centric shipping activity. The results suggest a total of 22.6 MT CO_2 in 2010, compared to 19.7 MT in 2000, with container ships accounting for the largest share (9.3 MT). Levels of transhipment were studied in order to understand whether this practice exacerbates emissions. Consultations and analyses suggest that only around 10% of container traffic is transhipped. Estimations of emissions for transhipped versus direct traffic were carried out and, while these results showed that feeder legs can increase emissions, the real issue to focus on is the total end-to-end emissions comprising all transport legs (not just maritime) and cargo handling activity. This led to work on supply chain mapping, which was of significant interest to the project’s industry partners. Analysis of end-to-end supply chain emissions was carried out with the cooperation of three partner companies, and quantified the contribution of maritime transport to total emissions; this also showed how modal shift to maritime can reduce end-to-end emissions.

The work on mapping the shipping network, measuring transhipment, seeking to calculate UK-centric maritime CO_2 emissions, and illustrating the contribution of shipping to end-to-end emissions in the supply chain, is all relevant to a wide range of stakeholders and will serve as a benchmark for future analyses and policy initiatives.

Overarching efforts to connect up all of the work and insights around logistics with future ship designs is a key output, and represents a considered view as to how logistics and ship design will intersect going forward, a topic of clear interest and importance to all stakeholders.

LOW CARBON SHIPPING ECONOMICS

Modelling of the through life environmental impact of shipping and its available carbon mitigation measures (and their associated environmental and economic cost) can inform policy makers at all levels (government, EU, IMO, UNFCCC) and industry stakeholders of the global cost-benefit balance inherent in the attempt to mitigate carbon emissions. Assessment of the balanced environmental impact highlights not only the opportunities to reduce the global impact of shipping, but also unintended consequences of efforts to mitigate fuel combustion-derived emissions.

Economic and Environmental cost of Ships

The impact of emissions from other phases than operation is small but a number of factors can significantly increase it:

- Larger/faster ships demonstrate less impact from other phases
- As speeds are reduced the impact from other phases increases (e.g. VLCC 9% at 13.3 knots, increasing to 44% at 6.7 knots)
- Scrapping a ship after only 10 years of operation may triple the relative impact of emissions from the construction and end of life phases (up to 26%).
- The efficacy of carbon reduction technologies was generally reduced by 1-2% if whole life emissions were considered

A carbon levy on shipbuilding emissions could introduce a new-build price premium of up to 11.8%.

Carbon Reduction Technologies

The whole life cost-benefit ($/t.$CO_2e_{avoided}$) of a majority of CRTs demonstrates a reduction in cost as well as life cycle GHG emissions. Where the potential savings are greatest (e.g. wind assistance technologies) there is also the greatest opportunity for the emissions from manufacture to become significant when a whole systems approach is taken.

Likely Future Demand and Prices for Shipping

Expectations of trends in dry bulk shipping flows to 2050 highlight drivers including Arctic ice melt, canal upgrades, piracy and mode splits. Globally, the expected doubling of raw materials shipments to Western economies and quadrupling elsewhere will be partially offset by expectations of shorter hauls. Moderate annual expected tonnage growth globally compares with rapid annual growth in coal shipments, although more localized and multi-sourcing will shorten global coal hauls.

Predicted changing patterns of maritime oil freight flows to 2050 were conservative. Local sourcing, new Arctic seaways and fossil fuel intolerance will tend to reduce oil freight work but ship re-routing to avoid Emissions Control Areas (ECAs) and piracy would lengthen hauls. In advanced industrial nations, reducing energy intensities and diminishing social tolerance of fossil fuels imply reducing maritime oil shipments. Achieving radical national commitments to carbon emissions reductions will necessitate specialist education for naturally conservative maritime professionals and vigorous oil import reduction policies to curtail domestic demand for oil shipments.

The impact of bunker fuel price changes on spot freight rates for shipping coal revealed a relatively stable market before 2005 followed by high elasticities in a volatile market in subsequent years. In a volatile market, market -based measures to reduce such emissions (which might include a bunker fuel levy) have greater impacts on freight rates.

POLICY AND REGULATION

In order to understand the impacts of possible future regulations, particularly market-based measures, a range of policy scenarios were studied. The results demonstrate a number of important findings, assuming that the cumulative emissions target for the industry (the stringency) remains consistent:

- Early adoption of a measure leads to a less dramatic trajectory of carbon price;
- In all scenarios studied, a sizeable quantity of out-of-sector offsetting is required to reach the target trajectory;

- Increasing the level of out-of-sector offsetting permitted has a small impact on the amount of in-sector decarbonisation achieved, but a large (negative) impact on the carbon price that the industry experiences, so there does not appear to be a significant benefit either to the industry or society of overly constraining offsetting;

- Bioenergy (biofuel and biogas) resources will have a beneficial impact on the sector's operational emissions, but apportioning an equitable share of the expected resource to the shipping industry is expected to have only a modest beneficial impact on the emissions trajectory. To have a greater impact, either the industry needs to justify a requirement for a disproportionately large share of this resource, or a technology breakthrough that increases the resource available needs to be found;

- A policy of emission reductions in shipping consistent with the Copenhagen Accord is likely have a significant impact on the cost base of the industry, applying additional operational costs equal to, and in many cases exceeding, those associated with the fuel cost at current fuel prices.

Implementation Barriers to Low Carbon Shipping

Analysis has suggested that there could be unrealised efficiency improvements and abatement potential that are not being taken up because of market barriers, market failures or more general implementation barriers. Understanding the barriers is important because of their potential to obstruct future regulatory attempts to reduce emissions, as well as for identifying opportunities for commercial opportunity and high cost-effectiveness policy.

A survey was undertaken of nearly 150 ship owners, charterers and ship management companies to quantify their uptake and attitudes towards a variety of operational energy efficiency interventions (weather routing, hull scrubbing, slow steaming, etc.). There were many operational efficiency interventions that the survey respondents believed to have significant potential, with approximately 70% of respondents agreeing on three in particular: fuel consumption monitoring, general speed reduction and weather routing.

This finding is useful in confirming that there are a number of interventions, that a large majority believe to have potential, as this refutes the concept that 'nothing can be done and all potential improvements are already fully embedded in the industry'. The most regular explanations for not implementing solutions included: lack of reliable information on cost and savings, difficulties of implementation under some charter parties and lack of direct control over operation. Both the informational barriers and the consequences of certain charter party clauses have been referred to by many others and are the subject of ongoing discussion in the policy space.

These survey findings were supported by econometric analysis of the relationship between energy efficiency and prices in the time charter, new build and second hand markets, which showed that more energy efficient ships commanded higher prices, but that the price premium was commonly only 20% of the cost savings associated with the energy efficiency differential (i.e. not all of the cost savings are being passed on).

Analysis of a number of standard charter parties was used to evaluate the prevalence of certain clauses that could be obstructing energy efficiency initiatives, and provided further evidence of the presence of a principal agent problem in shipping, more commonly referred to as the 'split-incentive'.

Measurement and Apportionment

'Measurement' refers to the process of estimating the emissions from the shipping industry and 'apportionment' to its allocation to different entities (e.g. firms, countries, regions). Whilst domestic shipping emissions are easily associated with the country from which their transport demand originates, the difficulty of fairly apportioning the emissions from 'international shipping' led to the allocation of their management 'as a whole' to the IMO in the UNFCCC Kyoto Protocol.

Measurement and apportionment are intrinsically linked because the viability of different types of measurement system can affect the implementation of apportionment schemes. Some progress on the subject of measurement has been made at both the IMO Marine Environment Protection Committee (MEPC) and the EU. For these reasons the work was focused on apportionment, although assumptions and recommendations were made for the most valuable measurement variables. A number of conclusions and implications can be drawn:

- The existing literature on the subject of emissions apportionment describes a variety of options and analyses their fairness and effectiveness;

- The concept of international shipping's top-down emission's allocation to individual countries is shown by a variety of authors to lack credibility;

- Nationally accounted fuel sales (normally described as a bottom-up apportionment philosophy) are found wanting with respect to fairness and openness to ease of evasion, and would do little to incentivise emissions reductions;

- This leaves variants of bottom-up options associated with ship movements and trade as the only credible mechanism for emissions allocation;

- The part-utilisation of a ship's cargo capacity, the multi-pick-up multi-drop-off nature of cargo movements and the ballast voyage are all operational details that deserve careful consideration in the design of an apportionment mechanism;

- Different mechanism details can result in substantial differences in emissions allocated;
- Data is difficult to obtain and would also have to be enacted globally for some apportionment methods. For unilateral action, data (such as EEOI) would only be captured at the port of the country enacting the policy or reported by nationally registered vessels. The ports of non-cooperating member states would be under no obligation to capture this data and would be unlikely to adopt the administrative burden. If using a policy based on annually reported EEOI a global classification and verification system would be required. Verification of emissions has not been standardised and therefore an internationally recognised approach would have to be agreed;
- Questions of fair treatment for a country with a role as a regional hub port remain unresolved.

OPERATIONS FOR LOW CARBON SHIPPING

Crew Awareness

A questionnaire was designed, distributed and analysed to identify the levels of seafarers' awareness, knowledge, motivation and ideas about carbon emissions, their reduction, and methods for achieving energy efficiency on board. Key findings were:

- Only 20% of participants have learnt about carbon emissions and their effects via an education or training course and the most common sources for knowledge acquisition are not technical or focused: there are clear education and training needs;
- There is a lack of awareness and focus towards energy efficient operation and a lack of consistent knowledge about best practice;
- There is a clear correlation between how much participants know about carbon emissions and the energy efficient efforts they make, and so there is a real benefit in increasing knowledge;
- There is a lack of knowledge about how individuals can contribute towards energy efficiency improvements (however small) and/or responsibility shifting between individuals and departments;
- Improvements in onshore support for energy efficient ship operation are required in addition to improved operations by seafarers at sea;
- Performance monitoring and performance feedback of the right information to the right people is important for generating awareness and motivation.

Monitoring fuel Consumption and Ship Performance

In order to understand the drivers of operational fuel consumption, noon-report data was collected from a number of ships and processed along with its key explanatory parameters (speed, time, weather). A key point identified by the analysis was the inaccuracy of some of the data fields and entries and hence their reliability to indicate ship performance. Reasons for the inaccuracies included human error, ambiguous observational methods and current procedures. The most significant data inaccuracies and absences relevant to performance monitoring are listed below.

- **Fuel consumption.** Several reasons as to why inaccuracies occur in noon-port report fuel consumption data were identified, including: uncertainties about the amount of fuel bunkered; inaccurate methods for measuring remaining fuel onboard/fuel consumed; and human error recording values. The variance in fuel consumption data is therefore high and provides a scatter of results for performance monitoring.
- **Weather.** The observation of weather effects is a field susceptible to a high level of error for several reasons: recorded values in noon/port reports are predominantly based on an individual's observation on the bridge; the observation recorded may or may not be an accurate representation of the average weather encountered over the reporting period; typically Beaufort and direction fields are recorded where a single Beaufort number encompasses a range of wave heights and wind speeds; wave, wind, swell and current strength and direction all have an effect on vessel performance but are typically not recorded in the noon/port reports.
- **Draft and deadweight.** It is known that the displacement of a ship changes the resistance, and therefore the power and fuel consumption of the ship. The shape of the underwater hull is also important and is influenced by trim. However, whilst these fields are recorded in separate documents they are not always included in the noon/port reports and are therefore rarely correlated to identify and explain ship performance.
- **Power:** Not all (most) ships are equipped with a torque meter and therefore direct power measurements, which would provide valuable information about a ship's performance, are not recorded in the noon/port.

Ship Hull and Propeller Maintenance

A review was made of existing procedures used for ship hull and propeller maintenance. At present most hull and propeller maintenance decisions are based on dry docking intervals, noted observations of significant performance loss and underwater inspections carried out by divers.

The amount and rate of fouling on hulls varies significantly with a ship's operating profile and the type of hull coating used. The gain from hull cleaning and dry dock repairs varies greatly on the condition of the hull before maintenance and the quality of maintenance carried out. Performance monitoring and modelling needs to be incorporated and utilised as a tool for improving hull and propeller maintenance strategies. To identify practical optimal maintenance scheduling, the costs must also be considered, including the cost of maintenance and facilities, paint, hire, and so on.

Voyage Optimisation

There are many aspects to voyage optimisation that should be considered, and the practical and logistical components are just as significant as the performance-related modelling.

The voyage optimisation framework studied in this project had two levels: (1) voyage prediction and planning based on the operational profile, time of the year and the past weather statistics for the voyage dates; and (2) real-time voyage optimisation and decision support system.

For the development of accurate voyage optimisation it is important that the ship's operational profile is recorded accurately and appropriate modelling should be utilised in the performance predictions. Furthermore, because voyage planning is affected by many factors, charter contracts need to ensure that the operational decisions and communication/relations between ship management, commercial departments and external stakeholder roles are clearly defined.

CONCLUSIONS AND NEXT STEPS

Low Carbon Shipping – A Systems Approach, was deliberately ambitious in its scope and breadth. The need to bring consistency, objectivity and numeracy to the assessment and optimisation of the various options meant that a system-wide approach was needed to understand shipping's potential to decarbonise.

GloTraM is the model developed in this project that links all the issues together, providing transparency of data and overall costs.

In addition to modelling, the project undertook a broad range of fundamental and multidisciplinary analyses in order to address many of the key drivers and the complex interactions that characterise the shipping industry, including:

- Capturing the logistic supply chain/ship design interactions;
- Joining up the technical and operational parameters to properly understand & evaluate energy efficiency interventions;
- Assessing the economic implications of radical departures from current technologies and operating practices;
- Completing the loop between the operational measurements of performance and the tools used to model and optimise ship specification;
- Taking the wider system view of carbon emissions (rather than just the emissions from the ship itself), e.g. work on alternative fuels;
- Capturing the interaction between mitigation policy and climate finance;
- Understanding the reasons for the gap between perception and reality, e.g. analysis of market barriers;
- Making visible the importance of lifecycle assessments.

The project found that shipping is a significant and growing climate change challenge. There is a wide range of evolutionary improvements in ship design that can be applied over the next few decades (enabled both through existing regulation - EEDI and SEEMP, expectations of sustained high energy prices, and technological advancements) that offer modest improvements but will fall short of delivering the levels of decarbonisation required to avoid dangerous climate change. Therefore more radical change is required and the sooner fair frameworks and mechanisms to enable this change are established the less damaging this will be for the industry.

The detailed explanation for this shortfall is that for many technologies, the savings are often found to be less than advertised by the technology's marketing literature. A shift to LNG offers significant improvements but also requires major changes in ship design and shipping infrastructure, and still can only deliver modest reductions in transport carbon intensity. Bioenergy is expected to be supply-constrained, solar energy provides insufficient power outputs, and the evaluation of the potential of wind-assistance shows that its potential and future role remain uncertain.

Operational measures (other than ship speed reduction) also offer improvements through better-informed hull/propeller maintenance and voyage optimisation. In combination with many of the technology and operational solutions, significant speed reduction has the potential to close the gap but markets alone won't do this, since slowing down beyond a certain speed is uneconomic and has an increasingly negative impact on the supply chains that shipping serves.

Given the expected long-term growth which is the backdrop to the emissions trajectories of the industry, all of the above changes are unlikely to achieve progress proportionate to shipping's responsibilities (as taken from the Copenhagen Accord) under the current tendency towards 'business as usual'.

There is therefore a need to develop further voluntary measures or regulation (market-based or command-and-control measures).

Owing to this project's outputs and an increase in the research activity on this subject internationally in recent years, the knowledge and understanding required to enable shipping to make its contribution to minimising the risks of dangerous climate change are now better understood and shared across the sector. However, a number of significant uncertainties remain:

- A lack of clarity on the drivers of ship performance in real conditions (fouling, speed, weather, crew), owing to the complexity of the marine environment and the low standard of data monitoring and analysis that is currently used in many firms.
- A lack of confidence that theoretical and experimental modelling of ship performance (particularly with respect to performance characterisation of energy efficiency technology) is representative of 'real world' performance. This is related to the complexity of the physical processes determining ship performance, a lack of clarity on the drivers of ship performance, and also the lack of standardisation in the way theoretical and experimental modelling is undertaken and the inevitable simplifications that are necessary to generate analysis affordably.
- The potential of step-change technologies to be commercially viable and create significant change in the industry (e.g. wind assistance, hydrogen and fuel cells). Mainly due to uncertainty in the performance and costs of the technology, uncertainty in infrastructure development and the high costs associated with the rigorous analysis of performance combined with a shortage of investment in research and development.
- The interaction between global and regional mitigation scenarios and their impact on global demand for different energy commodities, and shipping's transport demand. This is currently dominated in terms of mass lifted by crude oil movements, as well as substantial shares of its transport supply devoted to coal, oil products and gas transport demands.
- Shipping's responsibility to decarbonise, given the social benefits it supplies, e.g. in enabling global markets, which enable energy and food security.
- In the event that the ambition of the Copenhagen Accord is missed, and dangerous climate change modifies the production and consumption patterns of food, fuel, raw materials and goods, how this could affect shipping transport demand and therefore the wider shipping system.
- Opacity in the shipping markets (particularly the lack of transparency in the way prices are set) leads to challenges in forecasting the incentivisation of the investors in technology (typically ship owners) and therefore the technology uptake and flow of capital to the sector's technology providers.

The first round of EPSRC-funded projects have established a cadre of newly educated champions. A further EPSRC & Industry funded project is commencing shortly: ***Shipping in Changing Climates*** will build on investments made to date, pick up many of the areas identified as the source of continued uncertainty, and research how to transition shipping to a low carbon, more resilient future.

- **Theme 1:** Understanding the scope for greater efficiency on the transport's supply side
- **Theme 2:** Understanding demand side drivers and trends – trade and transport demand
- **Theme 3:** Understanding supply/demand interactions – transition and evolution of the shipping system

Pulling together the complementary strengths of the UK universities involved in this project and the support of key industry players, together with the volunteering of data and knowledge from across the shipping stakeholder space have been critical to the success of this project, as they will be for the successor project ***Shipping in Changing Climates.***

INTRODUCTION

WHAT IS THE PROJECT AND HOW IS THE WORK FUNDED?

In 2007 shipping was estimated to account for 3.3% of global anthropogenic CO_2 emissions. The second International Maritime Organisation (IMO) GreenHouse Gas (GHG) study (Buhaug et al. 2009) predicted that shipping would account for between 12 and 18% of global CO_2 emissions by 2050 if no action was taken to reduce emissions from shipping (allowing for a global temperature rise of no greater 2ºC by 2100). Compounding the issue, the life expectancy of the world's oil and gas reserves, from which the vast majority of shipping fuels are derived, is increasingly measured in decades (International Energy Agency, 2008).

The RCUK (Research Councils UK, a source for government funding of research in the UK) Energy programme, recognising the need for further research in this subject, issued a call for proposals on low carbon shipping in 2009. Three proposals were successful, one of which, Low Carbon Shipping – A Systems Approach was submitted by this consortium, including University College London, Newcastle University, University of Strathclyde, University of Hull and University of Plymouth, supported by a number of industry partners. The core funding of the consortium's effort (~£1.5m) came from RCUK, with additional staff time and PhD studentships being provided by support from four core industry partners (Shell, Lloyd's Register, BMT and Rolls-Royce).

This report summarises the output of the three-year research programme begun by the consortium in January 2010. The two other projects funded by this call are The High Seas Project: Assessing the technical and operational scope for rapid carbon emission reduction from global shipping at the University of Manchester and Decarbonising the Maritime Supply Chain: Assessing the Contribution of Shippers at Heriot-Watt University.

What are the aims and objectives and how is the work and the report structured?

In 2010, the consortium believed that there was no holistic understanding of the shipping industry. The drawn-out contractual, technological and financial evolution of the industry had obscured access to both top-down and bottom-up system level understanding of its sensitivities and left many commercial habits ingrained and unchanged for literally hundreds of years. The aims of the project were:

1. to develop knowledge and understanding of the shipping system, particularly the relationship between its principal components, transport logistics and ship designs, and clarify the many complex interfaces in the shipping industry (port operations, owner/operator relationships, contractual agreements and the links to other transport modes);
2. to deploy that understanding to explore future logistical and ship concepts and how they could achieve cost-effective reduction of carbon emissions; and
3. to develop projections for future trends in the demand for shipping, the impacts of technical and policy solutions and their associated implementation barriers, and the most just measurement and apportionment mechanisms.

To achieve these overarching aims required a multidisciplinary team, including geographers, economists, naval architects, marine engineers, human factor experts and energy modellers, and the division of the work into 6 work packages (WPs). Outputs from the packages are collated to provide inputs into the holistic analysis carried out in WP1:

WP1: **Modelling**. led by Dr Tristan Smith, UCL

WP2: **Technologies for low carbon shipping**, led . by Professor Sandy Day, Strathclyde

WP3: **Shipping, ports and logistics**, led by Professor John Mangan, Newcastle, Professor David Gibbs, Hull and Professor Chandra Lalwani, Hull

WP4: **Shipping economics**, led by Miss Melanie Landamore, Newcastle and Professor John Dinwoodie, Plymouth

WP5: **Regulation, policy and incentives,** led by Dr Tristan Smith, UCL

WP6: **Human Factors & Ship operations,** led by Professor Osman Turan, Strathclyde

All of the individual WPs were overseen by the project's chairman, Professor Paul Wrobel, its technical and management board (made up of representatives from academia and industry) and its coordinator, Dr Tristan Smith. While each WP focused on a particular domain it also referenced the work going on in the other work packages. The first half of this report includes a summary of the work undertaken and outputs produced from each of the WPs.

Outputs from each of the WPs were also connected via the collaborative analysis of five cross-cutting research questions:

RQ1:The relationship between transport logistics and future ship designs (e.g. novel propulsion systems) and their impact on the efficiencies of the whole system, e.g. port operations, human factors, and the supply chain, including integration with other modes such as air, rail and road

RQ2: Demand for shipping: looking at the drivers for using shipping (for freight and people) over other modes

RQ3: The impacts of technical and policy solutions on future shipping scenarios

RQ4: Implementation barriers to low carbon shipping

RQ5: Measurement and apportionment: how best to measure the impact of shipping and optimise environmental gain in an international context

These research questions are each published individually and available as referenced.

The collation of WP reports is framed by a description of both the overall context of ***Low Carbon Shipping – A Systems Approach*** as perceived during the period of the project (2010-2013), and a set of conclusions.

WHAT IS ITS SCOPE (EMISSIONS, SHIP TYPES, GEOGRAPHY)?

Whilst the title Low Carbon Shipping implies that this project is centred on carbon emissions (CO_2), the issue that the work plans to address is the GHG impact of shipping, which includes a greater range of emissions.

Justification for this focus on CO_2 can be found in Figure 1, which shows the contribution of a number of shipping's different emissions to both radiative forcing (RF) and temperature change in the year 2100. The contribution is calculated from emissions up to 2007.

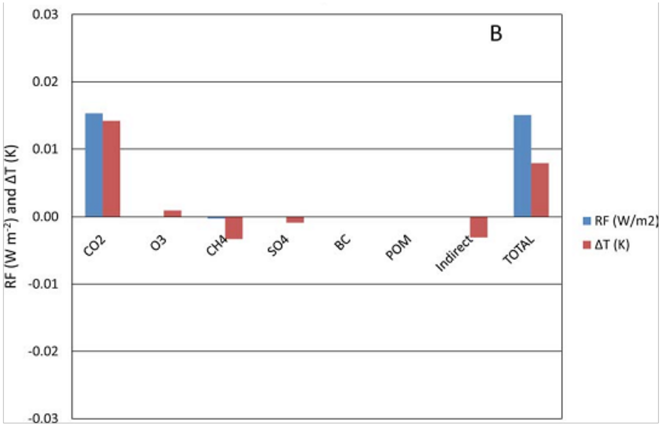


Figure 1: Residual radiative forcing and temperature responses from shipping emissions up to 2007 in 2100 (excluding albedo effects from black carbon) from Bahaug et al. 2009). Other RF and temperature change impacts include those from O3 (ozone), CH4 (methane), SO4 (sulphate aerosol), BC (black carbon) POM (particulate organic matter) and indirect effects.

Not only is CO_2 the main driver of shipping's contribution to RF, but it also has the longest-lasting impact, demonstrating that the challenge is not one of instantaneous emissions in any one year, but the cumulative emissions over time.

The emissions from the whole 'shipping system' include not only those from ships, but also emissions from ports in their general operations, and handling of freight, as well as in the construction of the ships themselves (often referred to as embodied emissions). Owing to the perceived relative dominance of operational CO_2 emissions, these are the main focus of the work. However, WP3 considers the emissions from ports and WP4 the wider environmental impacts (including upstream and downstream from shipping).

Figure 2 displays the breakdown of emissions between different ship types, according to IMO 2010a. The dominant emissions (75%) are from the freight shipping sector, particularly container ships, dry bulk and general cargo ships, and wet bulk (crude, products and chemicals) and gas ships (LPG and LNG). While other ship types also contribute significantly, no other sector represents more than 7% of the total and due to technology, and since operational differences between ship types make generalisation of analysis difficult, this study has chosen to focus on bulk (dry, wet, gas) and container shipping fleets, their associated supply chains and infrastructure.

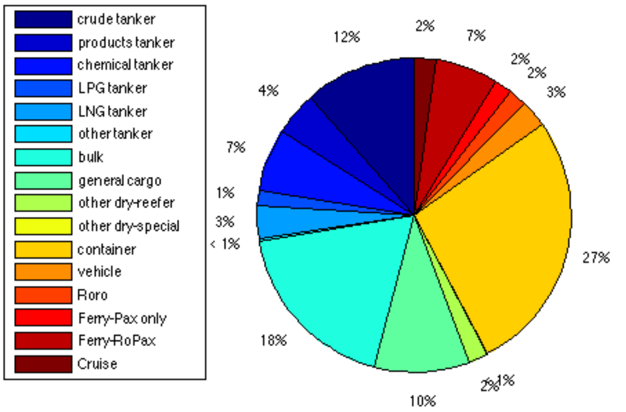


Figure 2: Estimated shares of emissions (totalling 977 million tonnes of CO2) of the highest emitting sectors of the shipping industry (data from IMO 2010a)

Selection of ship types dictates the geographical system boundary for this study. The analysis will focus on the UK shipping system, and this comprises both domestic shipping (ships satisfying transport demand from one UK port to another UK port), and international shipping (ships satisfying transport demand from a UK port to another country's port). The ship types selected for study (bulk and container), are significant components of the UK's international shipping system. Furthermore, a ship may be used to service UK international transport demand on one voyage, and that of another pair of countries on its next voyage. For these reasons, the scope, particularly in WP1, included both the global fleet of ships, and the global, international shipping system, but looked in greater detail at UK-centric trade flows and fleet.

CONTEXT

THE SHIPPING SYSTEM

For centuries specialist goods and commodities (e.g. cotton, wool, spices and other agricultural products) have been transported for long distances at sea to facilitate international trade. In some instances, that trade was driven by the demand for a good that could not be sourced locally (e.g. spices due to global climate and agricultural productivity variations). While this remains an explanation for the existing patterns of trade (particularly for extracted commodities which for geological reasons are distributed unevenly around the world and not necessarily co-located with their consumer base), a more recent trend in demand growth has been one most notable economic phenomena of the last half-century – globalisation.

Globalisation refers to the increasingly global nature of the market in which goods and services are produced and consumed. The principle can be summarized, for a good consumed in country b, as

$$CP_a + CT_{ab} \leq CP_b$$

where CP is the cost of production and CT is the cost of transport. Providing that the combined cost of production and cost of transport from country a to country b is less than the cost of local production in the destination country (b), then it is economically viable to locate production in country a. Wage and skills differentials between countries are one explanation for a geographical differential in production cost; however these have always existed. What has not always existed is a supply of safe, reliable and cheap transport connecting the world's consumers with the world's raw materials and skilled, low-cost labour markets.

That system for the majority of the world's trade is the shipping industry, and as the industry and global transport infrastructure has developed and become more efficient, the significance of distance to market as a parameter that identifies the competitiveness of many goods and commodities has diminished. These modern supply chains, and end-to-end flows of goods from factory to distribution centre, were the subject of in-depth analysis in WP3, and the input to the analysis of the future development of transport demand in WP1.

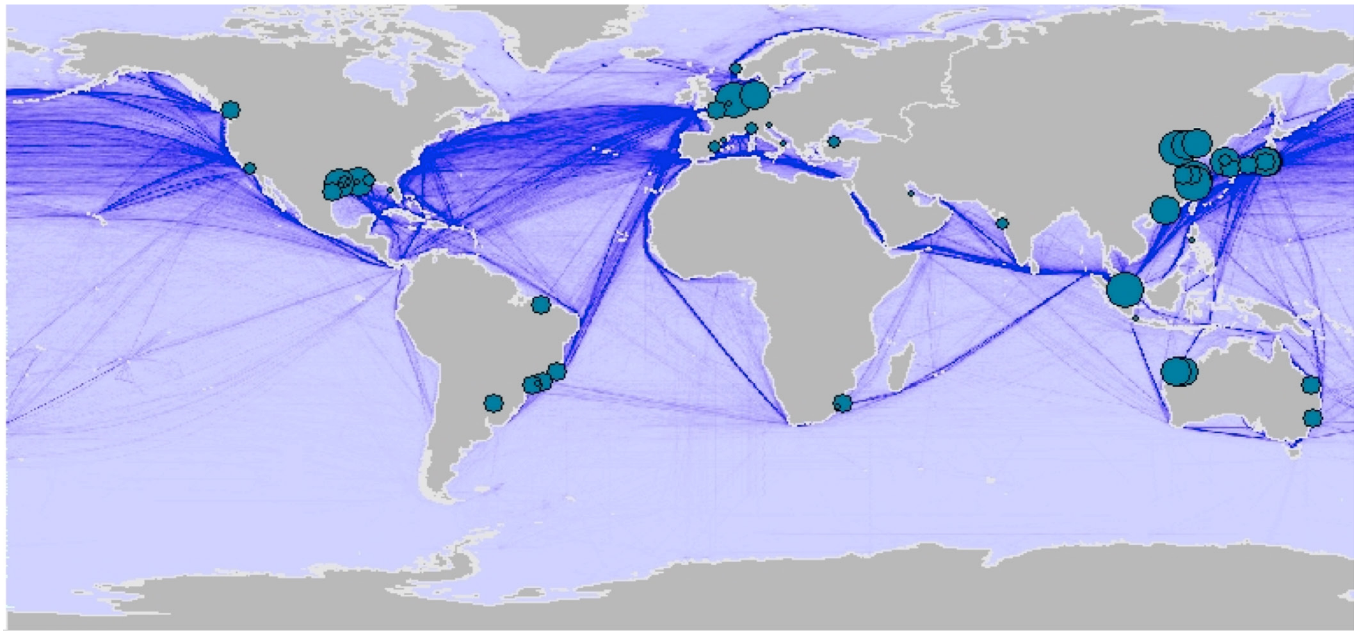


Figure 3: Global shipping routes and the world's largest ports (radius of circle indicates the import and export of freight flowing through the port in tonnes)

COMMERCIAL AND ECONOMIC BACKDROP FOR THIS WORK

Since the global financial crisis of 2008, the shipping industry has entered a new economic paradigm, of sustained high oil prices, progressive regulation on efficiency and emissions and low revenues. The scale of the change experienced by owners and operators of ships, and the erosion of their profits, can be seen in Figure 4, a specific example generated using data describing the chemical tanker sector, but representative of the change seen across all ship types. The combination of these pressures on the sector has created substantial incentive to change. Responses since 2008 have included:

- reduction in ship speeds;
- some (cautious) investment in retrofit technologies for the existing fleet (e.g. propeller boss cap fin, coatings);
- limited scrapping (due to the delicate position of balance sheets and the reluctance of banks financing ships to declare write-downs);
- increased attention to energy efficiency in new builds, with a new breed of 'eco-ships';
- advertising efficiencies 10-30% greater than the existing fleet.

These responses that have been discussed at length in the industry, policy fora, and the specialist shipping media over the period of this research project. Attempting to understand some of these recent developments, particularly reduction in ship speed, was an important activity under WP1 and WP6, and the analysis was then also applied to the longer-term perspective that this project took (out to 2050) during which recovery from the current downturn should occur, but with the expectation that pressure on energy efficiency remains.

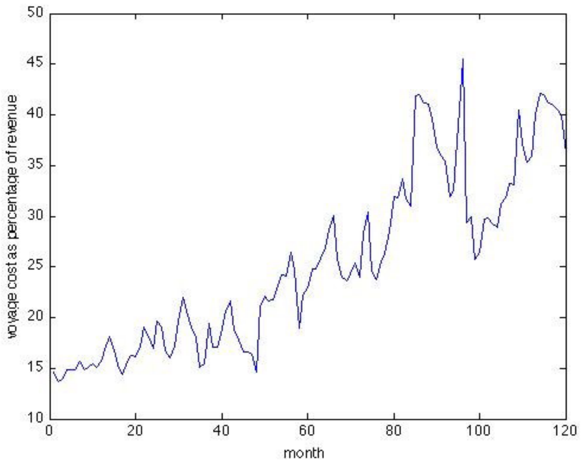


Figure 4: Evolution of the relationship between revenue and voyage cost during the period 2000-2010, (example taken is a Chemical tanker on the Rotterdam/Houston route, data from Clarksons (2011)).

Volatility in prices and costs and deep recessions have characterized much of the recent history of modern merchant shipping and are expected to continue to do so in the future. The relationship between freight prices and fuel prices is key to the shipping industry and is therefore subjected to greater analysis in WP4.

Figure 5 shows the volatility of the time charter price in a number of sectors of the crude tanker fleet over the period 2000-2010. That volatility is partly to do with the relative inelasticity in supply due to the lead time between ordering and receiving a ship (typically three years for large merchant ships), and the difficulty of forecasting global transport demand (world trade). The current protracted period of oversupply started in 2008, and is now expected to continue for a number of years yet. However, even assuming eventual recovery of revenues, it is expected by all mainstream forecasts (IEA, EIA, DECC, oil majors), that the era of $600/t bunker fuel is here to stay or worsen, and this will therefore remain as a strong driver for energy efficiency in both the new build and existing fleet.

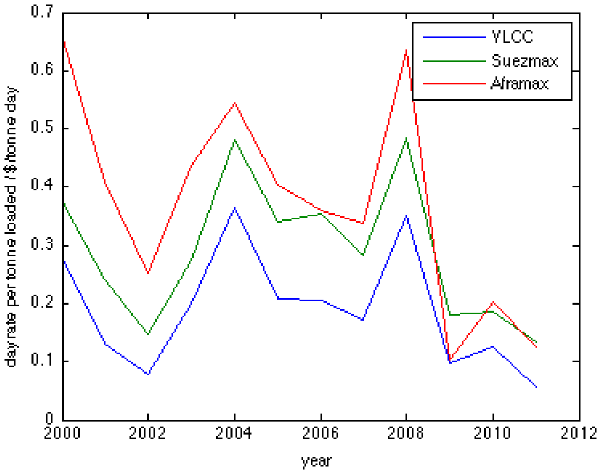


Figure 5: Proxies for time charter day rates over the period 2010-2011, for three sizes of crude oil tanker (Source: Intertanko)

The performance claims of the 'eco-ship' breed are still yet to be verified publicly, and whilst some of the higher end claims (30%) appear lacking in evidence and are possibly overinflated, it is expected that there is some advantage of this new tonnage over the existing tonnage. Consequently it will either command higher prices (e.g. time charter day rates), greater market share, or some combination of the two. WP2 focuses both on the credibility of these claims, and on the potential for yet further gains in efficiency in the future. Figure 6 displays the trend in the average design efficiency (gCO_2/tnm) of tankers built between 1980 and 2010. It displays the novelty of the situation that the industry now faces, with the disruptive effect of a step-change in energy efficiency (albeit probably small), as well as the resistance to adoption of new technology that has occurred in the industry over a thirty-year period. Whilst this apparent technological consistency may be justified by the industry having found, in hull forms and machinery, a mature set of design solutions to meet transport demand, in the context of this project's interest in creating change over the next thirty years, Figure 6 illustrates a daunting challenge.

As observed (in WP5) there is pressure on the existing fleet to match or exceed the new build's fuel consumption and performance, provide its services at significantly discounted prices, or face premature scrappage. Similarly, the market for retrofit technology has responded and a number of companies are offering ship owners and operators technologies or operational tools that can achieve payback using fuel savings. Both the viability of implementation in the existing fleet and the difference between the claimed performance and the actual performance remain uncertain and are the subject of debate in policy documentation, the published literature and specialist media press. The veracity of the performance potential, particularly the range identified in the IMO 2nd GHG of 25-75%, but also the performance of a ship containing multiple 'devices', was also the subject of much of WP2's detailed analysis.

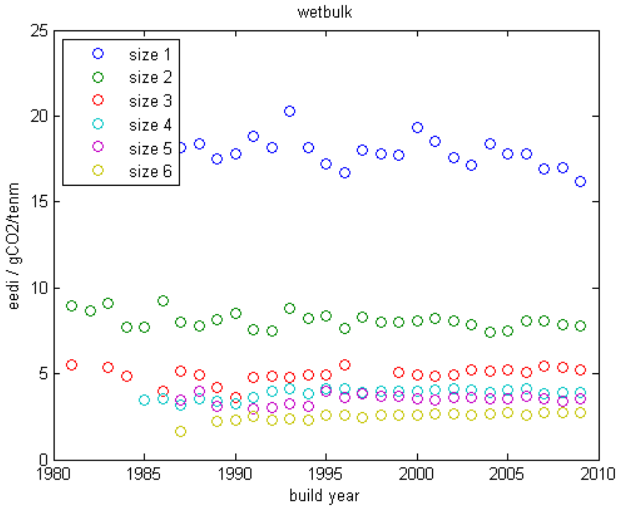


Figure 6: The evolution of the technical efficiency of the global fleet over time for ships built between 1980 and 2010 data from Clarksons World Fleet Register). Sizes (deadweight ranges) following Bahaug *et al* 2009 categorisation: size 1 = 0-10,000t, size 2 = 10,000-60,000t, size 3 = 60,000-80,000t, size 4 = 80,000-120,000t, size 5 = 120,000-200,000t, size 6 = 200,000+t.

REGULATORY AND POLICY BACKDROP FOR THIS WORK

When this project began in 2010, the policy and regulatory backdrop to the CO$_2$ emissions of shipping was immature, complex and evolving. A number of proposals existed for regulation at a number of levels (UN, EU, UK), but there was uncertainty around the final path and stringency that would become the final implementation. For this reason, responsibility for study of the evolving discussions was given to WP5, with the requirement to develop foreseeable scenarios of future policy for use in the modelling undertaken in WP1.

Throughout the lifetime of this project the IMO had the mandate of the United Nations Framework Convention on Climate Change (UNFCCC) to develop international agreements and instruments for CO$_2$ emission reduction in shipping. After the failure of the Conference Of Parties (COP) 15 meeting in Copenhagen (December 2009) to reach agreement on the international legal framework for CO$_2$ emission reduction, there is no clear basis for the management of the constituents (e.g. shipping) of a nation's CO$_2$ emissions. The IMO has therefore continued to develop 'freestanding' agreements and instruments to control GHG emissions for shipping.

Over the course of this project, the shipping industry has progressed from being the subject of mounting pressure to curb its emissions, to becoming the first industry with international, legally binding commitments on efficiency increases: the amendments to MARPOL Annex VI include the mandatory minimum Energy Efficiency Design Index (EEDI) for new ships and the Ship Energy Efficiency Management Plan (SEEMP) for both the new and existing fleets.

WP5 and WP1 investigated and modelled the consequences of these new regulations for the future emissions of the fleet, and, similarly to the findings of other studies (IMO, 2011), found that these still create expectations of substantial growth in emissions over time. This in turn leads to a requirement to develop further regulation.

On this subject, the IMO has been discussing Market Based Measures (MBM) for some time, and has a number of candidate instruments that underwent comparative analysis during the course of the project by the IMO's expert committee (IMO 2010b). Some consolidation of the candidate instruments has occurred but still two broad categories remain:

1. measures which place a price on carbon (e.g. Emissions Trading Scheme or Fuel Levy); and
2. measures which set mandatory efficiency standards for new and existing ships, some of which then allow trading of credits between ships or shipping companies

WP5 developed a number of scenarios for measures of type (1), allowing the effect of carbon prices associated with a range of levels of emissions stringency to be simulated in the modelling carried out by WP1. Unfortunately, progress at IMO MEPC has not resolved or concluded the discussion, and its next phase appears to be a focus on the development of Monitoring Reporting and Verification (MRV) procedures for the industry, which is both consistent with the US proposal (IMO 2013) and the EU push for greater understanding of shipping emissions (EC 2013).

One consequence of the IMO and UNFCCC's failure to progress the development of more stringent regulation of GHG emissions from shipping is greater pressure from regional authorities (e.g. the EU) to include shipping within regional CO_2 instruments. The aviation industry faced similar regulatory challenges because of its international nature and over the course of this project was first included in the EU Emissions Trading Scheme (ETS), before a lengthy legal challenge from member states or industry, and temporary suspension of certain elements of the implementation. WP5 attempted to study both the similarities and the differences between these two sectors in order to consider the likelihood of shipping being included in EU ETS, and the legal challenges that might be used to prevent this.

WHY IS THE WORK IMPORTANT AND WHAT CAN IT BE USED FOR?

Understanding the shipping industry's future emissions trajectory

Whilst the 2009 UNFCCC COP failed to develop a global instrument, it did produce the Copenhagen Accord, which defined a global commitment to develop policy that prevents dangerous anthropogenic interference with the climate system. There are an infinite number of pathways that can achieve this goal, with earlier action allowing for a relatively more gradual transition to a new energy system. The UK's Committee on Climate Change (CCC) has calculated one possible pathway for global emissions, consistent with the aims of the Copenhagen Accord, and this is demonstrated in Figure 7.

Overlaying two forecasts of scenarios for the future emissions from international shipping (Gilbert et al. 2010) demonstrates the inconsistency between these two versions of the future. Furthermore, it shows that while shipping accounts for only a small share of international emissions in 2010, its relative contribution will grow, leading to ever-increasing pressure to decarbonise.

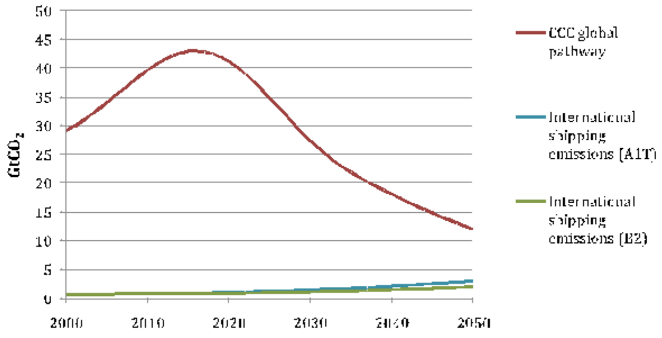


Figure 7: The global emissions trajectory and the relative magnitude to forecasts of international shipping emissions (source: Committee on Climate Change, 2011)

Just as Figure 7 depicts the emissions trajectory for the global economy required to avoid dangerous climate change, Figure 8 proposes what this might need to look like for the shipping industry.

An added complication of this trajectory is represented by the period 2007-2013. The IMO 2nd GHG Study focused on the year 2007, which is the year from which the baseline projections used here were taken. Due to the complexity of estimating shipping's emissions from a bottom-up perspective, no authoritative study has been undertaken since 2007 to verify whether the projected emissions match what has happened in practice. However, there is evidence (see WP1 report) to suggest that two influences have led to a lower emissions trajectory over this period than was expected in 2007:

1. a lower rate of growth in transport demand due to the global financial crisis; and
2. lower emissions intensity from slow steaming (and other operational measures), premature scrappage, 'eco-ship' building and retrofit activities, owing to the combined effects of high oil prices and low revenues.

While these recent events have been bad news for many industry stakeholders commercially, they are good news for the environment: however, they do not remove the imperative for action because they are expected to be short-run effects only. In the long-run, which is the period relevant to this study (2010-2050), the expectations are that:

- transport demand will continue to grow, as global economic growth continues;
- with the recovery of prices in the sector (particularly freight rates), the profitability of higher ship speeds will return and much of the efficiency gains of the last few years will be rescinded.

Figure 8 therefore shows three (estimated) scenarios:

1. The A1B scenario from the IMO 2nd GHG Study, inclusive of expectations of further year-on-year efficiency gains, which estimates that emissions from shipping will triple over the next 40 years;
2. A similar A1B scenario updated for the actual emissions over the period 2007-2013 and with some learning of the efficiency gains obtained during this period, and the effects of EEDI and SEEMP included; and
3. A trajectory consistent with the implementation of a market-based measure designed to meet the ambitions for shipping's emissions trajectory that will help society avoid dangerous climate change (e.g. from UNEP 2011 and EU 2011).

Whilst WP1 investigated some of the components contributing to this deviation (ship speed), both the response and the likely longer-term impacts deserve greater attention as they could provide insights relevant to the design of future regulations. However, a greater unknown is the consequence of the more dramatic deviation of emissions for the period between when a global measure is implemented, e.g. 2025 (allowing for realism in the timescales of drafting and adoption at the IMO), and the ensuing years.

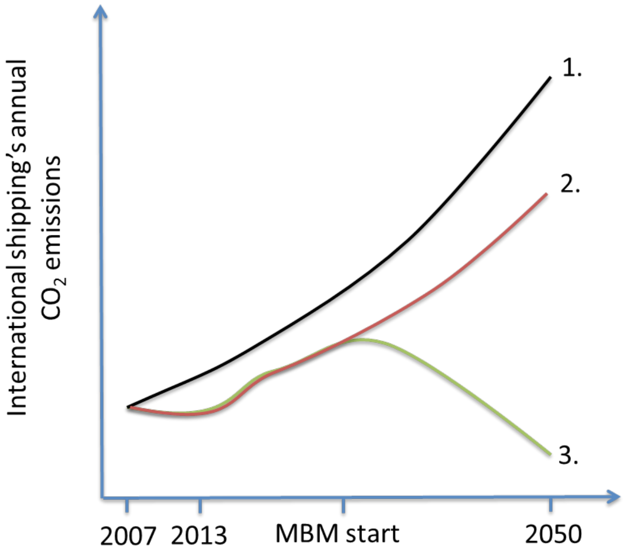


Figure 8: The shipping emission gap: (1) the IMO 2nd GHG Study forecast (A1B); (2) estimated emissions evolution since 2007; and (3) a target trajectory.

Outputs from all of the WPs contribute towards understanding what these trajectories will mean to the shipping system and the ships that will service future transport demand. This understanding then allows policymakers to consider the foreseeable consequences of regulations in advance of their implementation, and firms within the shipping system to plan ahead with an informed strategy.

Understanding the drivers of emissions and emissions growth: transport demand

In the study of maritime freight demand, mass is commonly used as the quantity parameter, while number of passengers is the quantity parameter used when looking at passenger transport demand. The development of demand can therefore be thought about as the development of each of those parameters in isolation or their development in combination.

Figure 9 shows the historical trend in the transport demand (in units of billion tonne miles: 1e9 x mass in tonnes x distance in nautical miles) for some of the main commodity groups of the shipping industry. The graph shows that, at least for global aggregations of flows of commodities, there is a high level of correlation between GDP and transport demand. However, since trade growth is a contributor to GDP growth this should not be misconstrued as GDP growth causing trade and therefore transport demand. Many of the commodities that are moved by ship (bulky, low value commodities) are those associated with heavy manufacturing and infrastructure development (e.g. coal, iron ore) and so if global maritime transport demand is disaggregated between the developed and developing world, these correlations may not be observed for the former – particularly those economies where the contribution of the manufacturing sector to GDP has diminished.

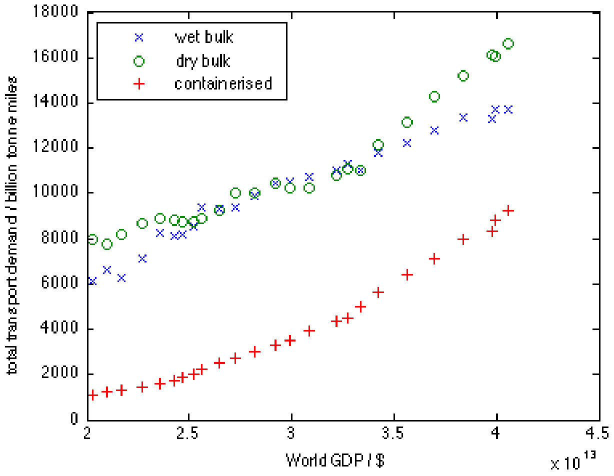


Figure 9: Relationship between world GDP (1985-2009) and transport demand for different marine transport commodities (Source: UNCTAD)

Despite this philosophical complication and the 'shakiness' of making extrapolations from historical trends to estimate what might happen in the future, some transport demand scenarios are developed using correlation with GDP forecasts (e.g. those available for IPCC scenarios, SRES). This method can produce dramatic growth rates and so others have tried to apply resource constraints or wider mitigation scenarios (e.g. finite oil), for example (OPRF 2008; Bauhaug et al. 2009). Using the latter approach, Bauhaug et al. estimate the transport demand in 2050 as a function of different SRES scenarios to be represented by the values in Table 1. The values are indexed to the 2007 transport demand (100). The range of values shows an expectation that total maritime transport demand will increase by between a factor of 3 and 5.4 over the next 40 years.

Table 1: Transport demand in 2050

SRES scenario	A1B	A2	B1	B2
Ocean-going shipping	320	240	220	180
Coastwise shipping	320	270	220	220
Container	1230	960	850	690
Average (all ships)	540	421	372	302

In order to enable comparability with existing work, the modelling in WP1 deploys transport demand scenarios consistent with A1B, whereas both WP3 and

WP4 discuss alternative perspectives and scenarios, particularly evolutions of the UK's transport demand.

Understanding the drivers of emissions and emissions growth: shipping's carbon intensity

Technically, ships are something of a dichotomy. As demonstrated by their history, over thousands of years, they have a low technology burden in terms of both design and manufacture. However, because of the complicated environment in which they operate (the interface between two fluids, air and water), the physics of their performance, particularly in rough weather, remains a challenge to model and measure with low uncertainty. This challenge is demonstrated in Figure 10, which displays a dataset covering four years of a dry bulk carrier's operation. The data is taken from noon-reports, a daily measurement of a number of variables by the crew, including fuel consumption. Among other sources, WP6 deployed this information to produce a greater understanding of the performance of ships in operation, and in particular the effects of fouling.

Adding to the complexity of the physics is the shortage of data in the public domain to describe the actual operation, behaviour and fuel consumption of different ships. The application of much of WP2's output is to address this shortage, particularly with respect to the performance of specific energy efficiency technologies and design choices, through computational and laboratory scale analysis and experiments.

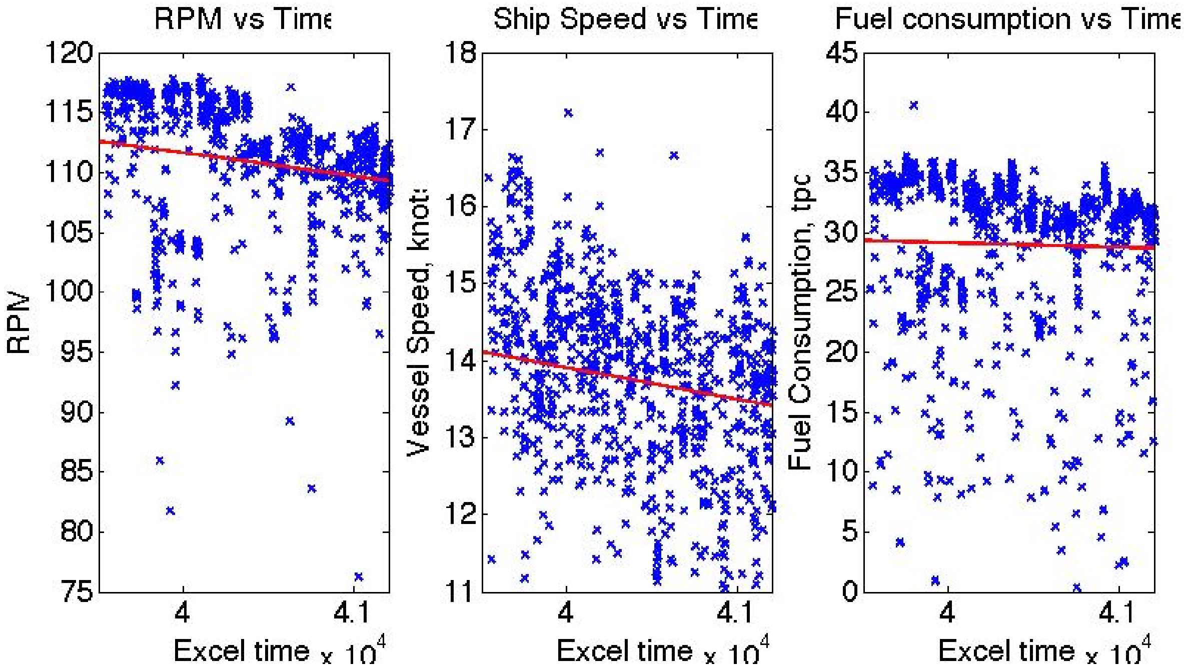


Figure 10: Example onboard measurements of RPM, ship speed and fuel consumption

References

Buhaug Ø, Corbett JJ, Endresen Ø, Eyring V, Faber J, Hanayama S, Lee DS, Lee D, Lindstad H, Markowska AZ, Mjelde A, Nelissen D, Nilsen J, Pålsson C, Winebrake JJ, Wu W-Q, Yoshida K (2009) *Second IMO GHG study*, IMO London, UK

Committee on Climate Change (2011) *Review of UK Shipping Emissions. CCC, London.*

EC (2011) *White Paper Roadmap to a single European transport area – towards a competitive and resource efficient transport system*

EC (2013) *Proposal for a regulation of the European parliament and of the council on the monitoring, reporting and verification of carbon dioxide emissions from maritime transport and emending regulation (EU) No 525/2013. 2013/0224* European Commission. Brussels.

IMO MEPC 60/WP.5 22 March (2010a) *Information to facilitate discussion on GHG emissions from ships, secretariat.* IMO, London

IMO MEPC 63/Inf.2 (2011) *Assessment of IMO mandated energy efficiency measures for international shipping.* IMO, London

IMO MEPC 61/Inf. 2 (2010b) *Full report of the work undertaken by the expert group on feasibility study and impact assessment of possible market-based measures.* IMO, London

IMO MEPC 65/4/19 (2013) *Proposal of the United States to enhance energy efficiency in international shipping.* IMO, London.

Gilbert, P. Bows, A. Starkey, R. (2010) *Shipping and climate change: scope for unilateral action.* University of Manchester, Manchester.

UNEP (2011) *Bridging the gap.* United Nations Environment Programme (UNEP).

WORK PACKAGE REPORTS

WORK PACKAGE 1

MODELLING THE SHIPPING SYSTEM

Led by Tristan Smith and Mark Barrett with Eoin O'Keeffe, Sophie Parker and Lucy Aldous (UCL Energy Institute).

WP1 – MODELLING THE SHIPPING SYSTEM

Led by Tristan Smith and Mark Barrett with Eoin O'Keeffe, Sophie Parker and Lucy Aldous (UCL Energy Institute).

Overview

At the outset, the project identified that the research questions and the overall challenge of understanding the potential for a low carbon future in the shipping industry could not be addressed through research in a single subject. There needed to be a research activity that took a multidisciplinary, whole-system view of shipping, so that the different areas of knowledge could be brought together and the interactions of the different components (technical, economic, logistic, regulatory, etc.) and research outputs from the other WPs could be integrated.

The approach chosen as the focus of the work in WP1 is the development of a model (GloTraM, Global Transport Model) for simulating the evolution of the global fleet over time, changes to its technology and operation, the activity of this fleet as it meets the global transport demand, and the consequence of this activity in terms of energy demand and emissions.

The development process for this holistic, whole-system model of shipping included a number of studies looking both at the current fleet, its activity and its emissions, and at the way some of the key parameters describing shipping (e.g. speed) interact. Brief overviews of the work done and findings are given below, and greater detail can be found in a number of referenced publications produced by the consortium.

Main Research Focus/Activity

The main research questions addressed by WP1 include all those associated with whole-system thinking:

- the relationship between transport logistics and future ship designs and their impact on the efficiencies of the whole system;
- demand for shipping: looking at the drivers for using shipping over other modes of transportation;
- the impacts of technical and policy solutions on future shipping scenarios;
- implementation barriers to low carbon shipping; and
- measurement and apportionment: how best to measure the impact of shipping and optimise environmental gain in an international context.

In order to address this list of aims, the WP developed a conceptualisation of the shipping system shown in Figure 11, and converted this into a series of input datasets and algorithms that could be used to explore a number of 'what if' scenarios.

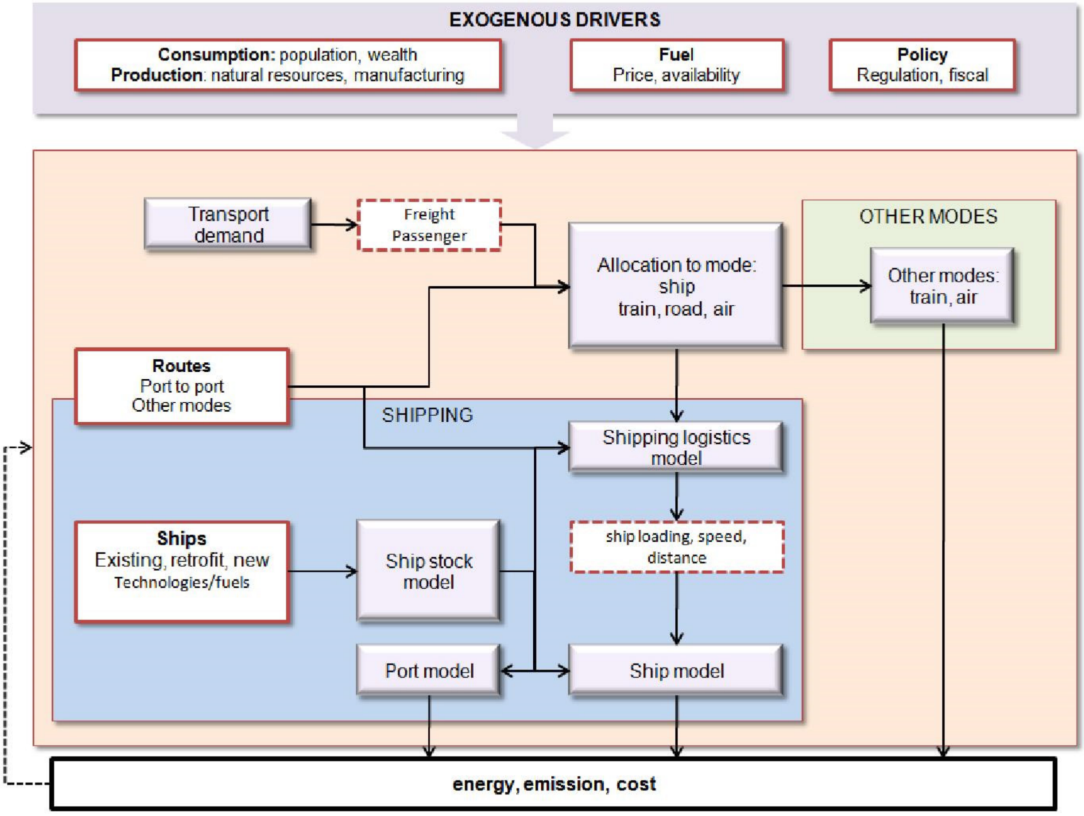


Figure 11: The components of the shipping system and the links between them.

Further to this whole-system modelling activity, two PhD students within WP have been developing detailed knowledge in specific areas of the shipping system. Their specific RQs are outlined below.

Eoin O'Keeffe: ***The effects of climate change on the dry bulk shipping sector through to 2050***

- How might the dry bulk shipping network evolve to 2050 under projected climate change impacts within various scenarios of global development and climate change mitigation policy, when considering the dry bulk shipping sector as a system of heterogeneous learning agents?
- When considering these market agents as learning agents in real market conditions, what is the impact on technology take-up and operational activities?
- How might the dry bulk transport network be impacted by changes in demand for energy commodities, changes in grain production and opening of new routes due to climate change impacts?
- What will the impact be on the ship stock distribution of the dry bulk fleet of projected changes in trade and changes in transport cost (e.g. fuel price increases and market-based measures for reducing GHG emissions)? What are the limits to the penetration of larger vessels on global shipping routes?

Sophie Parker: ***Dynamic matching in the oil industry: implications for carbon policy***

- What economic factors determine who matches with whom in the oil shipping market and the intra-allocation of the gain generated by a match?
- How do the location and physical characteristics of ships affect the matching?
- How do tanker movements (and hence emissions) change when bunker fuel prices increase?
- What is the effect of a demand shock on freight rates, tonne-miles and emissions?
- How do oil movements change when agents have forward-looking strategies (as compared to myopic strategies)?

Main Outputs and Activities

The outputs from this WP can be broken down into those analysing the global fleet (data analysis and model development) and those associated with the work undertaken on the models studying subsets of the global fleet (the work undertaken within the PhD studentships).

Understanding the activity, efficiency and emissions of the existing fleet

An important component of any model simulating the future evolution of the shipping industry is a clear understanding of its current state, i.e. the starting point of its evolution. Investigating data characterising the current global fleet also provides input to which parameters are likely to be of significance in the estimation of future trends and where there might be important interactions and relationships.

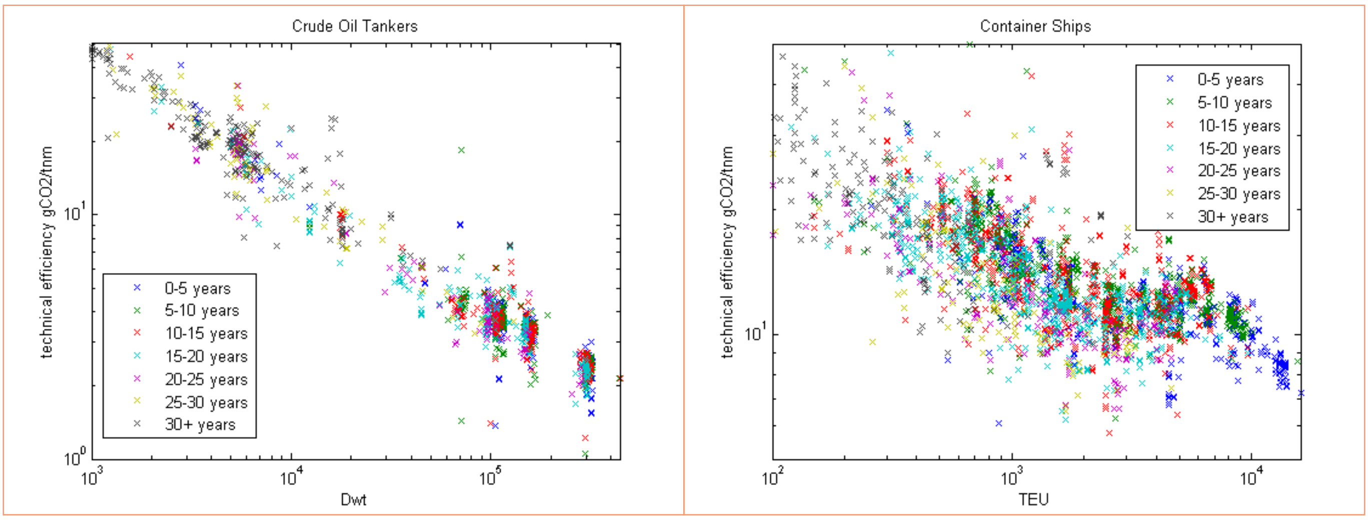


Figure 12: Technical efficiency in the crude oil tanker and container ship fleet (source data Clarksons World Fleet Register)

A driver for shipping emissions is the carbon intensity of the ships in their design condition. Figure 12 details the relationship between ship size and carbon intensity (named technical efficiency in this instance) for the crude oil tanker and container ship fleet. The individual data points represent individual ships in the global fleet and are grouped into age categories (0-5 years represents ships built within the last 5 years). The data show, as observed in many similar studies, that as ships increase in size they achieve lower carbon intensity, and that, as Figure 6 also shows, there is no strong trend in increasing carbon intensity with ship age.

However, a ship may not be operated in its 'design' condition. Much has been written and discussed in the literature over the last five years on the subject of slow steaming, which can have a significant impact on efficiency and emissions (Dinwoodie 2010). This raises important questions about the extent to which the existing fleet is already taking steps to increase efficiency, which can only be answered by studying the combination of a ship's technical specification with data describing ship activity and speeds.

This project coincided with the arrival of a new source of information on the activity of shipping, S-AIS (Satellite Automatic Identification System) data. AIS is a facility whose primary purpose is to report the current location of vessels for the avoidance of collisions. Under IMO regulations all vessels over 300GT on international transport (IMO 2012) are required to carry transmitters. Along with location of vessel, other data including vessel identity, course and speed are also reported. While the system was originally constrained to using shore-based stations with limited range, from 2010 low earth orbit satellites also started collecting the data, providing global coverage and, for the first time, detailed measurement of shipping activity across the whole fleet and on the high seas.

In order to use this new data source to extract insights into the current fleet's activity, emissions and energy efficiency, an AIS data processor was developed, which matched the S-AIS data to Clarksons World Fleet Register and SIN data in order to estimate global trends in ship operation (e.g. speed, days at sea) and patterns of activity. The detailed description of the modelling developed in order to achieve this can be found in (Smith et al. 2013), along with data and analysis for a number of subsets of the global fleet. A few key results are included in Figure 13 and Figure 14. All data is for 2011.

Figure 13 displays the relationship between ship size (Dwt) and the estimated operational efficiency/intensity for both crude oil tankers and container ships. The indicator is normalised to the IMO 2nd GHG Study estimate of the capacity utilisation of each ship type, due to uncertainty in the data describing the actual capacity utilisation.

The results are important because they suggest that within given size categories (e.g. the VLCC, Suezmax or Aframax, or the 2-4000, 4-8000 or 8000 + TEU categories), there is wide variability in the actual transport carbon intensity (the lowest operational carbon intensity in the crude oil tanker fleet is about 5 times less than the worst). Certainly for the larger crude oil tankers, and less so for the container ships, there is significantly greater variability than observed in Figure 12.

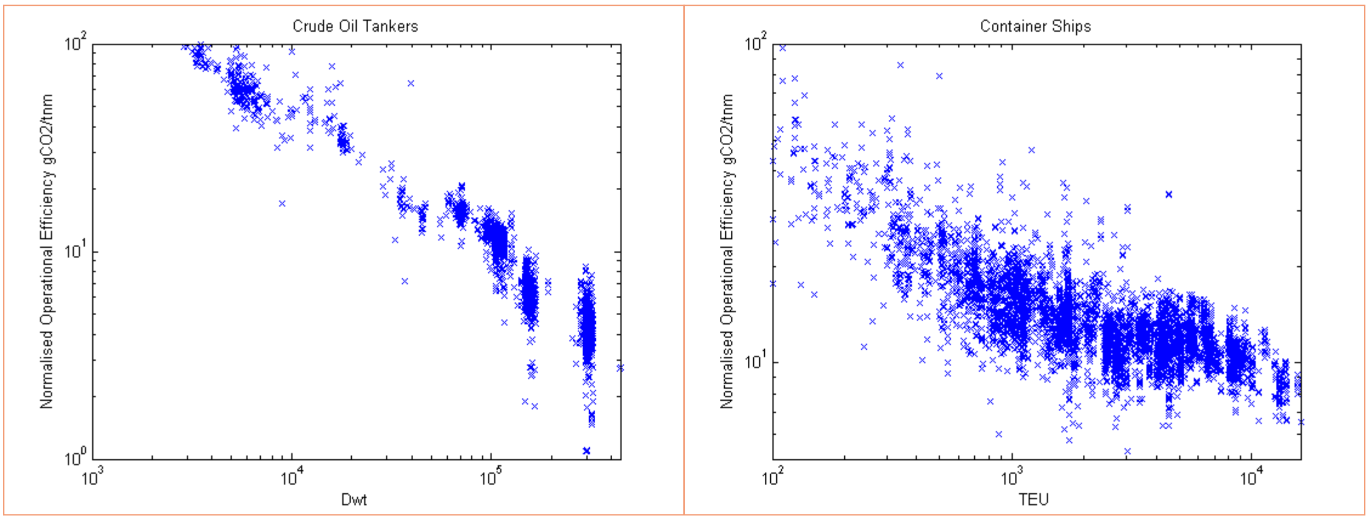


Figure 13: Operational efficiency in the crude oil tanker and container ship fleet

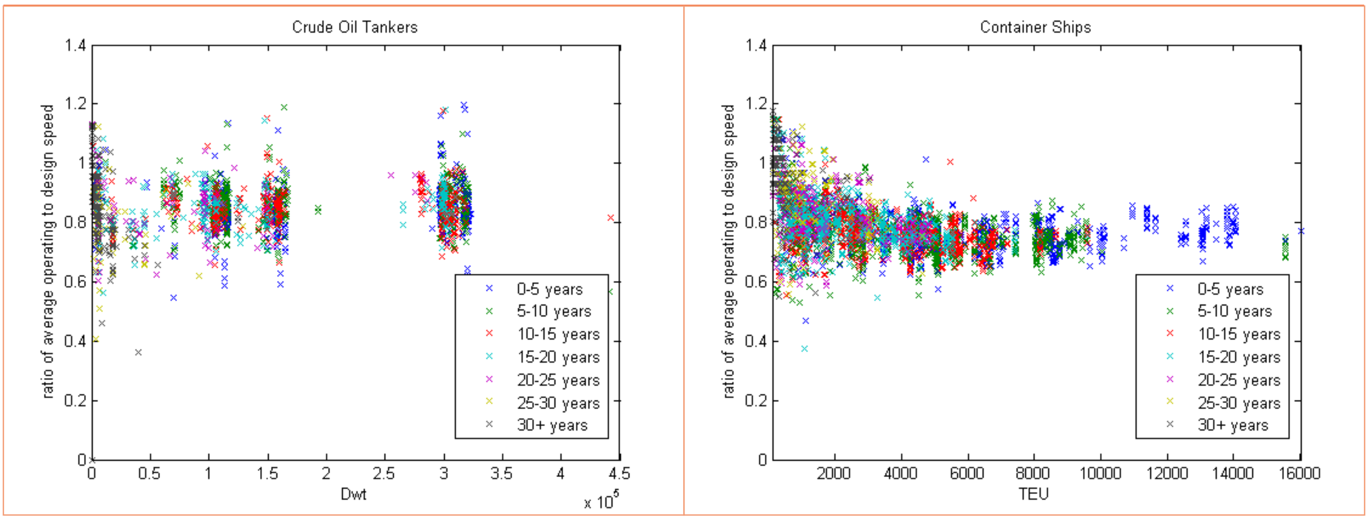


Figure 14: Ratio of average operating to design speed, crude oil tankers and container ships, all ages

Figure 14 provides some of the explanation for the observation of wide variability in operational intensity; the average speeds at which ships are being operated are not homogenous. Whilst it can be seen that all but the smallest container ships are operating at speeds lower than their reported design speed, many crude oil tankers were still operated, on average, at (or even above) their design speed, whilst many others were operated at only 75% of their design speed.

This study, enabled by the arrival of S-AIS data, enabled a rich characterisation of the existing fleet to be used as an input dataset to GloTraM. However, the consequence of these outputs to the modelling activity undertaken throughout WP1 and the wider project is that both the design and the operating speed parameter describing categories of ship types and sizes require careful consideration, as does the consideration that there may be significant heterogeneity in the fleets - that is to say that it may be difficult to assume behaviour is consistently taken up across the owner and operator stakeholder community within a given sub-sector of the global fleet, let alone across all of global shipping.

GloTraM model development

The aim of GloTraM is to provide a tool that estimates, for a given macroeconomic, transport demand and regulation scenario, what the foreseeable take-up of different technology and operational options might be and the potential consequences of this take-up for the shipping industry's economics, performance and emissions. The key components that have been developed to enable this scenario exploration include:

- a transport demand module, including tools for generating scenarios of future trade of different commodities between countries and regions;
- a route-mapping module, including tools for mapping future trade flows onto specific ship types, sizes and routes; and
- a ship stock module, with tools for simulating the evolution over time of a fleet of ships, including both their technical and operational specifics and their economics, as a result of regulatory, price and technology availability scenarios.

There are a number of publications (listed in dissemination) describing the detail of GloTraM and the development of its algorithms. In addition to this, there are a number of reports describing scenario analysis carried out using GloTraM to investigate various questions about shipping's future, summarised in Table 2.

Table 2: Key GloTraM references

Reference	Content
User guide (Smith *et al*. 2013b)	Description of how to set up the model's pre-processor with bespoke run parameters and execute scenario analysis using its two graphical user interfaces (GUIs)
External factors (Smith *et al.* 2013c)	Derivation of the standard set of baseline year input assumptions and projections
Method (Smith *et al.* 2013d)	Description of the model's structure, and calculation procedures in its sub-routines and modelling assumptions

The key components of the model are described below.

Transport demand

Shipping activity is a derived demand: it exists in order to service the flow of goods, commodities and passengers from their origin to their destination (for goods and commodities, from where they are produced to where they are consumed).

The drivers of this demand, are a combination of the distribution of natural resources, the location of the centres of population and their relative size and needs (often a function of wealth), the relative wage rates in different economies and the costs of transport. The historically low transport costs of shipping, enabled by the economies of scale and logistic efficiency that bulk and container shipping offer, have in turn been enablers of the globalised society in which we live.

However, determining with rigour how each driver will evolve in the future and how the interaction results in the specific tonnes of freight traded between countries was considered outside of the scope of this study. Instead, trade data and projections were harvested from a number of different sources and used to build detailed GloTraM datasets both for current and future trade flows, and the resulting tonnes, tonne-nm and average hauls (cargo distance).

The growth and evolution of the global fleet is determined by the evolution of global trade, whereas the UK's activity and shipping emissions requires information on UK-centric trade (e.g. UK imports and exports).

WP3 focused on the latter and greater detail on current patterns, including the detail of end-to-end supply chains, can be found in its report. However, there remained a need for a scenario that extended both UK and global trade in trends out to 2050. Figure 15 characterises the trends used for the three main ship types' freight in BTeKm (billion tonne kilometre).

These are the aggregations of trends for individual commodities (100 categorisations used according to the NSTR system) at the level of country-country flows. The source of the information used is from the company NEA (iTRENS), which uses an agent-based model to simulate trade and maritime transport demand over time. However, to enable comparison with other work, this forecast was then calibrated to the IPCC SRES A1B scenario used as representative of a central scenario in the IMO 2nd GHG study.

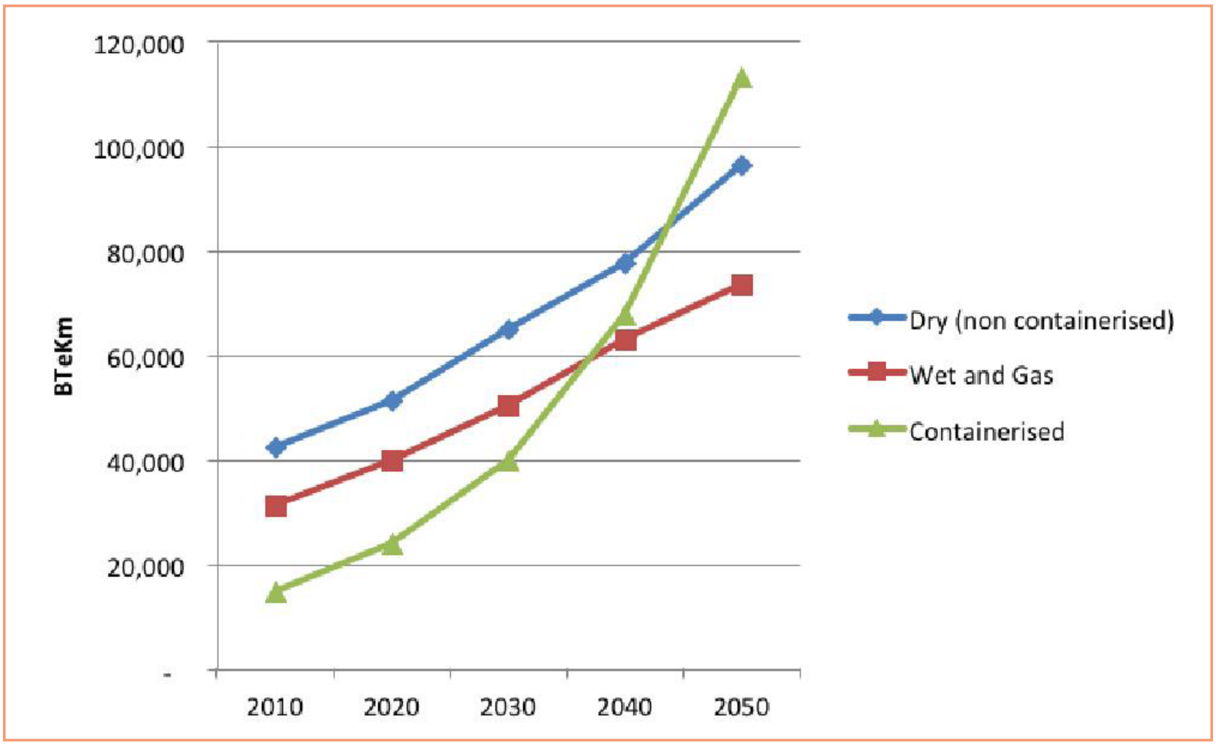


Figure 15: Projections of global transport demand in BteKm. Wet and Gas is the aggregated trade in wet_other, wet_prod_chem, wet_crude and gas. Dry is the non-containerised flow in dry and dry-reefer. Note that transport demand is based on estimated average hauls for each trade and may vary in GloTraM, as trades are allocated to routes.

In order to be able to quantify the detail of UK shipping emissions, where the UK is a node within the global shipping system, specific attention was paid to the transport demand scenarios for the UK within this global scenario. The modelling carried out by iTRENS did not include current mitigation policy such as the UK's Climate Change Act. This omission may be approximately appropriate for global transport demand trends, but for the UK this is a shortcoming as the Act and its ambitious GHG reduction target are expected to fundamentally change the mix of commodities flowing into and out of the UK. Concurrent with the development of GloTraM, the UK CCC was undertaking analysis to develop a coherent set of transport demand projections for the UK (CCC 2011), and so these were used to calibrate UK specific trade flows. The scenarios deployed within the global transport demand dataset can be seen in Figure 16. Its notable that even in the high demand scenario, UK demand is expected to grow at a substantially lower rate than global demand, primarily because relative to other countries the UK is considered to be a developed economy.

Change in technology and operation

There are a number of key options available to ship owners and operators, which could modify the carbon intensity of a given ship type/size:

- increase the energy efficiency of the prime mover, propulsion system or hull;
- select a new design or operating speed; and/or
- adopt an alternative fuel.

The drivers for owners/operators to deviate from the current technology and operation specifications of ships are considered to be primarily regulation and economics (Bauhaug et al. 2009), and so GloTraM requires a method to evaluate how changes to the regulatory and landscape might have an impact. Existing work to evaluate changes to technology and operation can be broadly divided into (1) analysis of optimum speed; and (2) deployment of MACC (Marginal Abatement Cost Curve) analysis (e.g. IMO 2011).

Whilst the optimum speed analysis applies a variety of perspectives (from profit maximisation to cost minimisation), it has typically focused on a single abatement option (speed). MACC analysis applied to shipping includes both technical and operational abatement options, but within the cost minimisation framework, which, at least for ship speed analysis, may limit its applicability.

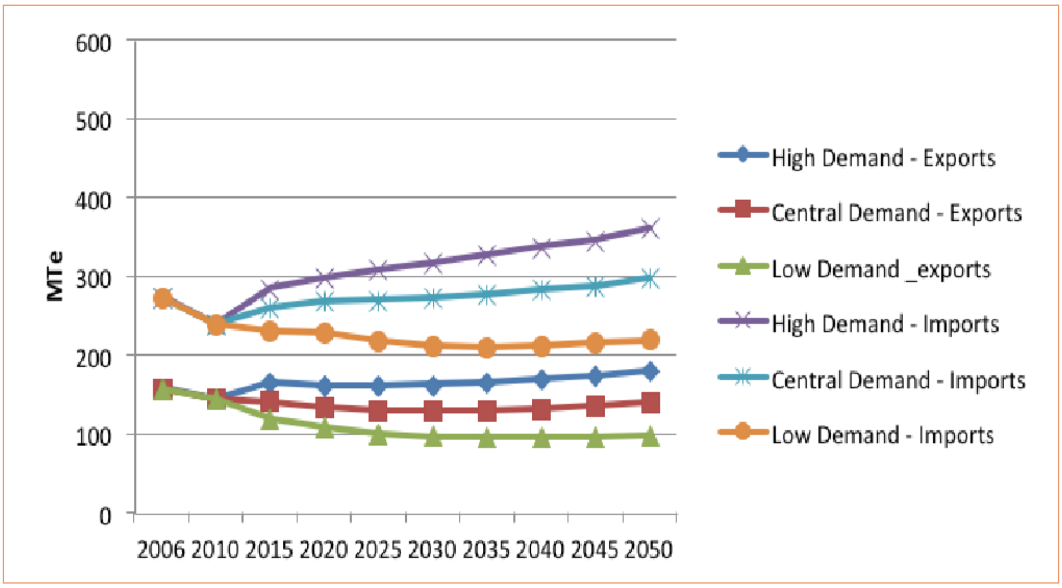


Figure 16: UK-specific transport demand (source: CCC (2011))

A further disadvantage of MACC analysis is its constraints of linear superposition and incremental assessment of abatement options, which can misrepresent the compatibility constraints and interactions that occur at the level of the engineering systems on board a ship.

For these reasons, the assessment for technology and operation change in GloTraM is undertaken using a profit maximisation model applied to a range of combinations of technology, speed and alternative fuel selections. Each 'option' and combination of 'options' is assessed to see whether cost savings (fuel savings or carbon reduction if there is carbon pricing) achieved in adopting the option are justified against the impacts on capital costs and revenue. A standard accountancy tool for calculating this is NPV (net present value), as shown by the following equation:

$$NPV = C_0 - \frac{\sum_{t=0}^{T}(R-C)}{(1+d)^T}$$

where C_0 is the capital cost of the carbon reducing technology (CRT); R is the revenue that the ship will generate (including any changes due to the presence of the CRT e.g. loss of dwt); C is the cost (e.g. including cost savings due to the CRT and the operating costs associated with the CRT); d is the discount rate (the interest rate or 'cost of money' for the ship owner); and T is the number of years over which the evaluation of NPV is applied. Values of d and T specific to the typical values used to represent investment hurdles within shipping operator and owner firms can be selected (Smith et al. 2013c), and further sophistication can be added to represent the effect of market barriers between the ship owner and the time charterer or the time charterer and voyage charterer (Smith et al. 2013d).

A further important detail in the implementation of technology change models in GloTraM is the provenance, coherency and specificity of the input data. Figure 17 displays how, through working with WP2, 4 and 6, analysis is first undertaken for concept ship designs and using high fidelity analysis techniques (e.g. CFD, towing tank and bespoke modelling and simulation approaches). These detailed findings are then applied to parameterised models that scale to ensure a balanced ship design before being developed into a series of coefficients capturing the impact of a technology or operation change on some key variables (e.g. installed engine power, specific fuel consumption, % MCR in the operating condition), and combined with cost data in a consistent format for use in GloTraM. For greater detail, see the WP2 report.

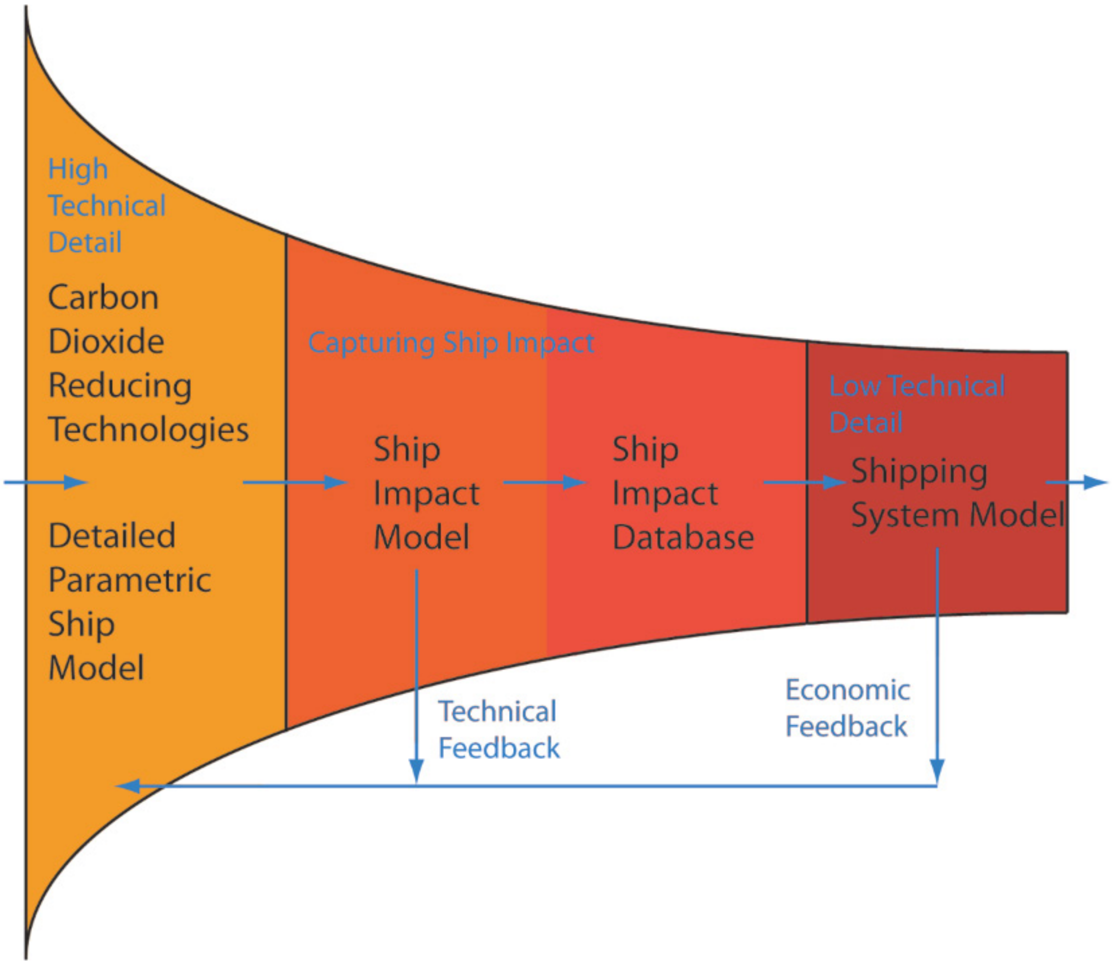


Figure 17: Concurrent modelling approach, with a reducing level of technical detail from left to right

Logistics (ship size, route, operating speed, capacity utilisation)

Further to the technology and operational changes of ships themselves, the evolution of the shipping logistics system is another important component in the estimation of future shipping efficiency and emissions.

A customer (or shipper) needing a good to be moved from A to B does not just see the cost of the transport. There are inventory costs whilst goods are in transit or storage, risks on price (both of the good transported and transport itself), and, assuming that the production and consumption of the good are continuous processes and the transport of it a discrete process, there are some additional costs associated with storage (potentially both at the origin and the destination). For these and other reasons, some (Kendall 1972) have suggested that a shipper's selection of ship size is not determined solely by the economy of scale. Kendall (1972) expressed formulae for the components of cost seen by the shipper including:

- the cost of the sea voyage, *F*
- the handling cost, *H*
- the storage cost, *S*

Taking Kendall's equations for the cost components, an expression for the 'total' cost can be obtained, which when differentiated with respect to ship size (Qs) reveals the relationship:

$$\frac{\partial T}{\partial Q_s} = \frac{VI}{Q_y 200} + \frac{\partial F}{\partial Q_s}$$

where *V* is the value of the commodity, *I* is the percentage rate of return on the capital invested in it (during transport and storage) and Q_y is the total annualised flow of the commodity on a specific trade route. Besides the importance of the relationship between freight rate and ship size, this relationship suggests that as *V* or *I* increase, or as Q_y decreases, the 'optimal' ship size decreases.

Following validation against the activity of the existing fleet, this equation is the basis for the algorithms in GloTraM used for modelling the evolution of bulk shipping routing and allocation of ship type to specific commodity and country O-D flows.

Due to the difference between unitised and bulk freight, not least that the former is predominantly serviced by the liner trader, the algorithm is not as effective for representing the evolution of the container route network.

In order to consider this important ship type, an approach was used that combined trade data with S-AIS data in order to map the current direct and transhipment flows globally and produce a set of rules that could be applied within GloTraM for its future evolution. Details of this approach can be found in (Haji *et al.* 2013).

A matching model for understanding oil tanker fixtures

In a market with heterogeneous populations (ships and traders), who is matched with whom and the intra-allocation of the gain generated by a match is a function not only of the pair considering matching but also the other market players. A matching model is a particularly relevant framework for the shipping market because ships and traders are heterogeneous: ships are differentiated by their location and physical characteristics, and traders by their expected net oil revenue and cargo demand requirements. It is crucial to consider agents' outside options or the opportunity cost of matching because there are large stakes of money involved (millions of dollars) and different matching options.

These considerations arise due to specific features of the market - the fact that ships are dispersed in different parts of the world and have to sail empty after they drop off a trader's cargo. The location and energy efficiency of a ship is a significant factor in determining the shipment cost and time, affecting a trader's oil revenue and a ship's local market competition.

The latter feature means that ship operators need to understand the implications of matching to a trader in terms of not only the current match-specific trading costs and benefits but also the consequences of the decision in terms of future employment from the destination (called an option value). Not only are there considerations about who to match with, but there is also an inter-temporal decision - whether to match in the current period or wait a period and match in the next period. Each match also generates a match-specific speed (assuming no charter party restrictions), which reflects the trade-off between revenue, costs and future expectations of the market.

The matching model is a novel approach to solving, through economic optimisation, the problem of matching ship owners to traders, quantifying the aforementioned match-specific costs and benefits. The model is being run for the VLCC sector but could be deployed for other sectors of the shipping industry if sufficient input detail can be derived.

Figure 18 illustrates output from the model showing the profitability of matches (measured as Surplus) between a trader requiring cargo to be shipped from Brazil to South China and VLCC ships located in Brazil of three different types, where Type 1 is the largest ship and Type 3 the smallest.

The figure shows that Type 2 is the most energy-efficient in terms of fuel cost per tonne-mile, followed by Type 3 and Type 1 (assuming a constant payload of 260,000 tonnes and constant speed). However, Type 1 can achieve the highest payload so its profitability depends on the capacity utilization rate.

In the 'Bigger is Better' scenario, Type 1 beats Type 2 and 3, but when the payload is equivalent across ship types (260,000 tonnes), Type 2 wins and energy efficiency rules.

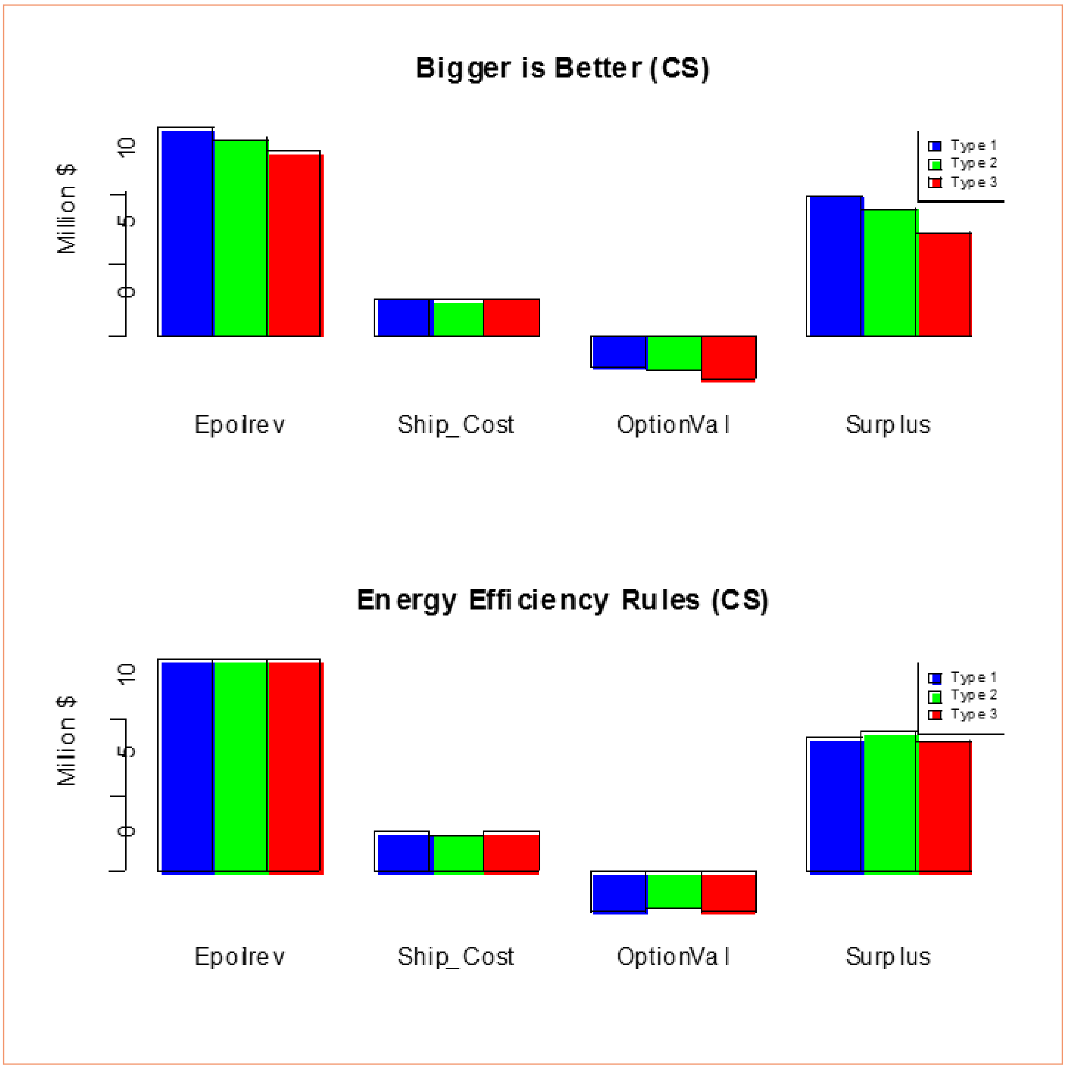


Figure 18: Comparison of the match surplus when different assumptions are made about capacity utilization (Epoilrev= Expected oil revenue, Ship_Cost = shipment cost, Option Value = the value to be at the destination, and Surplus = Epoilrev-Ship_Cost +Option Value)

In the larger matching model where ships are also differentiated by location and ships of each physical character type are dispersed evenly across locations according to their fleet share, the model shows that location matters. For example, in ‘Bigger is Better’, traders match with all three ship types but to varying extents. Ships of Type 1 that are located in close proximity to the local market are associated with the highest surplus and therefore have the highest utilization rate (70%), followed by Type 2 (45%) and Type 1 (1%). In contrast, Type 1 ships that are located farther away from the local market are at a disadvantage compared to ships located closer to the market. This is evidenced by the Type 1 ships that do not match; they are all located farther away from load area markets, the majority in California and the Far East. The results are intuitive: ships that are not strategically located are less competitive than ships located near the local market, despite their comparative advantage in other dimensions (size and technical efficiency).

Agent-based simulation of the dry bulk industry

An agent-based model was developed to simulate the behaviour of agents (in this case different shipping companies) in the dry bulk sector. This is intended to explore both heterogeneity (e.g. different attitudes among the shipping companies), to enable the inclusion of endogenised transport demand, and as an alternative to the deterministic and ‘average agent’ approach used in GloTraM.

The model captures the full shipper/shipowner interactions through generating the key markets in which they cooperate: spot market; time charter market; and, to a lesser extent, the contract of affreightment market. These markets are endogenously generated within the model. Each agent adapts its behaviour through the various planning stages:

- **Operational planning:** Shipper agents alter their bidding strategies for the spot market, whilst shipowners alter reserve and ask prices to maximise profit in the market
- **Tactical planning:** Shippers and shipowners time charter a vessel as a risk hedging strategy to spot market rates and move vessels in and out of lay up
- **Strategic planning:** Shippers and shipowners alter their fleet stock by scrapping and purchasing vessels

The key outputs from the work will be:

- The development of a decision support tool for testing policy measures and investigating impacts of changes in trade;
- The evolution of the dry bulk global fleet in terms of changes in vessel size and technological changes; and
- Changes in the parcel size of the various dry bulk commodities.

Elements of the work have already been presented at conferences (O’Keeffe 2010; O’Keeffe 2013).

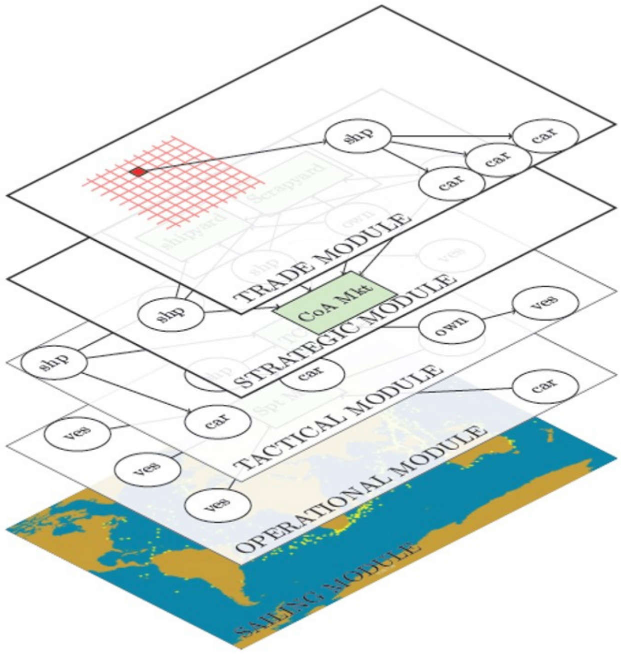


Figure 19: Example of the approach taken to represent the different modules within an agent-based simulation of the shipping industry

What are The Key Findings and What is Their Relevance to Commercial and Policy Issues?

The detailed outputs of scenario runs from GloTraM are detailed in a number of the publications. However, the process of model development and data analysis revealed a number of key findings about the dynamics of the shipping industry relevant to understanding its low carbon potential and how this can be achieved.

The significance of speed, operational and embodied CO_2 emissions and the operational efficiency opportunity

The relationship between a ship’s speed and the power required for propulsion presents a substantial opportunity for increased energy efficiency. The investigation into the existing fleet, in this era of ‘slow steaming’, estimates that in 2011 average operating speeds were 10-15% lower for many of the bulk fleets (tankers, dry bulk) than in 2007, and approximately 25% lower for container ships. The consequence of these observed differences in speed is a significant reductions in fuel consumption, of up to 40% for many of the bulk fleets, and 50% and above for some container ship fleets, relative to the estimates presented in the IMO 2nd GHG study. Ultimately, the speed reduction, which in turn reduces transport work, absorbs some of the impact of the main engine fuel consumption on energy efficiency, so that relative to the IMO 2nd GHG study estimates of overall efficiency, the improvement in operational efficiency is approximately 10% for many of the bulk fleets, rising to 30% for some of the container fleets.

This led to further effort to understand the economic drivers of speed (particularly Smith *et al*. 2011), as well as the wider implications of speed reductions. One observation made by some commentators is that lower ship speeds necessitate the construction of a greater number of ships, and that the manufacturing process is associated with GHG emission production that can offset the benefits of reduced speed. Smith (2011) describes the derivation of an equation to explore the relationship between the operational and embodied emissions:

$$V_{opt} = \sqrt[3]{\frac{12\, C_{steel}\, lightship}{C_{fuel}\, kT_{as}\, l}}$$

This equation was applied to a number of case studies, and the results are presented in Figure 20, plotting the ratio of total CO_2 emissions for each speed (embodied and operational), against the CO_2 emissions at the current design configuration. The shape of the relationship shows a minimum which occurs between 2 knots and 5 knots depending on the ship type specific case. At speeds below this, the embodied emissions dominate the relationship (i.e. the emissions from the additional ships required outweigh the operational emissions benefits of lower speed), whereas above the minimum speed, the operational emissions dominate.

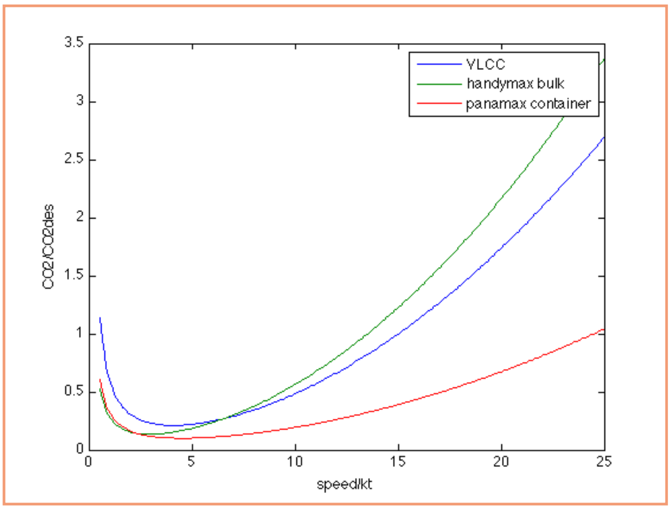


Figure 20: Relationship between operating speed and overall CO_2 emissions

In practice, there are commercial drivers of speed and safety issues which need to be taken into consideration, but these were omitted because the focus of this analysis was on understanding the trade-off between operational and embodied emissions: it shows that for all ship types considered, within the ranges of speed reductions currently under discussion, the limiting lower value of whole-system efficiency gains through speed reduction is unlikely to be reached.

The potential for take back (technical and operational efficiency)

Another paper (Smith 2012) considered the interaction between ship speed, technology-derived energy efficiency and the profit maximisation of ship owner/operators. Acknowledging that improved technology was associated with additional capital cost, and that lower speeds of operation affect both fuel costs and capital costs, a simplified model was developed to evaluate the sensitivity of the ship owner/operator's profits across a range of possible scenarios.

The model uses the same theoretical conceptualisation of technology and operational techno-economics as GloTraM, but over a simplified range of scenarios and for a single ship and technology type. The simplification was used to seek greater clarity on the emergent take-back phenomenon that was also appearing in the results from GloTraM.

Two technology cost scenarios were considered (high and low technology cost), and four combinations of the key economic parameters fuel price and freight rate (see Table 3). The results for the high technology cost scenario are presented in Figure 21, with the layout matching the scenarios listed in Table 3, i.e. the top left plot in Figure 21 corresponds to Scenario 1. In each scenario, 4 discrete technology uptake are considered (without being explicit about what the technology consists of), corresponding to changes in energy efficiency of 0, 10, 20 and 30%.

Table 3: Scenarios for combination of freight rate and fuel price

1. Low fuel price, low freight rate	2. Low fuel price, high freight rate
3. High fuel price, low freight rate	4. High fuel price, high freight rate

The results show that maximum profit occurs at a different speed and for a different level of technology uptake in each fuel price/freight rate combination.

The results also show that for any given level of technology uptake in each scenario, the speed at which profits are maximised is higher as the ship becomes increasingly more technically energy efficient (e.g. has a higher energy efficiency when measured at a benchmark speed).

This can be explained as being driven by two effects:

- the magnitude of cost savings through speed reduction diminish as a ship becomes more technically energy efficient through technology (i.e. in fuel cost terms, it becomes cheaper to ‘go fast’);

- the higher capital cost of the higher technology ships creates a further incentive for higher speed (as optimal speed is arrived at because of the relationship between a ship’s capital and operating costs).

While the model developed in order to illustrate this sensitivity omitted some of the features of real markets, for purposes of simplicity, this reveals that there is a risk of a take-back effect (gains in technical efficiency being offset by losses in operational efficiency) occurring in shipping if the wrong incentive or policy lever is used to attempt to create change.

This model also demonstrates the significant influence of the market (both fuel price and freight rates) on efficiency, and therefore on the emissions from shipping. Due to the theoretical framework adopted in Marginal Abatement Cost Curve analysis, which seeks to minimise total cost, rather than consider the responses of individual firms, this take-back effect has not been identified in previous analyses (e.g. IMO 2011). Therefore, this work was submitted to IMO MEPC 65 (IMO 2013), so that it could be incorporated in the ongoing debate on Market Based Mechanisms.

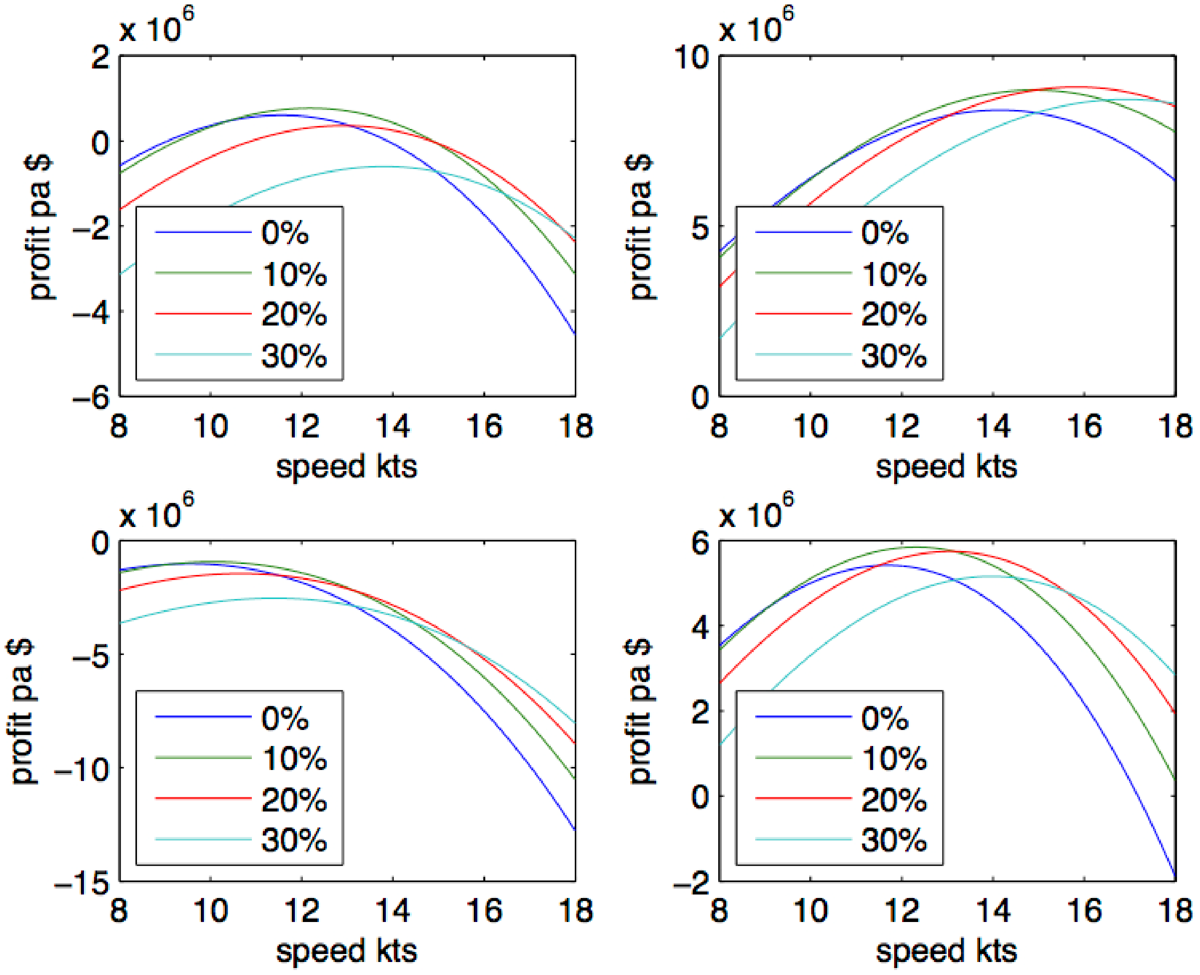


Figure 21: Curves of ship owner/operator profit against ship speed for four levels of energy efficiency technology uptake and in four scenarios (see Table 3) of fuel price/freight rate combination. The legend details three levels of energy efficiency uptake corresponding to baseline specification (0%) and investment in technology to achieve reduction in EEDI (10%, 20% and 30% respectively).

Future scenarios for shipping, and the role of alternative fuels

As well as adopting energy efficiency technology and operational changes (e.g. speed), shipping also has an option to adopt alternative fuels. GloTraM allows the consideration of a variety of fuel and machinery choices, both conventional (e.g. HFO and MDO with 2-stroke and 4-stroke machinery) and future fuels (e.g. LNG and Hydrogen both with internal combustion and fuel cell/electric propulsion technology).

As with energy efficiency and operational options, the metric for assessing the viability of different fuels and machinery is the maximisation of a ship owner's profits over a given timeframe. For this assessment, both future price scenarios of the different fuels, and their associated technologies (power generation and fuel storage) are required. The core fuel price scenarios are derived from the DECC (2011), and separate models are used to generate scenarios for both LNG and hydrogen prices (including considerations for the supply chain and infrastructure cost modifications).

The relative costs and benefits of different fuel choices are also influenced by the regulations on SOx and NOx emissions (particularly MARPOL Annex VI). For all fuels, particularly conventional fuels and machinery (e.g. HFO in 2-stroke engines), the impact of these regulations (e.g. additional costs due to scrubbers and/or Selected Catalytic Reduction or other NOx treatment) is taken into account and included in the model.

In addition to fossil and synthetic fuels, there are a number of biofuel options that exist for shipping, such as biogas, ethanol, etc. (Smith *et al*. 2013e). These are difficult to consider in a model with a system boundary limited to the shipping industry, and which incorporates no relationship between fuel price and demand. The characteristic between price and demand for biofuels is particularly important because it is anticipated that production rates could place constraints on supply and competition between different fossil fuel demanding industries for the share of biofuel supply (since all industries are under pressure to decarbonise), as well as competition for food production resources. To approximate these expected constraints, GloTraM is allocated a 'biofuel quota' or maximum bioenergy supply for each time-step. This quota is allocated across all fossil fuel demand and incorporated as a reduction in the operational fuel carbon factor.

Smith *et al*. (2013c) and Smith *et al*. (2013d) describe the derivation of cost assumptions and the method in greater detail. Smith et al. (2013e) and Smith et al. (2013f)) describe a range of results for different future scenarios. Figure 22 presents the output from two example scenarios for the GloTraM estimated fuels mix over the next 40 years. In Scenario 2, the sector is given the ability to offset 80% of its emissions by buying carbon permits from other sectors, whereas in Scenario 4, the share of emissions that can be offset is highly constrained (only 20% of the sector's carbon permits can be bought outside of the sector).

While the actual evolution of the many drivers of these different scenarios (fuel prices, trade and transport demand and regulation) is unlikely to map exactly onto the modelled scenarios, the important finding from this work is the frequent emergence of hydrogen as a future alternative marine fuel – from 2030 onwards.

Under a number of scenarios, LNG presents an advantage over the existing fuels (HFO and MDO), particularly with respect to non- CO_2 emissions. The favourable outlook on LNG fuel price also creates an incentive for its take-up. However, LNG remains a fossil fuel and whilst there are advantages in operational CO_2 emissions relative to HFO and MDO, the carbon factor of the fuel means that 2.75 tonnes of CO_2 are produced for every tonne consumed onboard (this can be contrasted with the carbon factor of HFO/MDO which is approximately 3.1).

These carbon emissions mean that with even (in relative terms), a modest carbon price (e.g. $3000/t, which is achieved in scenario 3 in 2050, in Smith et al. 2013e), the economics switch to a preference of zero-emissions hydrogen. This is in spite of the high capital costs of hydrogen fuel storage and energy generation technology, demonstrating how dominant the operating costs (driven by fuel cost) are relative to the capital costs.

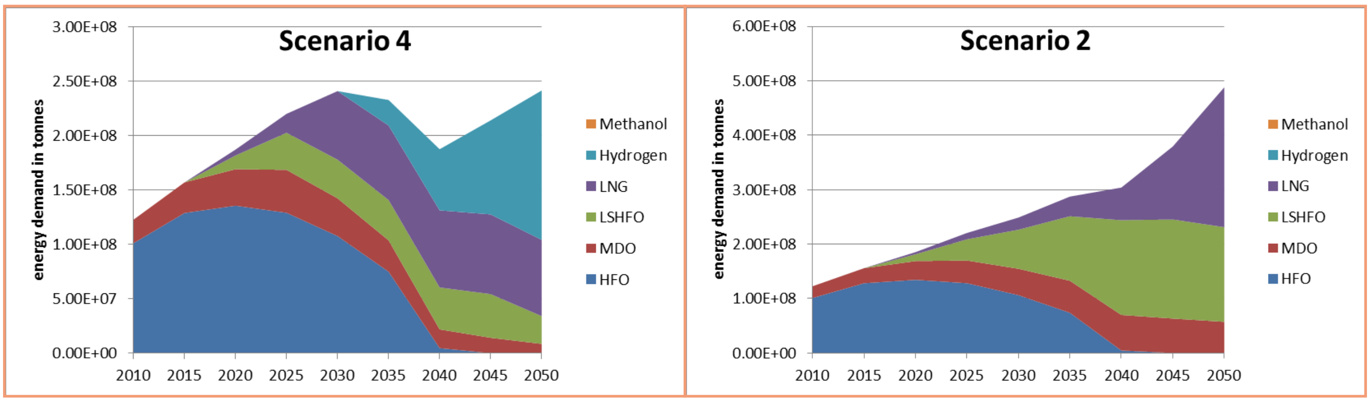


Figure 22: Possible future scenarios for the mix of marine fuels

The consequence of these alternative scenarios and the policy choices that create different CO_2 emissions trajectories for the industry are discussed in more detail in Smith et al. 2013e.

What Further Work is There and What Key Challenges Remain?

To date, the knowledge and analysis gained in WP1 has been disseminated into UNEP's Bridging the Gap report, the CCC's review of UK Aviation and Shipping Emissions, and OCIMF's submission to IMO and to IMO MEPC. GloTraM has been distributed to a number of shipping industry stakeholders and trialled, for its usefulness in developing strategic insights and research and development choices. Both the policy and commercial areas of deployment present a number of options for further development of GloTraM's inputs and models/algorithms. A number of these areas as discussed below.

Alternative future trade scenarios

The current approach uses an exogenously defined transport demand scenario, generated from a forecast for global trade. This approach was chosen for its simplicity and comparability to existing studies, which have used similar assumptions. However, the growth of the shipping industry, the turnover of the fleet and the future emissions are all highly sensitive to the transport demand. They could each, in turn, feed back to the transport demand, modifying its trajectory.

To endogenise transport demand in GloTraM would present a significant computational challenge. Other work (Faber et al. 2012) has linked to existing trade forecasts or alternatively energy system models might be able to be soft-linked to GloTraM, and allow a degree of iteration between transport demand and transport supply.

Another extension would be to develop alternative input transport demand scenarios to the IPCC SRES A1B scenario, which is the basis of the current demand forecast, e.g. allowing for different levels of global emissions mitigation not included in the current A1B scenario.

Both of these approaches would allow the sensitivity and robustness of the current scenarios to be explored. If integrated with trade modelling, this would enable the exploration of the impact of different shipping industry policy options on the economic development of regions and individual countries.

Market behaviour modelling

Analysis of the relationship between price and energy efficiency (Smith et al. 2013a), has revealed a level of complexity in the shipping markets that is not captured in the NPV formulation currently used in GloTraM. There appear to be differences in behaviour both between the different ship types and between the different types of firm that operate ships (owner/operators, time charterers, voyage charterers). Furthermore, as found in WP5, the specific charter party used can also create differences in the incentivisation of both investment and operational decisions.

In some of the scenarios forecast by GloTraM there is rapid technology change in the fleet, which would create greater differentials in the relative operating costs of different ships than those currently discussed in the context of today's alleged two-tier market. The influence that rapid technology change could have on the residual values of assets in the shipping fleet, affecting both refinancing, second-hand values and scrappage, is not currently taken into account in GloTraM.

There is therefore a need to further develop knowledge in this area. This can be done by analysing the historical transactions and prices, particularly to build further understanding in the representation of energy efficiency in the different markets and the competitiveness of the emerging 'ecoship' fleet. This understanding can then be used to refine the existing models of market behaviour used in GloTraM in order to improve the fidelity of technology and operational change modelling in the new and existing fleet. These improvements could be applied by shipping firms to assess the merits of different strategic decisions. However, this understanding and evidence base is also crucial for the assessment of the efficacy of emissions reduction of different MBM – particularly those which use carbon prices to incentivise change.

Regional modelling

Due to the international nature of UK shipping, and the influence of global transport demand on the turnover of the global fleet, GloTraM uses a representation of international transport demand (using both inter-region and intra-region transport demand). However, fleet activity, fuel price and fleet technology are assumed to be globally homogenous.

For the larger ships involved in international shipping, identified as the main focus of this work (see Context), and for current fuels (HFO, MDO), these assumptions are appropriate. However, they may no longer be appropriate in understanding the evolution of the smaller ship sizes which could be affected by regulation to a greater or lesser extent depending on local regulation in their region of operation (e.g. Emission Control Area specifications). Furthermore, regional differences could arise if future fuels such as LNG and hydrogen continue to lack a globally homogenous price. LNG already has a significant price spread between the US, Europe and Asia due to the regional differentials of supply and demand, the cost of LNG long distance transport and the constraints on the supply of LNG transport capacity.

For both of these reasons, the current assumption that globally homogenous fleets will continue to exist into the future requires reassessment, which could be achieved through the development of greater detail around the strategies employed for bunker purchasing, and the regionality of operation of different ship types and sizes.

Ship operation parameters

Smith et al. (2013a) outline the work done using S-AIS to evaluate the operational parameters of the existing fleet. The analysis of ship speed, carried out cross-sectionally for the year 2011, revealed significant homogeneity and a trend towards speeds lower than the ship design speeds quoted in databases such as Clarksons World Fleet Register, and assumed in emissions inventories (e.g. IMO 2ND GHG Study).

Extension of this analysis over a number of years to study speed trends longitudinally and their variance as a function of market parameters (e.g. fuel price and freight rate) could produce valuable insights with GHG policy design applications. The existing study also demonstrates that significant uncertainty remains around some important operational parameters, for example capacity utilisation. Figure 23 demonstrates the data captured from S-AIS on capacity utilisation of the crude tanker fleet. The origin of the data is the draught measurement reported over AIS, a manually entered field which is subject to measurement error even before it is used to estimate the payload mass. However, taking into consideration this uncertainty, the data reveal a wide variability between different ships. Capacity utilisation in terms of number of loaded and ballast voyages, and average payload utilisation when loaded are important for understanding both the relationship between transport demand and theoretical transport supply (the fundamental determinants of freight-rates), and the operational efficiency of the fleet (lower capacity utilisation leads to lower efficiency).

Whilst further work, at least for speed, can be carried out using longer time-series of AIS data, the analysis of capacity utilisation needs to be combined with a number of data sources (trade data, fixture data) in order to cross-reference the trends observed and validate against other sources. However, if successful this could bring valuable insights both into the current efficiency of the market, and the behaviour and trends of these parameters over time (in response both to policy and market forces).

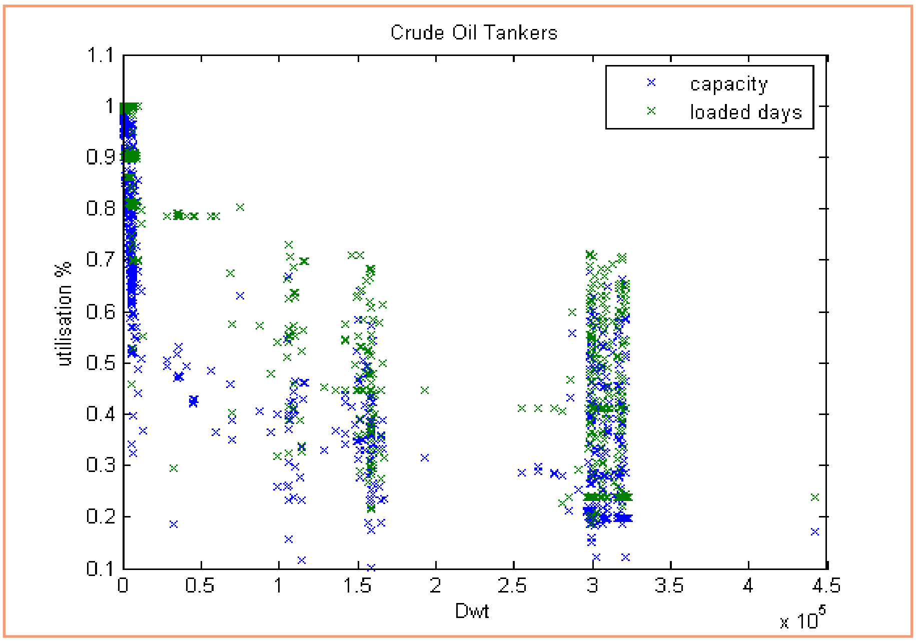


Figure 23: Average capacity utilisation and ratio of loaded days to days at sea, crude oil tanker

Dissemination

Argyros, D. Smith, T.W.P., Sabio, N. Raucci, C. (2013) Evaluating scenarios for alternative fuels in international shipping. LCS 2013.

Smith, T.W.P, Newton, P. Winn, G, Grech La Rosa, A. (2013) Analysis techniques for evaluating the fuel savings associated with wind assistance. LCS 2013

Aldous, L., Smith, T.W.P. (2013) Noon-report data uncertainty. LCS 2013

Haji S., O'Keefe, E., Smith, T.W.P. (2013) Estimating the global container shipping network using data and models. LCS 2013.

Smith, T.W.P., O'Keeffe E. (2013) GloTraM user guide. UCL, London.

Smith T.W.P, O'Keeffe, E., Haji, S., Agnolucci P. (2013c) GloTraM external factors. UCL, London.

Smith, T.W.P, O'Keeffe, E., Haji, S. (2013d) GloTraM method. UCL, London.

Smith, T.W.P., Haji, S., Sabio, N., Mangset, L.E. (2013e) Analysis of policy options to bridge shipping's emissions gap. UCL, London.

Smith, T.W.P., Sabio, N., Raucci, C., Argyros, D. (2013f) Alternative fuels for international shipping.

O'Keeffe, E. (2013) Agent-Based Modelling of the global dry bulk shipping sector.

26th European Conference on Operations Research, Rome, July 1-4, 2013.

O'Keeffe, E. (2010) Shipping and trade: a vulnerability analysis. CCCEP PHD Symposium, London, September 15, 2010.

Parker, S. (2013) A matching model of the oil tanker industry. LCS 2013

Parker, S. (2013) The influence of agent choices and spatial dynamics on tanker movements. Energy Working Group on Financial Commodities.

Parker, S. and Smith, T.W.P. (2013, working paper) Contract Type and Speed. UCL, London

Parker, S. and O'Keeffe, E. (2012, working paper) Mapping Tanker Movements to a Network. UCL, London.

Smith T.W.P., O'Keeffe, E., Aldous, L., Agnolucci, P. (2013a) Assessment of shipping's efficiency using Satellite AIS data. UCL, London.

Smith T.W.P. (2012) Technical energy efficiency, its interaction with optimal operating speeds and the implications for the management of shipping's carbon emissions. *Carbon Management* (2012) 3(6), 589-600.

Aldous, L., Smith, T.W.P. (2012) Speed optimization for Liquefied Natural Gas Carriers: A techno-economic model. LCS 2012.

Smith, T.W.P., O'Keeffe E. (2012) LCS Review of CCC's Review of UK Shipping Emissions. UCL, London

Calleya, J.C., Pawling, R., Smith, T.W.P., Greig, A. (2012) Ship Design and Evaluation for a GHG Constrained Future. RINA The Environmentally Friendly Ship Conference. London.

UNEP (2011) *Bridging the Emissions Gap.* United Nations Environment Programme.

King, D.A., Inderwildi, O.R. (2012) "Low Carbon Shipping", in Energy, Transport and The Environment

Smith, T.W.P., Parker, S., Rehmatulla, N. (2011) On the speed of ships. LCS 2011.

Smith, T.W.P., Barrett, M., Parker, S., O'Keeffe, E. (2011) Initial estimates on shipping's cost impacts and emissions for a range of policy options. LCS 2011

Smith, T.W.P., Bucknall, R.W.G., Dinwoodie, J., Gibbs, D., Mangan, D.J., Turan, O. (2010) "Low carbon shipping – a systems approach" in *Proceedings of RINA Ship Design and Operation for Environmental Sustainability.* London

References

Dinwoodie, J. (2010) Slow steaming and low carbon shipping: revolution or recession? LRN 2010

Faber, J. Pahuja, N. Garg, A. (2012) Raising Climate Finance from International Transport Sectors. Climate Strategies, Cambridge.

Newton, S. (2009a) WORLDNET Final Report. Available at

http://www.etisplus.eu/documents/Public/Archive Worldnet/D11 WORLDNET Final Report.pdf (last accessed July 2013).

Newton, S (2009b) WORLDNET: *Applying transport modelling techniques to long distance freight flows.*

IMO (2011) MEPC 61 Inf. 18. *Marginal abatement cost and cost-effectiveness of energy-efficiency measures.* IMO, London.

IMO (2013) MEPC 65/4/19. *Proposal of the United States to enhance energy efficiency in international shipping.* IMO, London.

DECC (2011) *Oil and Gas Price Trajectories.* DECC, London.

WORK PACKAGE 2

TECHNOLOGIES AND SHIP DESIGN FOR LOW CARBON SHIPPING

Led by Professor Sandy Day with support from Professor Richard Bucknall, Professor Atilla Incecik, Professor Pelin Zhou, David Clelland, Professor Mehmet Atlar, Dr Alan Murphy, Dr Michael Woodward, Dr Rachel Pawling, Dr Alistair Greig, John Calleya, Panos Mouzakis, David Trodden, Rankumar Vijaykumar, Ben Howett, Dr Mahdi Khorasanchi, Gonzalo Azqueta, and Jiqing He.

WP2 – TECHNOLOGIES AND SHIP DESIGN FOR LOW CARBON SHIPPING

Led by Professor Sandy Day with support from Professor Richard Bucknall, Professor Atilla Incecik, Professor Pelin Zhou, David Clelland, Professor Mehmet Atlar, Dr Alan Murphy, Dr Michael Woodward, Dr Rachel Pawling, Dr Alistair Greig, John Calleya, Panos Mouzakis, David Trodden, Rankumar Vijaykumar, Ben Howett, Dr Mahdi Khorasanchi, Gonzalo Azqueta, and Jiqing He.

Overview

WP2 was the largest and most diverse of the six work packages of the project. Three key aims were stated in in the original proposal:

1. To explore the range of technical solutions that offer potential for reduced carbon emissions from ships
2. To identify key areas where such technical improvements can be made:
    - in the short term via retrofit to existing ships;
    - in the medium term via improved design of new build ships;
    - in the longer term (i.e. to 2050) through radical new concepts;
    - examining synergistic aggregations of small gain as well as emerging technologies which might offer step-changes.
3. To provide techno-economic and ship modelling input to GloTraM, the global shipping system model being developed in WP1

The research effort was essentially divided between three tasks: the first task addressed technical solutions related to improvements in ship and propulsor hydrodynamics; the second looked at technical solutions related to marine engineering systems, including main and auxiliary engines and fuels; and in the third task a ship impact model was developed which could be used to identify the impact of technologies on the ship design in a holistic sense, and act as an interface between the technology assessments of WP2 and the global shipping model developed in WP1. The key technologies identified for assessment in the original proposal are listed below.

Ship and Propulsor Hydrodynamics:

- Hull form design for reduced resistance in realistic conditions
- Design/operation of vessels for reduced resistance in ballast condition
- Retrofit hydrodynamic technologies
- Development of propulsors for improved efficiency in realistic conditions
- Integration of renewable technology including wind

Marine Engineering Systems:

- Improved efficiency of main engines
- Improved efficiency of auxiliary systems
- Carbon reduction via introduction of new fuels
- Onboard application of Fuel Cells
- Integration of renewable technology including solar

Within these areas, the range of specific technologies available is wide; and resources for the WP were strictly limited. Furthermore, after the project started, industry partners requested that some additional technologies were considered. Hence the technologies were divided up for assessment purposes to be assessed on one or more of three levels:

1. **Complex analysis:** Assessment using high-fidelity first principles approaches
2. **Simple analysis:** Assessment using simple models based on simple physics-based assessments or fitting to data from other studies
3. **Peer review:** Assessment using data gathered from literature

For each technology a simple model was developed from the data obtained from the technology assessment study, at whichever level was chosen, which could capture the impact on the ship in terms of key design parameters. Compatibility issues were addressed in a simplistic manner by excluding combinations of technologies identified as incompatible.

In parallel with the two technology assessment tasks a ship impact model was developed for each of the ship types considered in the LCS project as a whole; the model represents the interactions between design parameters allowing a full understanding to be developed of how the ship design is affected by incorporation of technologies – for example reflecting not just impact on hull resistance, or engine efficiency, but also on stability, lightship and capacity. Design Models were then utilised to generate the ship database, which provides key data for the GloTraM.

The responsibilities for these studies were divided between three partners as shown in Figure 24, whilst the relationship between WP2 and the wider project is shown in Figure 25: WP2 Relationship with LCS Shipping model Figure 25

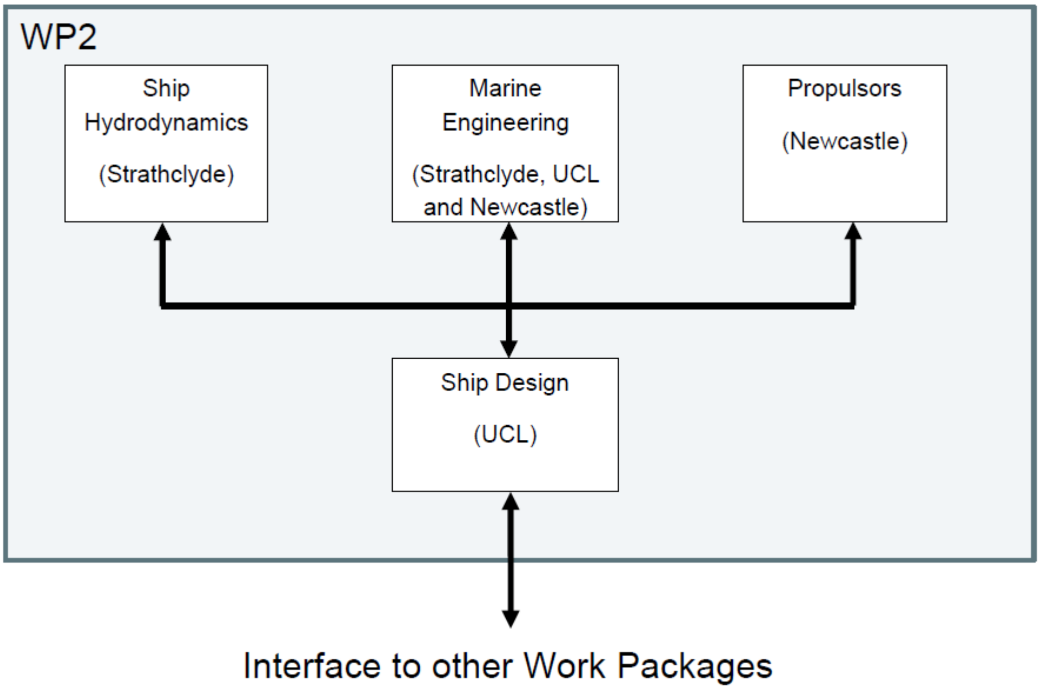


Figure 24 Relationship between sub-tasks in WP2

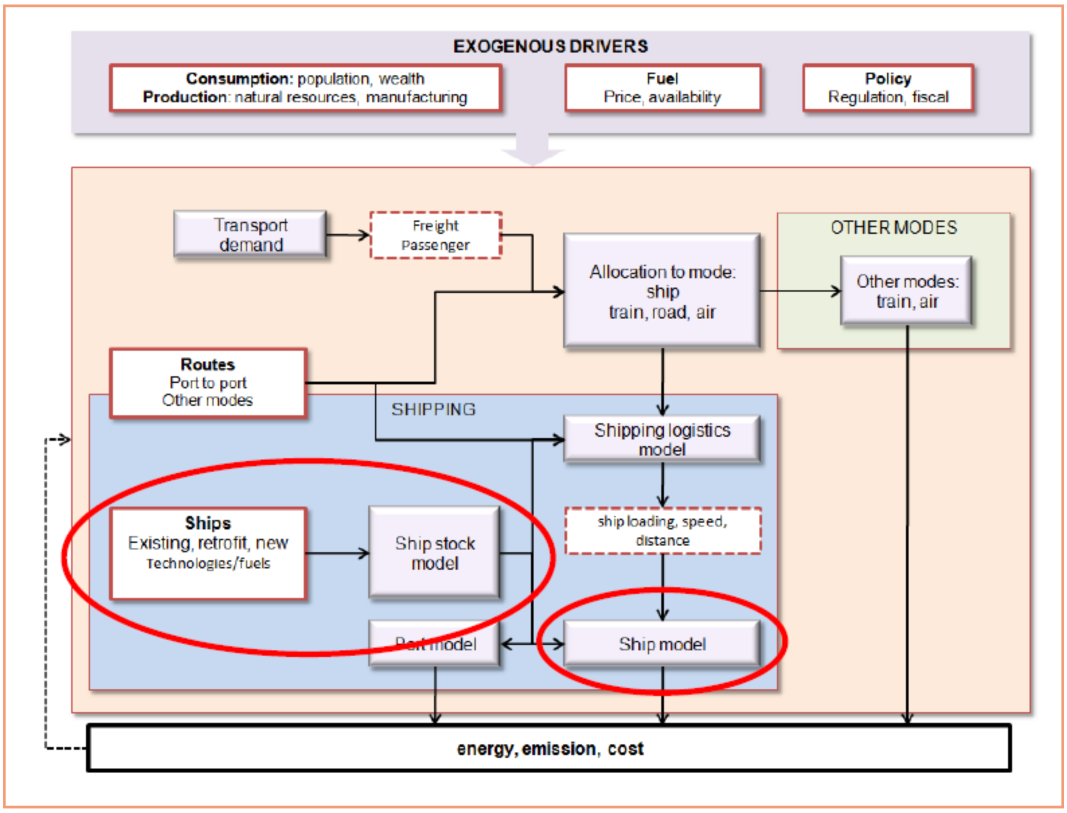


Figure 25 WP2 Relationship with LCS Shipping model

Ship and Propulsor Hydrodynamics Output and Key Findings

Hull form design for reduced resistance in realistic conditions

This study aims to improve the efficiency of a range of ship types by offering reduced resistance through improved hull form design for operation in realistic operational conditions. The study examines incremental improvements through refinements in conventional hull forms, whilst also exploring opportunities for radical changes based on new operational procedures relating to ballast loading and trim. Improvements will be assessed across the entire mission profile including both loaded and ballast conditions and in a range of expected sea-states.

Naval architects have been interested for thousands of years in improving performance in terms of either increasing speed or reducing powering requirements. Since the introduction of modern computational techniques for predicting resistance, many formal optimisation schemes have been adopted in order to improve hull shape and reduce resistance. In most cases, however, the optimisation is carried out for conditions that do not accurately represent the typical operating environment for the ship. Traditionally the resistance is minimised for calm water conditions at a design speed and full load condition. In reality, the ship will operate in a range of sea states, speeds and loading conditions, and the optimal design for these real-world conditions may well be different from a design optimised for calm water. The present study is designed to explore the potential benefits of optimising ship hull forms for realistic operating conditions.

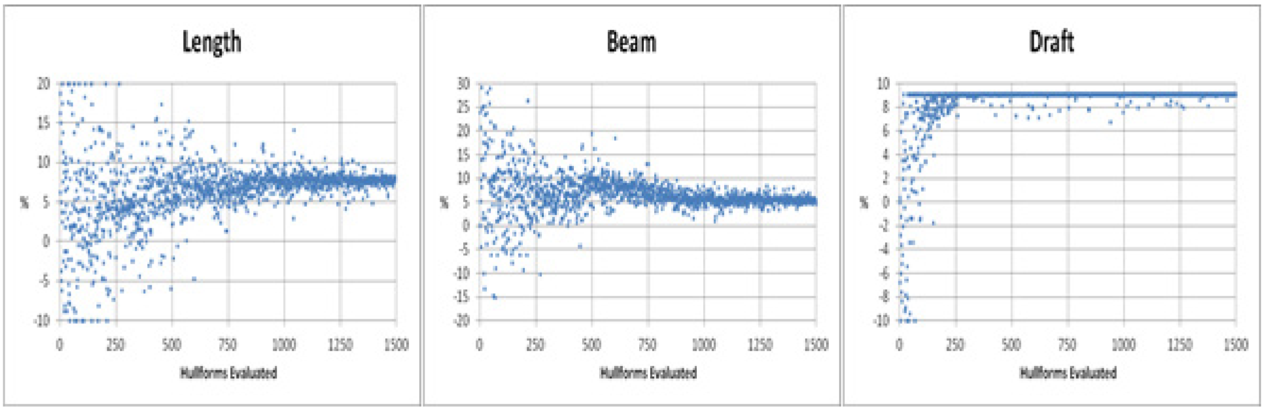


Figure 26 Evolution of ship dimensions during optimisation example

A software package was developed which incorporates a series of modules for the analysis of vessel performance, the modification of a basis ships form parameters and the optimisation of these parameters to produce a new, more efficient ship with lower carbon emissions. The software is primarily written in VBA (Visual Basic for Applications) with Microsoft Excel, and communication with third party analysis programs is achieved via the Microsoft COM interface. The program is constructed from a number of modules. These include analysis modules for the calculation of the resistance of the chosen vessel in both calm water and in waves, as well as vessel stability and motions. Further modules calculate the weight of a vessel based primarily on its principal dimensions and powering requirements, and describe the environment in which the ship operates. The objective function is based on the carbon emissions of the vessel over a range of sea states representative of a real round-trip voyage, and can account for speed variation between different sea states. The model can run in a relatively simple manner in which the geometry is optimised while trim and displacement are kept constant, or it can explore radical solutions for the ballast leg of the voyage, simultaneously modifying the geometry and de-ballasting the ship where appropriate in moderate conditions subject to restrictions on stability slamming and propeller immersion.

In order to explore improvements, a robust new method of generating potential hull forms is used. This function allows a thorough search of the design space in order to explore new design possibilities, while maintaining favourable features and preserving fairness. A semi-stochastic optimisation technique is used to assess the success of each generation of new hull forms evaluated and evolve future, improved generations.

The results presented here are for a 100,000 tonne LNG carrier, and the ship chosen is an example of a real vessel, currently in operation in the worldwide fleet so as to demonstrate that any savings found are meaningful, and not simply improvements over a theoretical design. A significant reduction in CO_2 of the order of 16% is possible, but in order to achieve these changes a substantial change must take place in the overall dimensions of the ship. This does mean that these improvements may not be practical when more realistic constructional, operational and financial constraints are imposed, but they are indicative of what may be achieved given a blank canvas.

Figure 26 illustrates how the principal dimensions for the population change as the optimisation procedure progresses. It is interesting to note that draft rapidly increased within the first few generations and was quickly limited by an artificial depth constraint imposed to simulate typical port depth restrictions for a vessel of that type. The basis and optimised vessels are presented in Figure 27. It is apparent from the results how a modest increase in principal dimensions of length, breadth and draft has contributed to redistributing the volume of the ship, allowing for reduced entry and exit angle and smoother waterlines and buttocks.

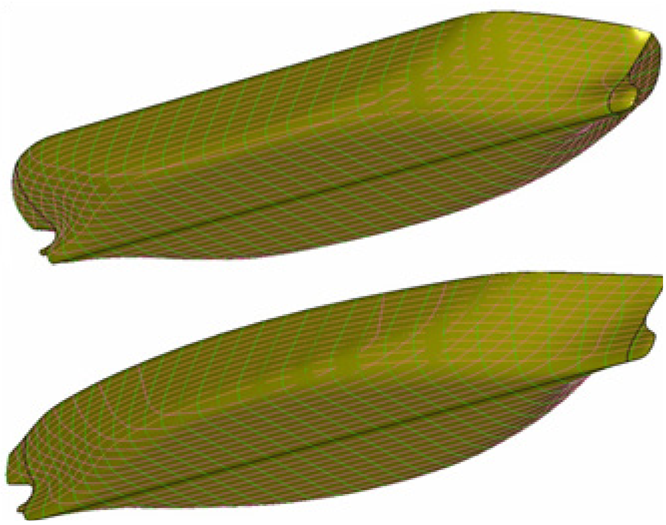
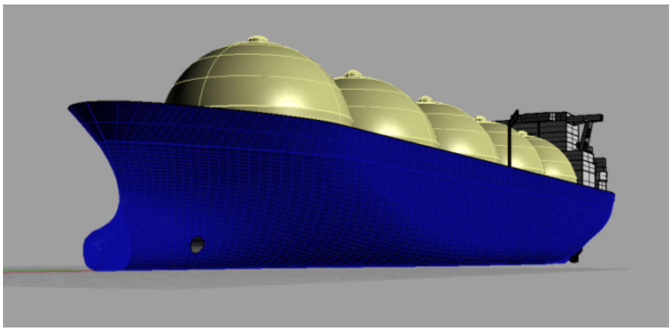


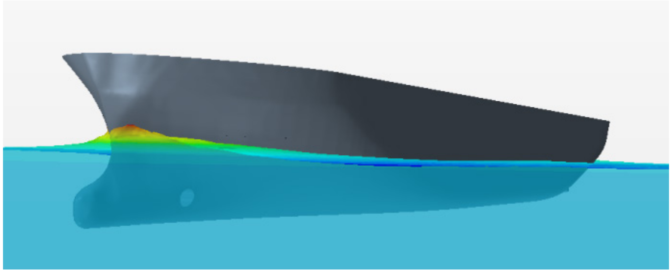
Figure 27: Basis form and optimised geometry

Retrofit solutions for flow modification on existing hulls

It takes many years for new generations of ships to be built to replace existing fleets. In the meanwhile, there is a need for retrofitting technologies to improve the hydrodynamic performance of existing ships and reduce CO_2 emission. This task of the LCS project aims to provide independent evaluation of the capability of these technologies. This task examined a set of devices suitable for retrofitting onto existing ships with the aim of assessing the likely gains in ship performance. Device manufacturers often promise substantial performance gains in terms of reduction in fuel consumption and eventually carbon emission. However, some of the proposed figures seem to be very optimistic and need independent evaluation.

These devices are small with respect to ship scale and in many cases operate predominantly or entirely within the ship hull boundary layer. Since model scale testing is typically based on Froude similarity, the boundary layer is not correctly represented, and hence the extrapolation of the performance of devices operating in the boundary layer from model to full scale will be unreliable. As a consequence, full-scale modelling is required to generate reliable results. In the current study a full-scale RANS CFD model was adopted using the STAR CCM+ code running on a high-performance computer at Strathclyde.





The majority of early runs were carried out using an LNG carrier for which extensive data including detailed hull and propeller geometry, model test and trials data was made available by one of the industrial partners. In the first instance ship resistance was evaluated without propeller. This was then complemented by a simulated open-water propeller test in order to develop propeller characteristics, allowing the implementation of a momentum source model of the propeller, identification of the self-propulsion point, and successful validation for the baseline ship against full-scale trials. A series of studies was then implemented examining the impact on the balance between resistance and propulsion at constant ship speed and RPM resulting from installation of some pre- and post-swirl devices. Results suggested that that the momentum source propeller model was not adequate to correctly reflect the relatively subtle changes in local flow caused by these devices; a more sophisticated multiple reference frame (MRF) model of the propeller was then implemented, correctly representing the detailed geometry of the propeller but at a fixed rotational position. Finally some selected runs were carried out using a sliding mesh representation of the propeller modelling fully detailed geometry, including the effect of rotation.

It was noticeable that some technologies affected both resistance and propulsion, and so assessing device performance at constant ship speed and propeller RPM did not give the full picture of the device's impact on carbon emissions. Hence the approach ultimately adopted was to fix ship speed and vary RPM until the self-propulsion point was achieved, and compare the delivered power. It is important to note that as the accuracy of propeller modelling increased from momentum source to MRF to sliding mesh, and as the performance metric was changed from force balance to power at self-propulsion, the predicted power savings reduced each time, demonstrating the importance of highly accurate modelling. It is suggested that many manufacturers' claims are not based on models as sophisticated as that adopted here, and that this is a key reason why savings predicted in this study are generally substantially lower than those claimed by manufacturers.

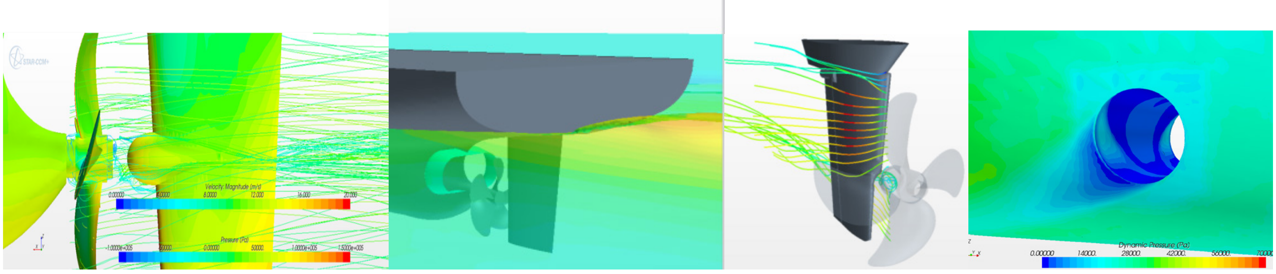


Figure 29 Selected technologies modelled: Propeller-Rudder Bulb; Wake Equalising Duct; Advanced Rudder; Bow Thruster; Tunnel closure

Initially, a set of ten retrofit technologies was installed on a LNG carrier and the ship performance with and without each of these technologies was analysed. These technologies include a new bulbous bow, closure of thruster tunnel, wake equalising duct (WED), rudder stator fins, rudder-hull integration, stern modification with fishtail device, NPT propeller, twisted rudder, costa-bulb rudder and, finally, a combination of stern technologies. Next, the effect of vessel type on the performance of these technologies was investigated. To this end, some of these technologies were applied to a Kriso container ship (KCS) and a tanker. Pre-swirl fins, WED, and rudder-propeller distance were the three technologies investigated on the KCS. The potential saving achieved by trim optimisation of the tanker in ballast condition was also quantified. Moreover, the hydrodynamic performance of vessels with the following technologies was investigated: two types of WEDs, a combination of WED and preswirl fins, a twisted rudder and propeller boss cap fins.

In all cases, the level of savings obtained from these technologies was lower than the values published in the literature; in many cases substantially so. There are two possible explanations for this discrepancy. Firstly, many previous studies are based on either model-scale physical tests or simplified CFD models; it is possible that either the method or metric (or both) adopted in these studies is not appropriate for performance prediction of these devices at full scale. Secondly, it might be argued that the devices in the present study did not deliver the expected savings because the designs in this study were not suitably optimised. In this case, the question then arises that if these devices must be optimised for a given ship in specific operational conditions, it is unclear how the devices behave when the vessel is operating in off-design conditions.

In addition to assessing the amount of gain for each technology, this study showed that the effect of a combination of technologies is not necessarily cumulative and any combination of devices should be analysed individually.

Design of Propulsors for In-Service Conditions

This study focuses on the development of a methodology for improved propeller efficiency by 'design for in-service conditions'; rather than steady state, dead-ahead conditions. Ship's propellers are usually optimised around a design point, taken at steady dead-ahead design speed. However, in the day-to-day operation of the ship, the loads on the propeller are heavily influenced by the manoeuvring performance including the ship's response to its environment. This effectively means the propeller is operating in the off-design condition. This research explores the design for ship-in-service philosophy and develops a methodology to exploit potential efficiency improvements.
The objectives of the research were: to model mathematically the motions of a ship in a seaway, and the response of the propulsion and steering systems; to determine a methodology for optimising a propeller for ship-in-service conditions; and to analyse factors affecting propeller performance of a ship in a seaway.

The motions in surge, sway and yaw of a ship and its response to a seaway have been modelled with non-linear ordinary differential equations. These have been solved in the time-domain using a fourth-order Runge-Kutta method. A disturbing force (wind) is applied to the ship and an autopilot ensures that the ship will arrive at the destination on time. (It is assumed that the weather never gets so bad that the captain needs to reduce speed voluntarily). In order to model the thrust and torque on the propeller in non-uniform flow, a modified

Blade-Element Momentum method is adopted. A new propeller optimisation cycle has been proposed for design for ship-in-service conditions as shown in Figure 30 below. This approach provides not only a good estimation as to the sea-margin, but also an analysis tool for propeller design, by accounting for the drift angle and flow vectors at the propeller plane.

The first step of the procedure is to optimise a propeller for a particular ship and operating profile (the basis propeller). This ship and propeller combination is then run through the simulator for a route that approximates the real ship's route. The optimisation process continues as shown below. The resulting final propeller is then compared against the original basis one to establish improvements in efficiency.

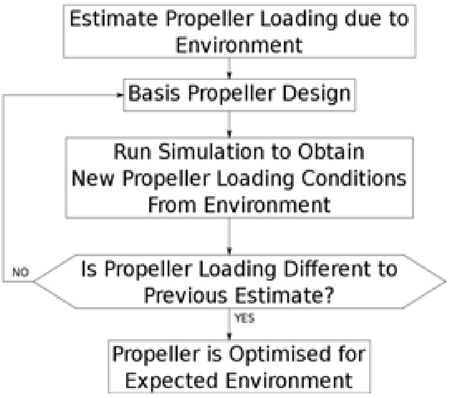


Figure 30 Proposed propeller design procedure for in-service conditions

Results are found to depend strongly on the ship type and operating profile. For ships that are subject to large forces from weather, e.g. container ships, improvements in efficiency over the basis propeller were found to be as much as 1.5%; efficiency improvements for ships for which weather loading is less significant, such as fully-laden VLCCs, may be of the order of 0.5%.

Wind Assist

All renewable energy technologies were addressed by simple modelling in the present study. The key challenge identified was the need to integrate further with WP1 and develop an approach that would allow a representative weather model for each route in the global shipping model. In the present version, the approach uses globally averaged weather data, which both underestimates performance on most routes for which these technologies are well-suited, and simultaneously overestimates performance on other routes. A possibility for exploring 'niche' trades and corresponding 'niche' solutions, involving modification both the ship design, routing and speed, should be included in future generations of the model to allow these technologies to be adequately represented.

In the present study it was initially proposed to use a global annual average wind speed to assess technology performance, with a uniform probability of all heading angles. Data shows that a suitable value would be around 14-15 knots. However, wind assist is typically only of marginal benefit in many conditions when true wind speed is less than ship speed; therefore, simply adding wind assist to conventional ships, operating at conventional speeds on conventional routes, leads to unrealistically low savings. Instead, a distribution of wind-speeds based on a study of an equatorial route was used. The present study still assumed the true wind direction to be equally distributed over all possible directions, suggesting that utilisation of realistic prevailing wind data for particular routes would lead to predictions of higher savings.

Three different types of wind assist technologies were considered: conventional soft sails, kites, and Flettner rotors (see Figure 31). Three types of soft sail rigs were considered, based on rigs of existing superyachts. In all cases, the rig performance was simply based upon typical published values of lift and drag coefficients for different apparent wind directions. Particular challenges were identified as selecting an appropriate approach to sail-plan sizing in the absence of stability data, and identification of limiting wind conditions under which sails can operate. For the purposes of the current study a simple approach relating sail-plan area to hull profile area (waterline length x draught) was adopted.

Results show that under the assumptions adopted for the wind speed and direction and ship speed none of the wind assist solutions appears to be very beneficial. However, for ships sailing relatively slowly it is possible that worthwhile benefits could be found on routes with suitable prevailing wind directions. Flettner rotors appear to offer improved performance over conventional sails or kites, but most data is based on relatively small scale or computational studies, and the technical issues related to the energy consumption and the durability of the rotor drive system may not be completely resolved.

Figure 31 Soft Sails and Flettner Rotors

Marine Engineering Output and Key Findings

Two-Stroke Diesel Engine investigations

A down select of the most promising technologies had to be undertaken after one year, with the two-stroke diesel engine, waste heat, and advanced electrical technologies becoming the main focus for more detailed analysis. The rationale was that most merchant ships use the two-stroke diesel engine with waste heat recovery, aside from LNG tankers for which the future order book is dominated by diesel-electric propulsion.

The two-stroke slow-speed crosshead diesel engine plays a significant role in the marine engineering of merchant ships including tankers, bulk carriers and container ships. The two-stroke diesel engine is also used in LNG carriers but steam propulsion and diesel-electric propulsion are more common. The main manufacturers of two-stroke diesel engines are Wartsila, MAN B&W, and Mitsubishi.

Two-stroke slow-speed diesel engines are large and heavy engines when compared with the medium- and high-speed diesel engines but are offered across a wide range of powers and operate with higher efficiency compared to other prime movers across the power range. The two-stroke diesel engine is characterised by low revolutions, which allow direct shaft connection to the propeller to minimise transmission losses. Such engines have the ability to operate in either direction of rotation for ahead and astern manoeuvring via camshaft position control. They burn low grade fuel oils (e.g. IFO 180), refined diesel fuel (e.g. DMA), and are now being developed to operate on LNG. The main attraction of these engines for the ship owner is their high efficiency, which increased from around 42% in 1980 to around 50% in 2010 (i.e. in modern diesel engines).

The basic dimensions of a two-stroke diesel engine are bore (cylinder diameter) and stroke (the distance the piston moves between top dead centre (TDC) and bottom dead centre (BDC)), upon which the swept volume (displacement) can be calculated and from this the bore-stroke ratio. A review of engines shows that in practice the bore-stroke ratio is governed by two important factors: the compression ratio and the combustion chamber shape. Whilst high compression ratios are desirable to increase maximum engine efficiency, this is limited by the structure required to support the combustion process: a higher compression ratio requires a stronger and heavier engine. Furthermore, the shape of the combustion chamber (the space between the piston crown and cylinder head when the piston is at TDC) is important in that it must provide an acceptable depth-to-diameter ratio so fuel can be mixed with the air uniformly to ensure combustion efficiencies of up to 100% while there is a maximum mean piston speed typically around 8m/s. The compression ratio, combustion chamber design and maximum average piston speed must be balanced in the design of a two-stroke diesel engine to achieve the required performance. In addition, the marine engineering plant makes use of waste heat from the two-stroke diesel engine by using the jacket water with evaporators to generate fresh water and exhaust gas waste heat recovery systems to reclaim the energy for heating (e.g. on crude oil tankers) and electricity (turbo-generators). Both systems are designed to ensure maximum heat recovery at normal operating speeds, ensuring that exhaust gas exit temperatures from the funnel are maintained at c.170oC, i.e. above the dew point of acids. Having established the current status of two-stroke diesel engines Panos Mouzakis at UCL considered what, if any, improvements to the two-stroke diesel engine and associated plant could be made to further increase its efficiency. The study considered fuel types, engine design, transmission, propulsor and waste heat recovery, and consisted of the development of computer-based models supported by analytical study.

The main findings, pointing to the likelihood that engine efficiency would improve in the future using some or all of the methods studied, are listed below.

- Switching to a low carbon fuel such as LNG potentially offers significant savings in CO$_2$. However, the technology is relatively immature, leaning on four-stroke dual-fuel diesel engines developed primarily for LNG carriers. Developments to enable the introduction of gas injection for two-stroke engines are underway using R&D programmes such as the HELIOS programme and using test engines such as the 4T50ME-GI research engine. More recently, new ship orders for 2016 using two-stroke engines with gas injection have been received e.g. by TOTE and Teekay LNG partners using the MAN B&W dual-fuel 5G70ME-GI engine in container ships and LNG tankers respectively.

- Engine de-rating provides a simple method for CO_2 reduction and has been commonly used to reduce fuel consumption. The engine's contracted maximum continuous rating (CMCR) can be selected at any point in its power/speed layout field: hence, an 'oversized' engine de-rated to a lower CMCR will give a lower fuel consumption at the operating design point. It was shown that engines with the same number of cylinders offered the highest savings e.g. the Wartsilla 6RT-flex50-D offers a c. 2.5% fuel saving over the standard 6RT-flex50. If a de-rated engine with an increased number of cylinders is selected then the savings are somewhat reduced due to increased friction of the extra cylinder and piston.
- Using power take-in and power take-off enables the main engine's torque characteristic to be modified so it can be operated at its maximum efficiency for a given speed.
- Electronic engine control optimises the fuel injection point in the thermodynamic cycle to maximise engine efficiency. Similarly, exhaust valve control allows variable timing to maximise scavenging. Electronic control allows combustion efficiency improvements and thermodynamic cycle improvements. Digital electronic control is now adopted widely on all diesel engine types.
- Conventional turbo-chargers are designed to have maximal efficiency at a single point, usually the normal operating speed of the engine. Variable geometry turbocharging allows increased efficiency across a range of speeds, thereby allowing optimised scavenging and a more efficient engine. Where ships operate across a range of powers and speeds then optimised scavenging is essential to achieve good efficiency.
- Reducing maximum revolutions of the engines reduces friction loss within the engine and thereby improves engine mechanical efficiency. Furthermore, a reduced engine speed also improves propeller efficiency, usually through larger diameter slow-speed propellers. This is seen in Figure 32 where the recent 7G80ME-C engine achieves an overall efficiency increase of 4.5% when compared with a 7S80ME-C9, due to a combination of a slower speed engine and larger diameter propeller.
- Increasing the bore of the engines reduces friction loss per unit of power produced, although combustion efficiency could be compromised if the combustion chamber is not optimised. The use of computational fluid dynamics has helped in optimising the design of combustion chambers.
- Waste heat recovery offers increased marine propulsion plant savings. The primary savings are made through using fresh water evaporators and through exhaust gas waste heat recovery plant. Development of a waste heat recovery model shows that the reclaim of the heat captured depends upon the inlet and outlet temperatures and mass flow rates. Whilst mass flow changes almost linearly with engine speed the inlet temperature to the exhaust gas unit changes with load in a non-linear way. At the engine design point the exhaust gas inlet temperature may fall to minimum values but rise at lower speeds when the engine is less efficient. The performance of the exhaust waste heat recovery plant depends upon its inlet temperature, which in turn depends upon engine and turbo-charger efficiency.

Research into two-stroke engine design using modelling methods has shown that the two-stroke diesel-engine has the potential for further development towards increased efficiency in the coming years. However, the Carnot Limit means that ultimately it is unlikely ever to improve its efficiency beyond around 55%, and to achieve this the NOx treatment must be off-engine because on-engine systems tend to reduce efficiency, as does the use of emulsified fuels. Further efficiency gains can be made using waste heat recovery utilising feed-water pre-heating and an exhaust gas waste heat unit, but the paradox of increased engine efficiency means lower exhaust gas temperatures, which in turn mean a smaller steam-generating unit. A switch to LNG with a lower Carbon Factor and low exhaust will reduce CO_2 emissions and slightly increase engine efficiency due to the more Otto cycle characteristic of the thermodynamic cycle.

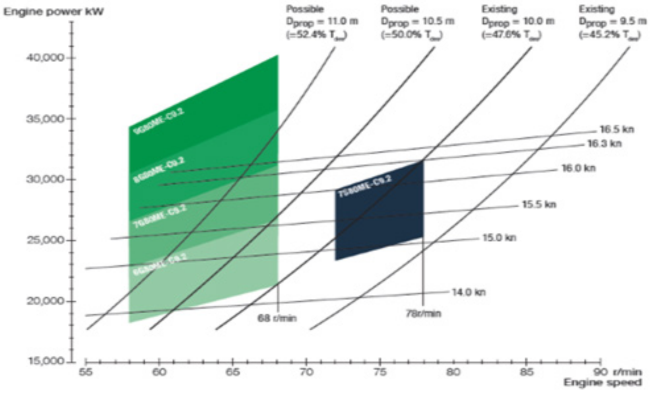


Figure 32. The application of a 7G80ME-C will give an overall efficiency increase of 4.5%, compared with a 7S80ME-C9 or an alternative engine with the same engine speed

Marine engineering propulsion systems are developing and the technology is improving, with future machines offering efficiency gains over existing technologies. The two-stroke diesel engine propulsion system is likely to improve its efficiency over time through a combination of improvements, rather than a via specific step-change in technology. A slow-speed long-stroke diesel engine operating on LNG fuel with digital electronic control to optimise injection, exhaust valve and turbo-charger (scavenge) performance, together with a waste heat recovery system, can be expected within a few years. In the long term, however, it is difficult to see what else can be done to further improve slow-speed diesel engine efficiency performance beyond 2020.

Electrical Propulsion

An electric propulsion system consists of prime-movers, an electric transmission, and a propulsor (usually a fixed pitch propeller). Such propulsion arrangements are being used in LNG tankers. The electric drive consists of generators, power converters and propulsion motors. In today's propulsion arrangement, the generators operate at constant speed: the power converters take a fixed frequency, fixed voltage supply and convert it to a variable voltage, variable frequency to drive the propulsion motors. In modern electrical propulsion there may be two motors connected to the fixed pitch propeller via a reduction gearbox or a larger single double-wound motor driving the propeller directly. It is not clear, from a technical perspective, why a reduction gearbox is used in some designs. The argument for weight and space saving appear weak and the argument that increased reliability comes from having two electric motors instead of a single double-wound unit is not substantiated.

Generators operate at fixed speed, meaning that in LNG carriers the dual-fuel diesel engines also operate at fixed speed. A change in power demand is accommodated by changes in engine torque (greater mean effective pressure) at the same speed. The converter changes fixed-voltage and fixed-frequency drives into variable-voltage variable-frequency to control the speed of the propulsion motor. Panos Mouzakis considered what, if any, improvements could be made to the electrical propulsion system to further increase the efficiency of electrical propulsion plant. The study considered engine arrangements and transmission system equipment including generators, converters and motors, and consisted of the development of computer-based models, mainly in PSCAD, supported by analytical study.

Efficiency of electrical propulsion equipment and systems was likely to improve in the future using some / most of the methods listed below.

- Prime movers: it is difficult to see that existing four-stroke medium-speed engines (with efficiency of c. 45%) are likely to be replaced with alternative prime-movers in the near term. Gas turbines are primarily available as simple cycle machines with lower efficiencies, while specialised complex cycle gas turbines offer superior performance (not as good as diesels) at higher initial cost. Fuel cells are immature and while they are unlikely to be used as a main prime mover in the near term, their rapid commercialisation over the past decade suggests the technology may be a long-term solution. The main advantage of fuel cells is that they are not limited by the Carnot Cycle limit in the way diesel engines are, so efficiencies of 60-80% are possible depending on type and arrangement.

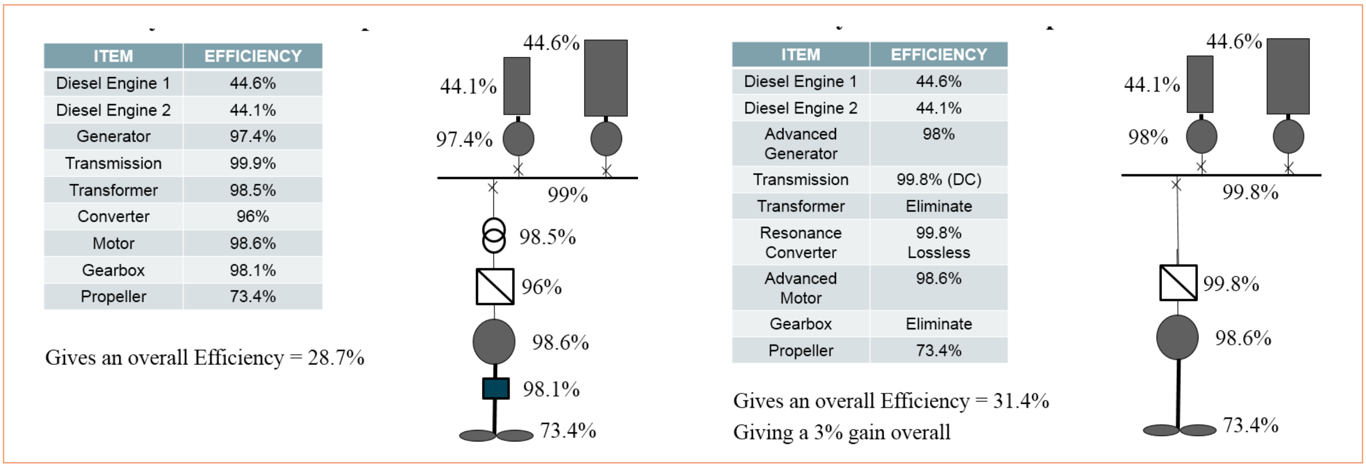
- The synchronous generator is the main means by which to generate electrical power. This machine already operates with efficiencies of 94% or greater, with losses attributed to iron loss of the magnetic circuit and copper loss of the windings. Permanent magnet synchronous machines reduce iron losses but do not reduce copper loss.

- Transformers are currently used to step voltage down between generator and power converter but are not used in all designs. Elimination of bulky transformers reduces transmission loss by around 1-2% but has the negative effect of increasing fault current levels.

- Whilst there is a range of power converters, the most common type found in modern ships is the pulse-width-modulated (PWM) drive. PWM drives are not as efficient as older drive types like the cycloconverter (CC) or load-commutated inverter (LCI), but waveform quality and controllability is superior. PWM drives typically have efficiencies of 95%. Losses in drives are conduction losses and switching losses. Future power system drives may include resonant types that eliminate switching loss and potentially increase efficiencies of power converters to 99%.

- Conventional DC motors have given way to AC motors, namely the induction and synchronous machines. Although these machines are efficient they are large and heavy. To reduce size and weight new motors have been developed, including the Advanced Induction Machine, Advanced Propulsion Motor, Magnematics Electrical Gear Motor, and Superconducting Motor. With all these motors efficiency increases with smaller size.

- Whilst existing electrical propulsion systems use three-phase AC distribution there is growing interest in DC distribution systems. The advantages of DC include greater efficiency and reduced number of cables. The disadvantage is that the technology for high power distribution is immature with a particular challenge around circuit breakers.



ITEM	EFFICIENCY
Diesel Engine 1	44.6%
Diesel Engine 2	44.1%
Generator	97.4%
Transmission	99.9%
Transformer	98.5%
Converter	96%
Motor	98.6%
Gearbox	98.1%
Propeller	73.4%

Gives an overall Efficiency = 28.7%

ITEM	EFFICIENCY
Diesel Engine 1	44.6%
Diesel Engine 2	44.1%
Advanced Generator	98%
Transmission	99.8% (DC)
Transformer	Eliminate
Resonance Converter	99.8% Lossless
Advanced Motor	98.6%
Gearbox	Eliminate
Propeller	73.4%

Gives an overall Efficiency = 31.4%
Giving a 3% gain overall

Figure 33 Conventional Electrical Propulsion System (LHS) and possible Future Electric Propulsion System (RHS)

The development of electrical propulsion systems is ongoing with new smaller, lighter and more efficient technologies emerging. Figure 33 shows how the efficiencies of individual equipment together with layouts will change as the new technology comes on stream.

Electrical technologies are developing rapidly, offering advanced systems that are flexible and more efficient than was previously the case. Advanced motor technologies are available today, whilst the next generation of power electronic drives is on the horizon. Superconductivity is too far away and too immature for significant projections to be made for its performance.

Reducing Carbon Footprint Examining Fuel Usage, Engine Operation and Exhaust Gas Treatment

The underlying philosophy of this study is that the net CO_2 emission for the ship is reliant on: firstly, the carbon budget of the fuel being used; secondly, the manner in which it is used considering actual (rather than assumed ideal) engine operation; and, thirdly, what is done with the exhaust products post-combustion. The principal aim in this research was therefore to undertake a three-fold investigation for low-carbon fuel-engine-exhaust systems concepts. The study addressed three objectives.

1. **Future fuel usage.** With the recent introduction of regulations for the reduction of exhaust emissions from ships, including NOx limits and the ban of high sulphur fuels, this research considered alternative fuelling and fuel use on ships in the context of reducing CO_2 emissions whilst acknowledging constraints imposed through existing emissions regulations. Aspects including hybrid use of light and residual fuel oils, biofuels and exotic alternatives such as (L)NG, hydrogen, etc., were considered.

2. **Engine and emissions modelling concepts.** On the premise that the total emission products (carbon as well as others) can be influenced through the actual operational conditions of the engine, accurately modelling emission production at the engine can be used as a tool for modifying engine operational conditions for net emissions reduction. This research therefore examined potential engine and emission modelling tools for this purpose.

3. **Future emission control measures.** This research focused on examining the feasibility of removing carbon emissions, as they are generated onboard, through ship-borne carbon capture and storage technologies (CCS), e.g. dry-ice production, compressed gas capture and chemical capture/absorption.

Unlike many other studies of this nature, and indeed, the premise behind emerging regulations, which generally only consider the carbon cost of fuels on a ‘pump-to-hull’ basis, this research considered the total carbon footprint of different fuel types used in the full range of marine engine types on a ‘well-to-hull’ basis (or ‘field-to-hull’ in the case of biofuels). This therefore included the upstream carbon cost of fuel production and transportation to the vessel. On this basis, there is a strong indication that existing residual and distillate marine fuels are actually already relatively ‘carbon-effective’ choices. A wide variety of biofuels was considered and under some conditions these can offer a net reduction in carbon cost, however, many do not if considered on a ‘field-to-hull’ basis owing to the carbon-intensive production processes (including fertilisers, farming methods, etc.). Given the competition between biofuel and food production, there is also a limit on how much biofuel could actually be used for fuelling shipping transportation, and, in some cases, the use of biofuels can increase the emission of species aside from CO_2. The best performers in terms of carbon footprint were blends with existing fossil fuels. LNG can also provide carbon (and other) emission reduction benefits as compared to traditional marine fuels, but again the picture is not as clear as might be supposed, owing to the highly carbon-intensive production cost of fossil fuel LNG. Hydrogen was also considered: however, under existing production methods this too can be carbon-intensive, although if renewable energy sources can be used for hydrogen production then this provides a realistic possibility for a net reduction in carbon footprint.

The extent of the research on engine and emissions modelling concepts was limited within the scope of this project, but a variety of existing engine and emission models were examined and some initial comparisons with experimental results (generated within this project) were made. It is apparent that on an engine-by-engine basis, highly sophisticated modelling tools can provide accurate results in terms of engine performance (in terms of power, efficiency, etc.), but these models are not necessarily concerned with precise emissions products. On the other hand, there are some relatively accurate emission prediction models, but many only focus on one (or a limited sub-set of) emission species and require a very accurate time-dependent description of the in-cylinder combustion conditions and are not necessarily coupled with engine performance prediction tools. Ultimately, in order to be able to predict/model emission production over the wide range of ship engines, on a vessel-by-vessel basis, a compromise between accuracy and computational and data-input effort is required and this has been taken forward as a recommendation for future work.

With respect to future emissions control measures, since no CCS methods exist on board ships at this time, an extensive review of the methods in use (or under research) for land-based applications was conducted and some initial calculations were performed to inform the feasibility of their application on board. The principal parameters considered were the energy, weight and volume implications of instigating different techniques on board ships. While some of the techniques/systems used for carbon capture did show some potential feasibility (e.g. amine absorption technology) in these terms, the fact that the captured carbon requires further processing for storage and needs to be retained on board the vessel, leads to the ultimate conclusion that, in reality, an onboard CCS system does not appear feasible given current methods and technologies.

Fuel Cells

High temperature solid oxide fuel cells have been considered for marine applications due to their system robustness, higher efficiency and longer life span, compared to other types of fuel cell systems. Natural gas has been considered as the primary fuel, and so reforming technology is also included as part of the fuel cell ancillary systems. Two complementary studies have been carried out in the present project, addressing the use of fuel cells for auxiliary power generation and fuel cell technology for propulsive power. For the two cases, the same fuel cell technology is considered but different ancillary systems are used depending on the fuel cell use onboard.

In order to assess the potential use of fuel cells for marine applications, the following steps were carried out.

- **Literature Review:** of fuel cell technology, reforming technology, fuel cell ancillary systems and ship power plant characteristics. There was a particular focus on the overall weight and dimensions of the fuel cell system, compared with a diesel engine generator for the same amount of power requirements. This step was common to both the propulsive and auxiliary power generation studies.
- **Fuel cell and ancillary systems selection:** methods for the selection of fuel cell technology, reforming technology and thermal output converter technology. The selection criteria for fuel cells were: system fuel flexibility, system robustness, system life span, system overall efficiency, and system ability to cope with alternating power demands. The selection criteria for reforming technology were: ability to work with the fuel cell technology selected, and external energy requirements. These two steps are common for both propulsion and auxiliary power generation. A gas turbine is employed as a thermal output converter for the propulsive case, whereas a counter current heat exchanger is considered for the auxiliary power generation case.
- **Fuel cell system macro-level modelling:** a solid oxide fuel cell system was modelled according to [2]. The selected systems were modelled in a zero dimensions, static condition, and a thermal, chemical and energy balance was carried out using Aspen Tech software. The fuel cell exhaust characteristics were identified, including their temperature and mass flow rate, in order to estimate the power output achieved by the gas turbine for the propulsive case, and the thermal energy export in the heat exchanger, in the auxiliary power generation case.
- **Fuel cell stack level modelling:** voltage and current output levels of the system were obtained by modelling the electrochemical and reforming reactions in one dimension: static condition along the cell length. The simulation was carried out using MATLAB software. This approach was used for both the propulsive and auxiliary power generation cases.
- **Design of control of strategy:** for the propulsive power case only, a control strategy was used for a fuel cell system consisting of a high temperature solid oxide fuel cell, gas turbine and battery bank.

The results from this process can be summarised as a number of key findings, listed below.

- **System dimensions:** The volume and weight of a fuel cell system are higher than those of a combustion engine with the same power output.

The fuel cell system weight can be assumed to be 10% higher than that of an internal combustion engine generator for the same power level, and the system volume is projected to be approximately 10 times higher. About 85% of this volume corresponds to the ancillary systems of the fuel cell system. The thermal recuperators, air and fuel heaters, and power converter units, boost converters and DC/AC inverters represent about 30% of the whole volume of the ancillary systems.

- **System efficiency:** When compared to a conventional marine diesel generator, a fuel cell system presents higher efficiency. This is translated into lower fuel consumption and also lower carbon emissions per energy unit. Fuel cells systems have 50% efficiency, based on the fuel low heating value, and also taking into account the parasitic losses exerted by the ancillary systems. It should be mentioned that the fuel cell stack reaches up to 60% efficiency at its operating point, 85% fuel utilization. At partial loads, the efficiency of the stack is higher, reaching up to 70%, but the losses exerted by the ancillary systems are higher in comparison. The overall efficiency of the system should be considered constant; 50-55% at maximum and partial load. About 12% of the thermal energy output is loss in the fuel reformer, and about 30% is loss in the air pre-heater. For the propulsion case, a synchronous motor should be included in order to provide the necessary mechanical power for the propulsion unit. This lowers the efficiency of the system, depending on the motor selected.
- **System emission levels:** In a fuel cell system, no internal fuel combustion is associated with the power output. Hence the SOx , NOx and CO_2 emissions are reduced to a negligible level. Fuel cell NOx emissions are about 0.01 gr/MJ, much lower than the typical 0.36 gr/MJ that a natural gas engine generator will produce. Similarly, a fuel cell system will produce 97 gr/MJ in comparison with a 128 gr/MJ of CO_2

Additional findings identified in the literature review phase, are summarised below.

- **Low Noise/Vibration:** owing to the fact that there are no moving parts, with the exception of the gas pumps and ventilation units, a fuel cell system will produce almost no noise and hardly any vibrations. This also translates into reduced maintenance time and maintenance cost.
- **Modular design:** fuel cell systems can be designed in a modular way. The different subsystems of the fuel cell system do not have to be adjacent. Multiple fuel cell stacks can be arranged in a broad range of different options, depending on the ship auxiliary power plant needs.
- **Cost:** at the present time, fuel cell systems carry a higher initial cost than the traditional combustion engine technology, but incur drastically lower maintenance costs.
- **Starting-up times:** the starting-up time for a fuel cell system is higher than for a regular combustion engine, especially when operating at high temperatures.
- **Transient load time:** the transient load time of a fuel cell system is higher than that of a combustion engine, but still within the seconds range. This time can, however, be reduced by operating the fuel cell system along a battery bank.

Solar

The amount of deck space relative to waterline length times beam was found by looking at detailed ship models. Only panamax size ships were examined, apart from the LNG carrier, which was medium-large. The assumed speed for the container ship was 25 knots; for the bulk carrier, 15 knots; for the oil tanker, 15 knots; and for the LNG carrier, 20 knots. For a container carrier it was assumed that only the top of the superstructure could be used. The sun's irradiance is assumed constant and energy is collected from the solar panels for half of the day (12 out of 24 hours).

A MATLAB programme for solar power system simulation was developed. The system volume and components required are estimated, and the performance of the components was calculated.

The results show that a reduction of up to 10% of the CO_2 produced by the auxiliary power plant could be achieved. The result of installing solar panels means that the same size generators are used, as power reductions are not large enough to facilitate the installation of a smaller auxiliary power plant. This means that there is no difference between a retrofit and new build.

The costs for solar panels have been extrapolated from the known cost of installing 40kW of solar panels on a Japanese car carrier (1.67M Yen) as per MEPC 61-INF 18 (IMarEST, 2010). The through life cost assumes that the panels will need replacing every ten years, and averages this cost over the full thirty-year lifespan of this ship. No other through life costs have been included.

Future solar technology is likely to have a lower cost and better efficiency: MEPC 61/18 estimates a learning rate of 15% based on onshore solar power analysis.

Ship Impact Modelling Output and Key Findings

Background and Aims

The key aim of this task was to construct a computer-based ship model, to absorb the outputs of the detailed studies into the technical options - Carbon Dioxide Reducing Technologies (CRTs) - for emissions reduction. This model would support the identification of synergies between ship types, design and operational decisions and technological options. Crucially, this ship model was to be used to provide inputs on ship impacts for the holistic shipping system model developed in WP1.

Integration and Structure

Figure 34 illustrates how this work integrated with the other parts of WP2 and other LCS project WPs. It also indicates how the level of detail used in the models varied between the WPs. The holistic shipping system model developed in WP1 necessarily contains greatly simplified descriptions of the ships and the impacts of low carbon technologies upon them. The tasks in WP2 examined specific technologies and operation options at a much higher level of detail; the ship impact modelling task bridged this detail gap.

This was accomplished by using two levels of modelling. Detailed parametric Whole Ship Models (WSM) were developed using the Paramarine software and used to populate a simplified MATLAB Ship Impact Model (SIM). These two models were then used to assess the impact of technologies on the overall ship, and this data was processed to populate a Ship Impact Database (SID). This database contained parametric descriptions of the technologies in a simplified form that represented their broad characteristics across the wide range of ship types and sizes used in the Shipping System Model.

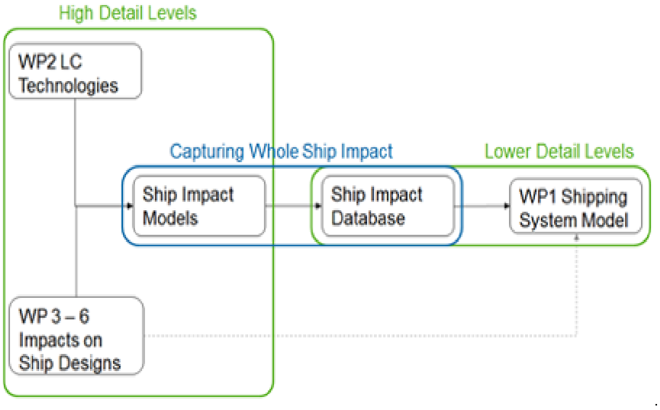


Figure 34 Integration of the ship models with the LCS project, showing varying detail levels

Ship Impact Models

The detailed parametric Whole Ship Model (WSM) was used to correctly size CRTs. The ships had to be modelled with enough accuracy and detail to ensure they realistically reflect the overall impact on cargo capacity and cost. Thirty-six parametric ship design models were generated, based on common design assumptions and a common dataset. This covered container ships, dry bulk carriers, oil tankers and LNG tankers. These four ship types were modelled in four size categories, and two or three design speeds (assumed to be at 75% MCR). This provides coverage of the main ship design topologies (overall layout). Figure 35 illustrates the level of detail in the Paramarine model.

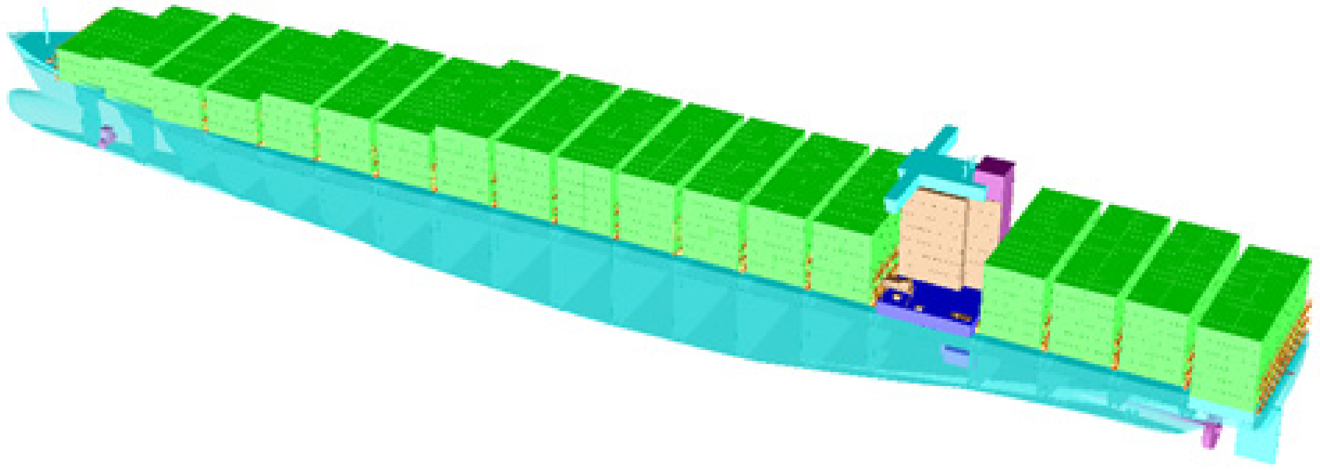


Figure 35 Paramarine model of a 25-knot panamax container ship

Table 4 Selected ship types, sizes and speeds: § Container ¤ Bulk Carrier ● Oil Tanker ◊ LNG Tanker.

			Design Speed (knots)			
Ship Type	**Ship Size Category**	**Displacement Range (te)**	**10**	**15**	**20**	**25**
Container Ship	Feeder	≈ 14 000		§	§	§
Solid Bulk	Handysize	33 000 - 34 000	¤	¤		
Solid Bulk	Handymax	≈ 42 000	¤	¤		
Solid Bulk	Panamax	71 000 - 73 000	¤ ●	§ ¤ ●	§	§
Liquid Bulk	Aframax	≈ 117 000	●	● ◊	◊	
LNG Tanker	Medium-sized LNG	≈ 115 000	●	● ◊	◊	
Container Ship	Post-panamax	122 000 - 123 000		§	§	§
Liquid Bulk	Suezmax	147000 - 165 000	●	● ◊	◊	
LNG Tanker	Q-Flex	154 000 - 155 000	●	● ◊	◊	
Container Ship	Ultra Large Container Ship (ULCC)	172 000 - 175 000		§	§	§
Dry Bulk	Cape	186 000 - 188 000	¤	¤		
Liquid Bulk	Very Large Crude Carrier (VLCC)	305 000 - 343 000	●	●		

Table 4 shows the ship designs that were modelled in detail. The designs covered a range of sizes – defined by port and infrastructure limitations – and design speeds. The focus was on ship types with the biggest potential for CO_2 emissions reduction, leading to four clearly delineated ship types: container ships, dry bulk, liquid bulk and LNG tankers. Within each type, the overall style and topology (i.e. arrangement) of the ship does not change with size, which allowed CRT ship impact assessments to be applied over the size range.

The WSMs were generated using a combination of UCL data and data from equipment suppliers' catalogues and ship design textbooks. The models were validated against the Clarksons ship database.

The WSMs were used to achieve two objectives: firstly to generate a virtual fleet that was used to populate the SIM with vessels representative of current technology; and secondly to investigate and characterise the ship impact of certain CRTs, so that they could be applied to a wider range of ship sizes and design speeds in the SIM. These studies were carried out using information from the wider membership of WP2. Most CRTs under consideration were found to have clearly defined effects in a limited area of the ship, allowing them to be integrated with the numerical SIM. Two technologies of note were the use of LNG fuel and wind assistance (particularly sails), which were investigated in more detail using the WSM so as to capture their broader impact on the design, including changes to the general arrangement.

The MATLAB-based SIM allows very quick calculation of the CO_2 emissions and other performance parameters (required for detail ship and system design) of different ship type, size, speed and CRT combinations. There are three main inputs to the SIM:

- CRT Descriptions (CRTs provided by subject matter experts in WP2 and incorporating WSM evaluations)
- Ship and Equipment Descriptions (design and utilisation assumptions)
- Ship Operating Profile

The SIM allows the CO_2 emissions to be calculated over an operating profile, alongside other performance metrics, such as CRT costs, fuel consumption, average speed and transport efficiency. The overall structure of the SIM is shown in Figure 36. The initial iterative design loop calculates and sets the characteristics of the selected ship and CRT combination, while later operational loops find the performance of the ship at different operational speeds and in different loading conditions. The inclusion of operating speeds was vital to ensure that the effectiveness of the CRTs when used in combination with operational measures such as slow steaming was captured.

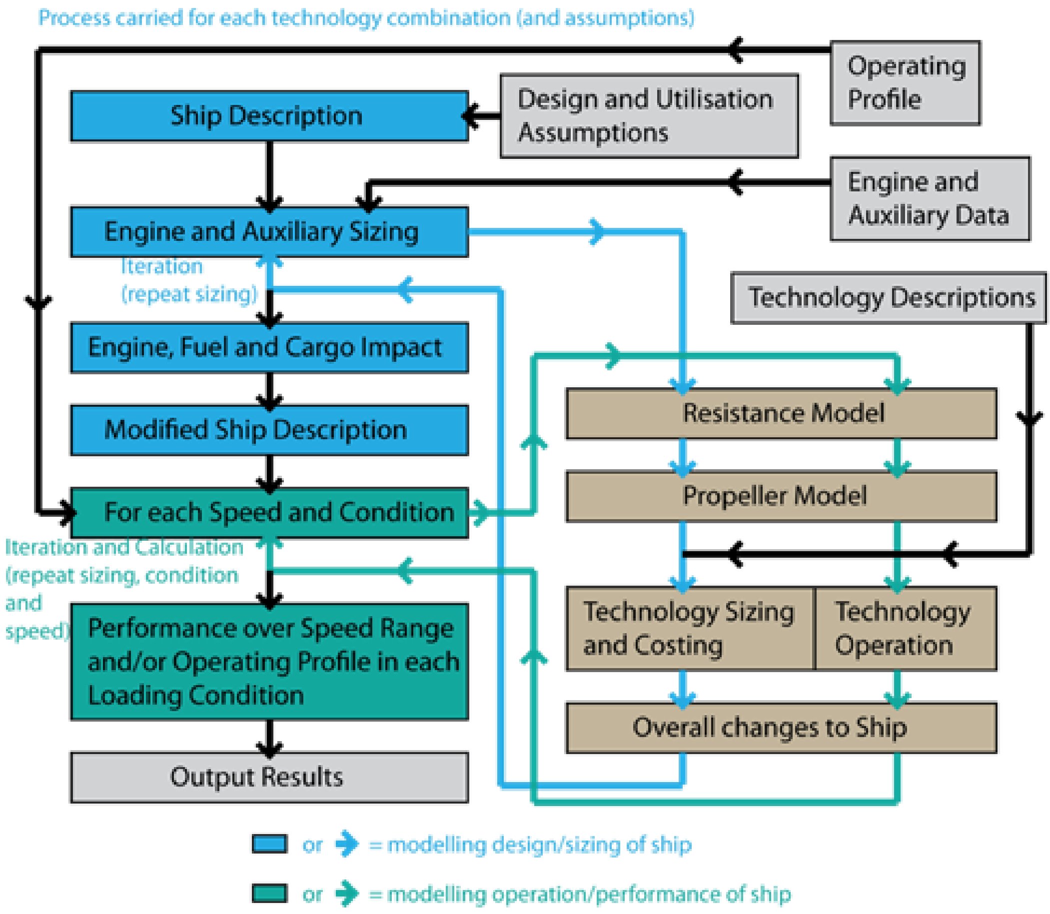


Figure 36 Structure of the Ship Impact Model (SIM)

The database of 36 WSM ships provides the SIM with a basis to scale the baseline ship before CRTs are applied. In a broader application, a ship operator or designer would replace the LCS ship database with models reflecting their own fleet. This is a key concept in that it allows future reuse of the SIM, by separating the ship data from the model itself. The SIM calculates the secondary effects of implementing a CRT (e.g. a decrease in resistance would lead to a smaller engine size), allowing the overall impact of a CRT to be assessed in a holistic manner.

Technical information on the performance of CRTs was generated by the subject matter experts in WP2, with additional information such as costing imported from the wider LCS consortium. A standard document format and MATLAB code structure were used to generate the ‘Technology Descriptions’ shown in Figure 3. The documents described the performance, ship impact and assumptions relating to each CRT and were used to elicit industry feedback on evaluations of CRTs. For some technologies there are multiple engineering approaches to exploiting a performance benefit or responding to the change in the design. The SIM allows these varying approaches to be explored and compared through the use of variant technology descriptions characterising the alternative concepts. The SIM can also be used to rapidly explore the impact of varying the operational profile, or the application of a given technology set to a different fleet (by changing the database of ships).

Ship Impact Database

The Ship Impact Database (SID) provides the interface between the detailed descriptions of the ship impact and emissions reduction potential of CRTs and the overall shipping system model. The population of this database involved two main tasks: simplification of the representation of the impact and emissions reduction of a CRT in a manner that retains the key characteristics but can be rapidly computed in the shipping system model; and the presentation of the data to the shipping system model in a uniform, consistent and comprehensible manner. The SID consists of an Excel spreadsheet, with titled columns of numerical and textual data, which can be read in by the MATLAB-based shipping system model. For each CRT, eight types of information, described below, are held in the database.

1. **Emissions Reduction Potential:** The emissions reduction potential of the CRT is given both as a maximum that could be achieved for the ship design, i.e. that achieved at the ‘optimum’ operating point, and that achieved in service. Emissions reduction potentials are described algorithmically,

and can be: constant; proportional or inversely proportional; maximum at a design point (i.e. quartic); or a step function. They scale with cargo deadweight, design speed and operational MCR. In addition to supporting the complexity of the shipping system model, this approach allows potentially complex relationships to be described and displayed with relatively little input data.

2. **Ship Impact:** The ship impact of a CRT is expressed as a loss-in-cargo deadweight. This significantly reduces the effort required to assess the impacts of the large range of CRTs in the LCS project, and can be used to generate larger ships to carry the same cargo. The ship impact is expressed algorithmically.
3. **Fuel Type Compatibility:** A simple flag is used to represent the compatibility of a CRT with different fuel types.
4. **Specific Fuel Consumption:** Changes in the SFC caused by the addition of a technology.
5. **Incompatibilities:** A list of incompatible technologies is provided for each CRT.
6. **Refit-ability:** A yes/no flag indicates whether a technology can be added in a refit.
7. **Availability:** The future availability of a technology is represented by dates and definition of the medium and long-term versions of some technologies.
8. **Applicability:** The applicability of the CRTs to the ship types is indicated by a flag.

Throughout the duration of the LCS project, the SID has been populated with data and updated several times. Four main methods were used for populating the database:

1. **Referenced figures:** initial population of the SID early in the project utilised published data, such as the IMO MEPC reports.
2. **Expert judgement:** the initial database was improved by expert judgement, calling on the multi-disciplinary expertise in the academic and industrial members of the consortium.
3. **Focused technology studies:** additional data required to fully populate the SID, such as estimates of ship impact before the SIM was complete, were performed by focused studies at a basic level of detail. Once the Paramarine ship models were complete they were used in focused studies of certain key technologies with high ship impact.
4. **Processed SIM runs:** the ultimate method of populating the SID was through the post-processing of large batches of SIM runs, where a given CRT was applied to the complete range of ship types, sizes and speeds. This approach captures secondary ship impacts assessed with complex models whilst retaining the simplicity of the SID structure. A total of five ship types (including two variants of LNG Tanker) in four ship size categories at three different design speeds were run with 34 different technology options, with a total of 3060 SIM calculation runs to populate the SID.

Key Outputs and Findings

From the perspective of the overall LCS project the primary output of the ship design work has been the development of the SID, characterising the performance and ship impacts of CRTs in a manner that allows them to be applied over the range of ship sizes and speeds used in the shipping system model. The findings from the shipping system model (WP1) are discussed elsewhere. The second output of this work is the SIM, which can be used as a ship design tool to select CRTs by evaluating ship and CRT performance. This tool is suited to future applications such as investigating future ships and evaluating wider operational aspects such as operational speed.

The development of the technology models incorporating wider WP2 expertise indicate that the majority of CRTs investigated have limited and clearly defined physical effects on cargo ships, and can be applied without requiring major redesign of the vessel. A more limited set of CRTs requires significant changes to the overall ship design. The availability of a range of CRTs that should be readily applicable to conventional designs – thus reducing technical risk – increases the importance of the broader socio-economic aspects in ensuring their adoption.

Dissemination

The outputs from this work package take three forms:

1) reports, theses and publications describing the complex analyses undertaken for this project;

2) technology data sheets summarising the performance of all technologies studied including complex, simple analyses and peer review;

3) data supplied to GloTraM in the form of the Ship Impact Database.

Publications in print:

Azqueta, G., Clelland, D., Zhou, P. (2011) Fuel Cells for marine applications. LCS 2011

Azqueta, G., Clelland, D., Zhou, P. (2012) Energy balance of a fuel cell system for onboard auxiliary power generation. LCS 2012

Calleya, J., Pawling, R., Greig, A. & Bucknall, R. (2011) 'Assessing the Dependence of Natural Gas on the Size and Topology of Container Carriers and Other Ship Types', Gas Fuelled Ships 2011, Rotterdam

Calleya, J., Mouzakis, P., Pawling, R., Bucknall, R. & Greig, A. (2011) Assessing the Carbon Dioxide Emission Potential of a Natural Gas Container Carrier. LCS 2011

Calleya, J., Pawling, R., Smith, T.W.P. & Greig, A., 2012 'Ship Design and Evaluation for a Greenhouse Gas constrained future', Presented to The Environmentally Friendly Ship, Royal Institute of Naval Architects, 28-29 Feb 2012. Reprinted as: 'Calibrating the Future' in The Naval Architect (January 2013). RINA, London.

He, J. *et al*. (2011) Development of a combined cycle of SOFC and micro gas turbine for marine power systems. LCS 2011

He, J. *et al*. Modelling and control of fuel cell and micro gas turbine hybrid power system for ship application. LCS 2012

Howett, B. and Day, A.H. (2012) 2nd International Conference on Technologies, Operations, Logistics & Modelling for Low Carbon Shipping (LCS 2012), Newcastle, UK

Trodden, D. and Woodward, M. (2012) Optimal Propeller Design when Accounting for the Manoeuvring Response due to Environmental Loading. MARSIM 2012, Singapore, 23-27 April

Trodden, D. and Woodward, M. (2012) Reduction of Greenhouse Gas Emissions by Propeller Design for Ship-In-Service Conditions. LCS 2012

Vijayakumar, V. (2011) *Reducing Carbon Emissions by Improving Marine Engine Technology*

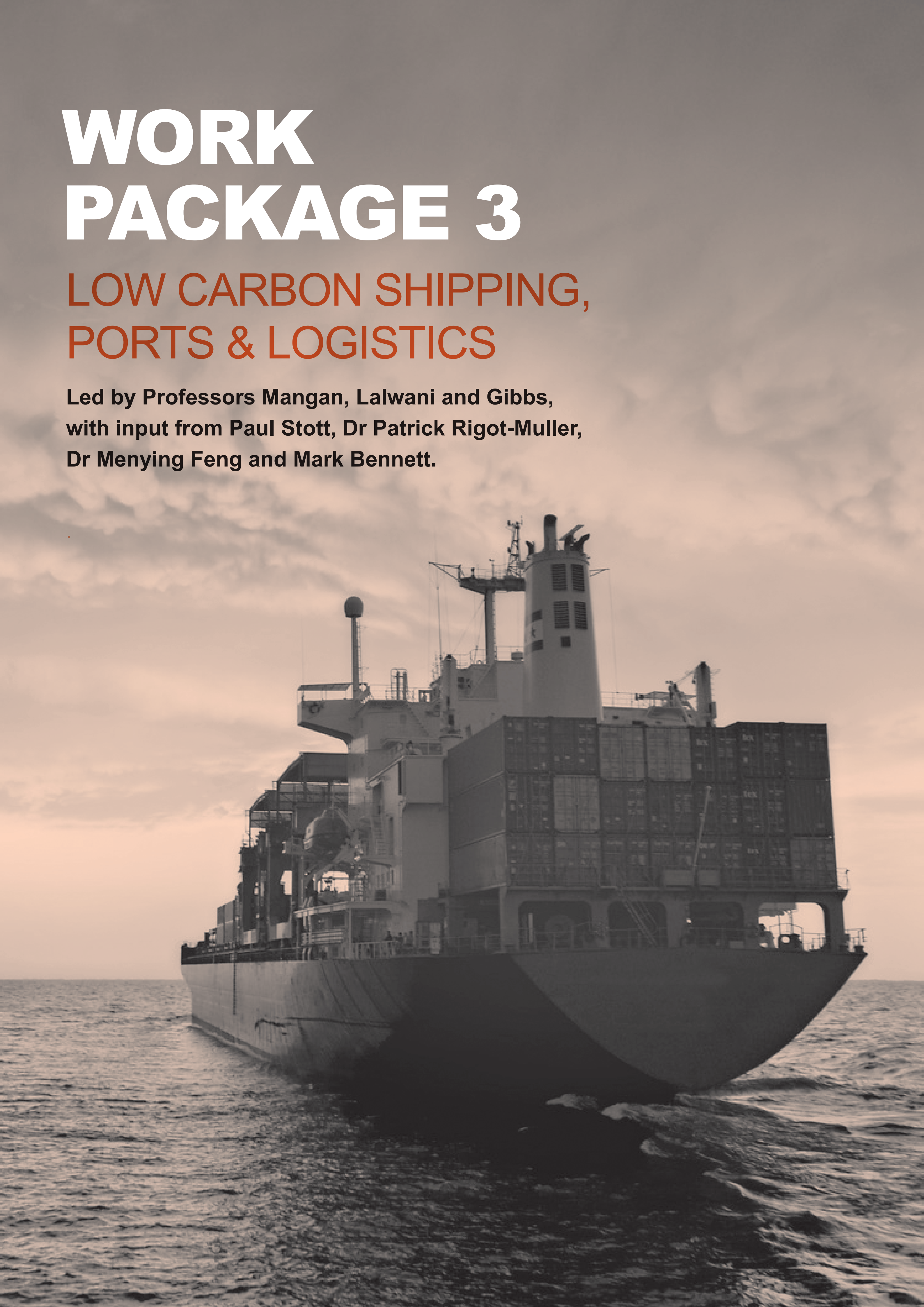
Publications in preparation

Calleya, J. (forthcoming, 2013) PhD focussed on the development and use of the SIM

Calleya, J., Pawling, R. & Greig, A. (forthcoming, 2013) Ship Impact Model (SIM) for Technical Assessment and Selection of Carbon Dioxide Reducing Technologies (CRTs)

Other dissemination

The UCL undergraduate (MEng) and postgraduate (MSc) naval architecture and marine engineering courses feature a three-month ship design exercise, where student teams are frequently given requirements to reduce the CO_2 emissions of their designs. The technology descriptions and ship impact assessments carried out in WP2 are being used to update the existing design databook to allow inclusion of these technologies in the academic year 2013-2014.



WORK PACKAGE 3

LOW CARBON SHIPPING, PORTS & LOGISTICS

Led by Professors Mangan, Lalwani and Gibbs, with input from Paul Stott, Dr Patrick Rigot-Muller, Dr Menying Feng and Mark Bennett.

WP3 – LOW CARBON SHIPPING, PORTS AND LOGISTICS

Led by Professors Mangan, Lalwani and Gibbs, with input from Paul Stott, Dr Patrick Rigot-Muller, Dr Menying Feng and Mark Bennett.

Overview

WP3 had the task of linking shipping with the wider logistics sector. We interpreted logistics in this context as being primarily concerned with:

- Maritime logistics infrastructure, especially ports
- Intermodal transport (i.e. how shipping connects up with the other transport modes) and the landside routing of freight
- Maritime route networks, modal split, and future projections of same

As our work progressed it became apparent that focusing just on maritime industry structure and industry dynamic would not be enough – we would need also to consider the factors underlying the 'what / how / why' questions concerned with the freight that flows through these maritime logistics networks. This then led us to also map the wider supply chains which comprise maritime logistics flows, a task conducted in conjunction with WP4, in order to understand both supply chain structures and the cost drivers therein.

We further delimited our work in two respects:

- our perspective is UK-centric, i.e. we are concerned primarily with logistics flows in and out of the UK; and
- we concentrated in particular on container vessels for a number of reasons:
    i. although they only comprise approximately 10% of the global fleet their emissions, at approximately 27%, represent a much higher share of the global total;
    ii) for developed and largely service-based economies such as the UK, containers are increasingly important for trade and their volumes in and out of the UK are set to grow into the future;
    iii) they are heavily interconnected and interdependent with wider logistics systems.

    For these reasons we believe they represent significant constituency for both analysis and potential improvement in terms of shipping's carbon footprint.

In summary our outputs comprised:

- informing both the global model and the wider consortium with these logistics and supply chain perspectives; in addition two industry facing workshops were facilitated by WP3;
- various analyses (freight flows, modal shifts, freight projections, supply chain maps, etc.); and
- generating a series of (briefing, conference and journal) papers both to report on our analyses and to inform the wider discussion.

Main Research Focus

It was initially envisaged that WP3 would focus on the following tasks:

- Mapping the current and future network
- Landside links and impact of port reconfiguration
- Environmental impact of port activities, infrastructure and institutional requirements.

In practice and as our work progressed we in effect expanded this listing to comprise the following seven research outputs:

WP3 -1 Map the 'as-is' shipping activity in the UK (all modes);

WP3 - 2 Catalogue port-related sustainability initiatives;

WP3 - 3 Estimate port-related CO_2 emissions;

WP3 - 4 Estimate the CO_2 emissions associated with UK-centric shipping activity (all modes);

o Assess the impact of transhipment on the CO_2 emissions associated with UK-centric shipping activity (containers only);

WP3- 5 Map supply chains for different types of containerised products and estimate

the share of maritime related CO_2 emissions (containers only) [in conjunction with WP4];

WP3 - 6 Examine the relationship between transport logistics and future ship designs (all modes) (RQ3).

The human resources deployed on WP3 over the period 2010-2012 comprised, in terms of FTE equivalent, approximately 6 months fulltime equivalent of Professor input and 18 months of fulltime equivalent postdoc time (we are grateful to Lloyd's Register for funding part of the latter postdoc activity, shared with WP4, to focus on cross-WP interaction). We are also grateful for the input to the WP received from Mr Paul Stott, who was appointed Senior Lecturer at Newcastle in 2011, and who contributed pro bono to WPs 3&4 in 2012.

WP3-1 Map the 'as-is' shipping activity in the UK (all modes)

Our benchmark briefing paper (Mangan *et al.* 2011) detailed the 'as is' picture of shipping activity calling to and from UK ports and drew on Department for Transport (DfT) statistical data, AIS data and ports websites. Interviews were also held with a number of industry experts to understand industry structure, etc. That paper provided the basis upon which we proceeded to analyse current freight flows, and sought to predict future freight flows. This work was also presented at the Logistics Research Network (LRN) conference in 2010 (Mangan *et al.* 2010). Both of the aforementioned papers noted that most of the analysis of shipping activity in the domain of low carbon shipping research has adopted top-down and/or bottom-up approaches. The top-down approach considers macro/global data, freight flows and trends, while the bottom-up approach seeks to aggregate up from the micro-level of individual shipping activity.

It was concluded from this stream of work that the latter approach in particular (aggregating up from a bottom-up approach) would be especially insightful in the context of this research effort which seeks to understand inter alia the logistics aspects of low carbon shipping, for example by: examining the role of transhipment activity; detailing emissions for individual shipping movements; and mapping the role and impact of shipping within individual supply chains. The decision to focus in particular on a bottom-up approach thus guided our subsequent research efforts. In essence we concluded that interpreting and extrapolating from macro level data on logistics and shipping activity would not be sufficient for the purposes of this project.

Some of the outputs from this stream of work were used in WPs 3-4 and 3-5, which look at apportioning emissions to UK trade and the role of transhipment in exacerbating emissions. The data generated in WP3-1 on vessel sizes/capacity/share is important as it can help identify which ports/vessels/patterns of activity are likely to lead to the greatest shares of emissions, and thus which should be targets for emissions reduction.

The analysis revealed the following profile of UK container (LoLo) traffic:[1] in 2011 UK ports handled 519 million tonnes of cargo, of which 11% (57.7 million tonnes) was in LoLo containers (representing 8.14 million TEUs). The average container weight (across all containers, loaded and empty) was thus 7.1 tonnes per TEU. Further analysis of the statistics shows that containers outbound from the UK are generally heavier than inbound containers owing to a different product mix within the containers (outbound containers for example carry more materials for recycling). In addition, approximately 26% of containers handled at UK ports are empty, with the vast majority (84%) being in the outbound direction.[2] Felixstowe is the UK's principal container port and handled 40% of all containers in 2011; in fact the top four container ports collectively handled 77% of all LoLo containers in 2011 (Southampton, 20%; London 8.7%; Liverpool 8.2%).

WP3-2 and WP3-3 Estimate port-related CO_2 emissions

A briefing paper on this topic, 'Ports as Drivers for a Sustainable Maritime Transport Sector' (Gibbs et al. 2012) was circulated in July 2012 and was based on both desk research and consultations with the ports sector. It was also, we believe, the first comprehensive review of port-related sustainability issues in the UK. This research stream investigated the role of ports in mitigating GHG emissions in the end-to-end maritime transport chain; although the analysis was primarily focused on the UK, it is international in application. Our research on this topic has recently been published in the journal Energy Policy (Gibbs et al, 2014).

We analysed secondary data and information on actions taken by ports to reduce their emissions, with the latter data collected for the main UK ports via their published reports and/or interviews. Only a small number of ports (representing 32% of UK port activity) actually measure and report their carbon emissions in the UK context. The emissions generated by ships calling at these ports were analysed using a method based on DfT Maritime Statistics data. In addition, a case study (Felixstowe) of emissions associated with HGV movements to and from ports was analysed, and data on vessel emissions at berth were also analysed. Our analyses indicated that emissions generated by ships during their voyages between ports are of a far greater magnitude than those generated by the port activities. Based on our analysis of operations at five major UK port companies, it has been demonstrated that emissions from shipping at berth (1.8 $MTCO_2$ in 2007) are ten times greater than those from ports' own operations (174 $KTCO_2$ in 2008 for ports companies representing 32% of tonnages). Moreover, it was observed that shipping emissions associated with seaborne trade at those ports (approximately 10 $MTCO_2$) are far more significant than the ones generated by port operations. Thus, while reducing ports' own emissions is worthwhile, the results suggest that ports might have more impact through focusing their efforts on helping/facilitating the reduction of shipping emissions. The ports sector is increasingly acting as a driver for policies on carbon emissions reduction in the maritime sector; ports working both individually and collectively have developed policies not only to reduce emissions from their own activities, but also to encourage shipping companies to reduce carbon emissions. There may be considerable future

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1. Data compiled from the DfT's annual 'Port freight statistics' series.
2. One has to be careful when analysing and interpreting these statistics and not confuse 'TEUs' (a measurement size – twenty foot equivalent) with 'containers' (which come in different sizes (20ft, 40ft, other). Obviously then the number of TEUs is not the same as the number of containers.

potential for port actions to have substantial global influence – as AEA stated:

> the ownership of the world's key ports is limited to a small number of companies…over 50% of global container throughput is controlled by seven major companies. Given this relatively organised structure, it is possible that given the right incentives, ports will participate in the implementation of a range of changes that would allow GHG emission reductions from ships.
>
> (AEA 2008: 54-5)

WP3-4 Estimate the CO_2 emissions associated with UK-centric shipping activity

Following on from the analysis of ports and their emissions detailed in WP3–2 and WP3–3 above, Dr Rigot-Muller presented a conference paper at LCS 2012 (Rigot-Muller et al. 2012a), which detailed our analysis and subsequent estimate of UK-centric shipping related CO_2 emissions. The analysis covered liquid bulk, dry bulk, containers and general cargo traffic, for inwards and outwards directions. The result (Table 1) showed a total of 22.6 MT CO_2 in 2010 (14.7 MT for inwards flows and 7.9 MT for outwards flows), compared to 19.7 MT in 2000 (one would have perhaps anticipated an increase in emissions, allied to trade growth, over the decade: not so, in fact total trade handled at UK ports declined from 573m tonnes in 2000 to 500m tonnes in 2009). Container cargo is the category with the largest contribution, 9.3 MT out of 22.6 MT in 2010, and the growth in container vessel activity in part explains why the UK's share of emissions has not declined.

In order to assess the validity of this estimate (22.6 MT CO_2 in 2010) for UK maritime emissions, comparison can be drawn with two recent studies (Gilbert et al. 2010; Committee on Climate Change, 2011). In the Gilbert study (Table 5 and Figure 38), we can see that excluding method 8, all proposed apportionment methods are considered on a basis that is not related to shipping emissions themselves (GDP, value of import/export, weight of loaded/unloaded cargo, etc.) or to the actual traffic (bunker sales). It appeared to us that methods linking the cargo and the ship work (shipping voyage), putting them into the 'method 8' class, should be explored in more detail. The Committee on Climate Change (CCC) released in 2011 a study aiming to assess shipping emissions under this approach. They used, to assess ship work, trade statistics and LMIU data. The scope of the analysis covered the years 1990-2006 (from which they then extrapolated in time) and the import trade only. The analysis also endeavoured to consider transhipped flows using some assumed transhipment point in the globe. The CCC then proposed a range of 12-16 $MTCO_2$ for UK international shipping, based on import flows.

In our approach, we provided results for the period 2000-2010, for inwards and outwards flows, and using DfT data. We used the emissions factors provided by the IMO in 2009 (segmented by ship type and size) and we estimated ship size using the average vessel size by port and by type, provided by Eurostat.

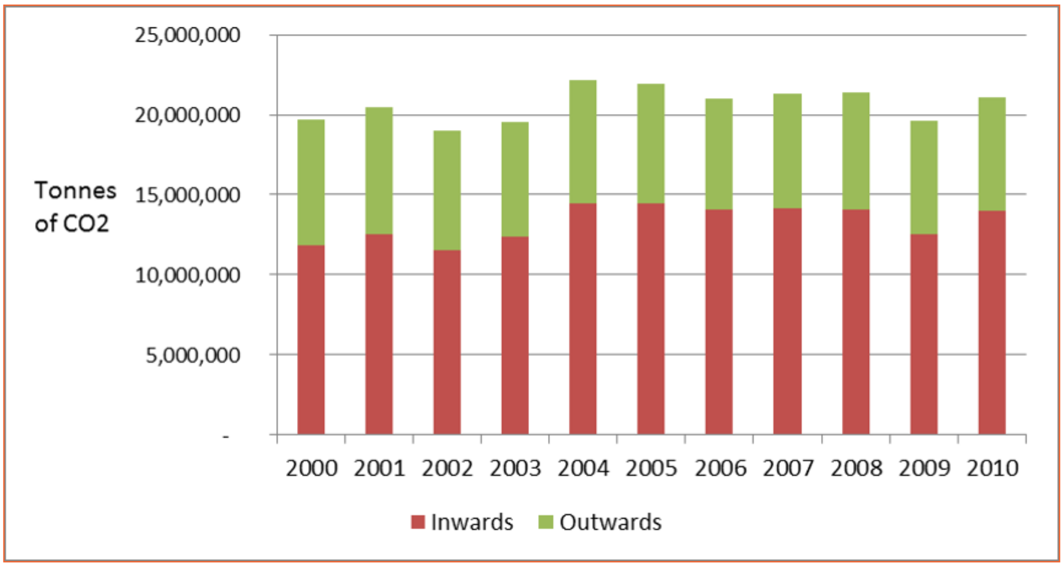
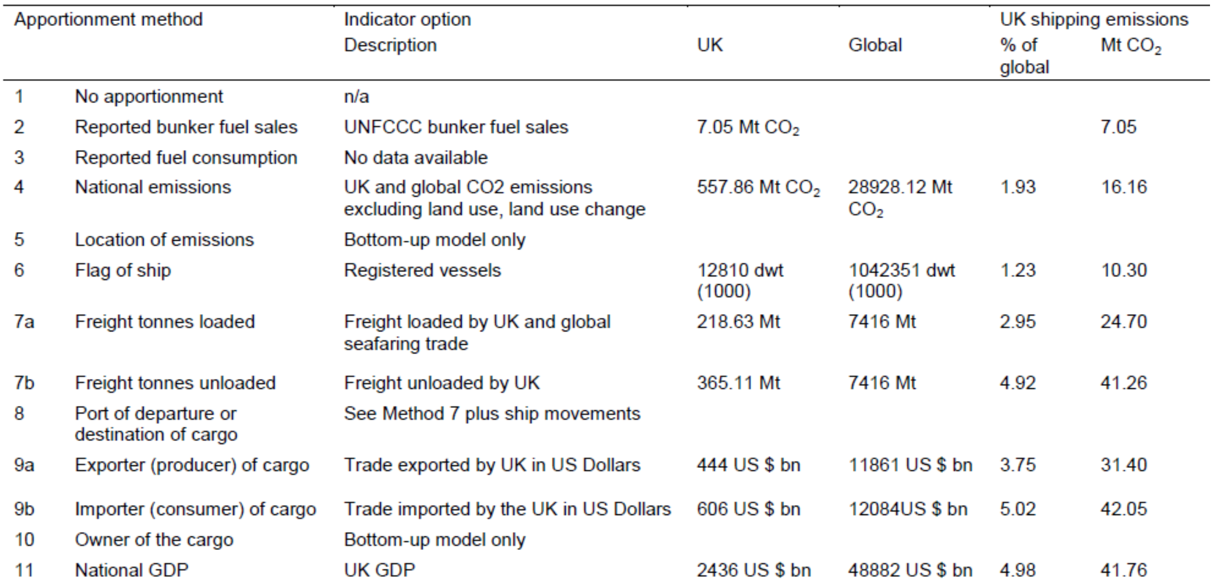


Figure 37: UK international seaborne traffic emissions 2000-2010



Apportionment method		Indicator option			UK shipping emissions	
		Description	UK	Global	% of global	Mt CO_2
1	No apportionment	n/a				
2	Reported bunker fuel sales	UNFCCC bunker fuel sales	7.05 Mt CO_2			7.05
3	Reported fuel consumption	No data available				
4	National emissions	UK and global CO2 emissions excluding land use, land use change	557.86 Mt CO_2	28928.12 Mt CO_2	1.93	16.16
5	Location of emissions	Bottom-up model only				
6	Flag of ship	Registered vessels	12810 dwt (1000)	1042351 dwt (1000)	1.23	10.30
7a	Freight tonnes loaded	Freight loaded by UK and global seafaring trade	218.63 Mt	7416 Mt	2.95	24.70
7b	Freight tonnes unloaded	Freight unloaded by UK	365.11 Mt	7416 Mt	4.92	41.26
8	Port of departure or destination of cargo	See Method 7 plus ship movements				
9a	Exporter (producer) of cargo	Trade exported by UK in US Dollars	444 US $ bn	11861 US $ bn	3.75	31.40
9b	Importer (consumer) of cargo	Trade imported by the UK in US Dollars	606 US $ bn	12084US $ bn	5.02	42.05
10	Owner of the cargo	Bottom-up model only				
11	National GDP	UK GDP	2436 US $ bn	48882 US $ bn	4.98	41.76

Table 5: Top-down proxy apportionment methods to determine UK's apportionment of CO_2 emissions from international shipping (Gilbert et al. 2010).

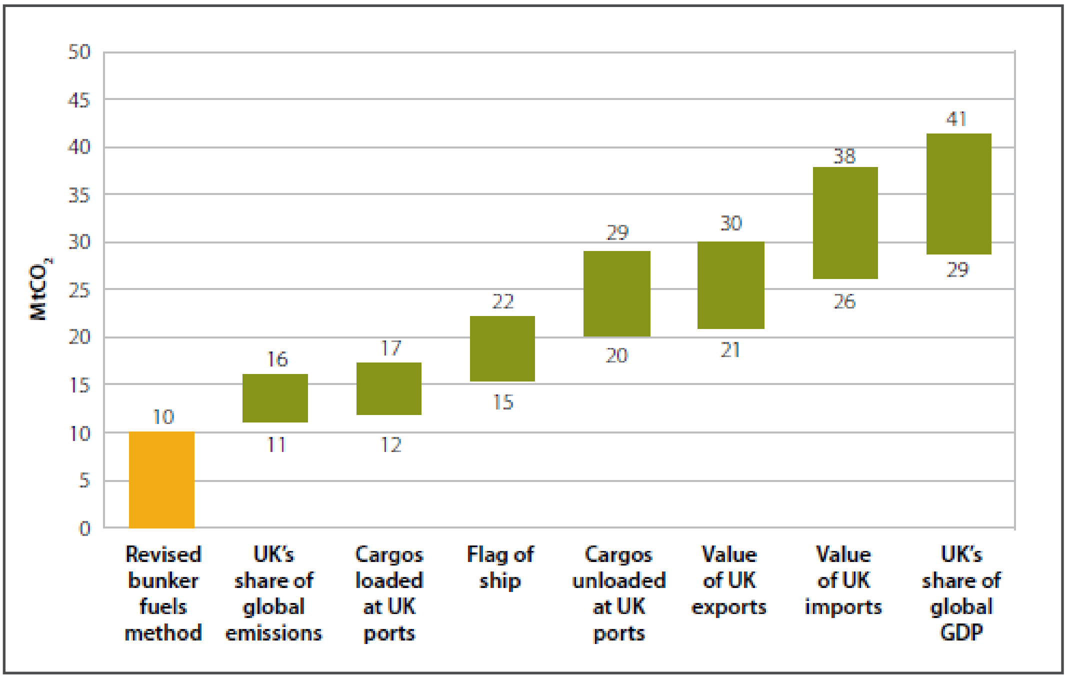
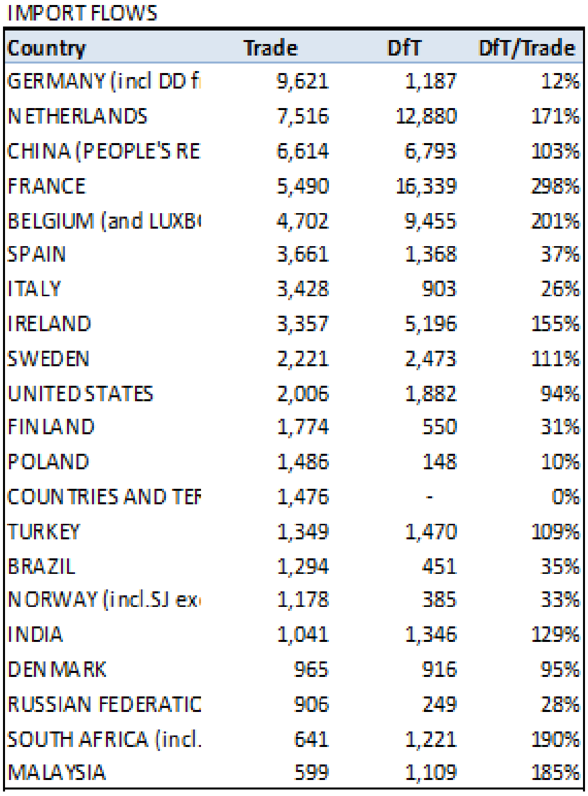


Figure 38: UK international shipping emissions in 2006 according to bunker fuel and top-down methodologies (Committee on Climate Change 2011)

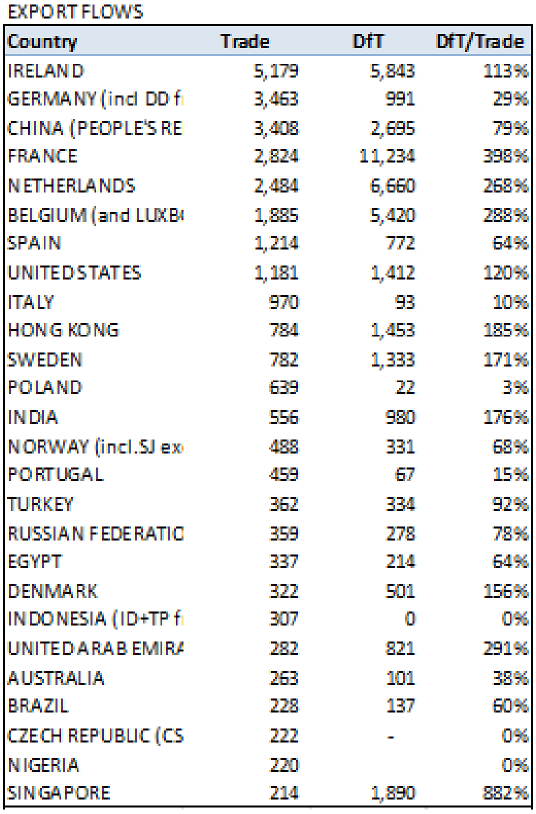
WP3-5 Assess the impact of transhipment on the CO_2 emissions associated with UK- centric shipping activity (containers only)

Interviews were held with various industry experts, who suggested that only approximately 10% of UK containers are transhipped and that the potential for reducing the carbon footprint by more direct shipments is minimal (industry experts also advised that for landside journeys of containers within the UK, approximately 35% of containers travel by rail, 5% by coastal shipping, and the remainder by road). For example, one of our interviewees (a large retailer in the non-food sector) noted that they avoid transhipment even for intercontinental long distance flows because of both the resulting time delay ('fresh doesn't like to tranship') and the difficulties that can ensue if something goes wrong (for example the deep-sea leg gets diverted). Dr Rigot-Muller presented a conference paper at LCS 2012 (Rigot-Muller *et al*. 2012b) which built upon some of the work done by Mark Bennett in the briefing paper in WP3-1 and which in particular reported on our further analysis around transhipment. We investigated the data available and possible approaches to mapping end-to-end flows circulating from and to the UK. It was intended that this analysis would also inform the next work package (WP3-6), which is focused on supply chain mapping.



IMPORT FLOWS

Country	Trade	DfT	DfT/Trade
GERMANY (incl DD f	9,621	1,187	12%
NETHERLANDS	7,516	12,880	171%
CHINA (PEOPLE'S RE	6,614	6,793	103%
FRANCE	5,490	16,339	298%
BELGIUM (and LUXB	4,702	9,455	201%
SPAIN	3,661	1,368	37%
ITALY	3,428	903	26%
IRELAND	3,357	5,196	155%
SWEDEN	2,221	2,473	111%
UNITED STATES	2,006	1,882	94%
FINLAND	1,774	550	31%
POLAND	1,486	148	10%
COUNTRIES AND TEF	1,476	-	0%
TURKEY	1,349	1,470	109%
BRAZIL	1,294	451	35%
NORWAY (incl.SJ ex	1,178	385	33%
INDIA	1,041	1,346	129%
DENMARK	965	916	95%
RUSSIAN FEDERATIC	906	249	28%
SOUTH AFRICA (incl.	641	1,221	190%
MALAYSIA	599	1,109	185%



EXPORT FLOWS

Country	Trade	DfT	DfT/Trade
IRELAND	5,179	5,843	113%
GERMANY (incl DD f	3,463	991	29%
CHINA (PEOPLE'S RE	3,408	2,695	79%
FRANCE	2,824	11,234	398%
NETHERLANDS	2,484	6,660	268%
BELGIUM (and LUXB	1,885	5,420	288%
SPAIN	1,214	772	64%
UNITED STATES	1,181	1,412	120%
ITALY	970	93	10%
HONG KONG	784	1,453	185%
SWEDEN	782	1,333	171%
POLAND	639	22	3%
INDIA	556	980	176%
NORWAY (incl.SJ ex	488	331	68%
PORTUGAL	459	67	15%
TURKEY	362	334	92%
RUSSIAN FEDERATIC	359	278	78%
EGYPT	337	214	64%
DENMARK	322	501	156%
INDONESIA (ID+TP f	307	0	0%
UNITED ARAB EMIRA	282	821	291%
AUSTRALIA	263	101	38%
BRAZIL	228	137	60%
CZECH REPUBLIC (CS	222	-	0%
NIGERIA	220		0%
SINGAPORE	214	1,890	882%

Tables 6a and 6b. Hubs for the UK trade of unitised goods. (Sources Eurostat, DfT 2010) (Note: the greater the 'DfT/Trade' ratio figure (column on the right of each table), the greater is the share of transhipped containers that flow via that country)

Our analysis was based on two datasets: trade statistics and transport (DfT) statistics. It is relatively easy to assess, on one side, the UK international trade in value, and, on the other side, the traffic at major UK ports; it is, however, much more difficult to identify the routes taken by these trades and their precise final destination. The assessment of routes and transhipment is a very difficult task to undertake through direct data collection; journeys with two or more transhipments are very difficult to track, as no statistical data are available for this. We concentrated our attention on major flows only (usually above 100 KT / year), since the analysis of minor flows could have high uncertainty due to the discrepancies between trade and traffic statistics. In general, it is quite difficult to define for all trade flows the precise routes used by every vessel (port calls, waiting times, etc.). It is possible, however, to estimate for each destination country a likely route used by the vessels. Shipping companies usually travel through the same routes for a specific destination, and only the number and location of stops varies year-on-year. Tables 6a and 6b summarise our analysis and illustrate the main hubs for the transhipment of UK-centric unitised goods.

Another, and often overlooked, dimension to the discussion on (container) transhipment is the need to understand the movements of the actual shipping vessels – a container may not be transhipped between different vessels / routes, but the (single) vessel it is loaded onto may in fact traverse multiple ports between origin and destination. We therefore also analysed, for a sample period at the UK's largest container port (Felixstowe), patterns of vessel activity (Figure 39 and Figure 40). Many ships entering Felixstowe arrived from Rotterdam, with fifteen scheduled arrivals within a seven-day period; the next most frequent last ports of call were Antwerp and Bremerhaven; it is apparent also that many (but not all) ships arriving into Felixstowe last called at ports in northern Europe. This accords with the schedule structures of the major container lines whose 'strings' (network of ports on a route) involve calls to a number of European ports once the deep-sea leg from Asia has been completed. Of course the feeder vessels shuttling between Felixstowe and the key Northern Europe port hubs are also included in the data.

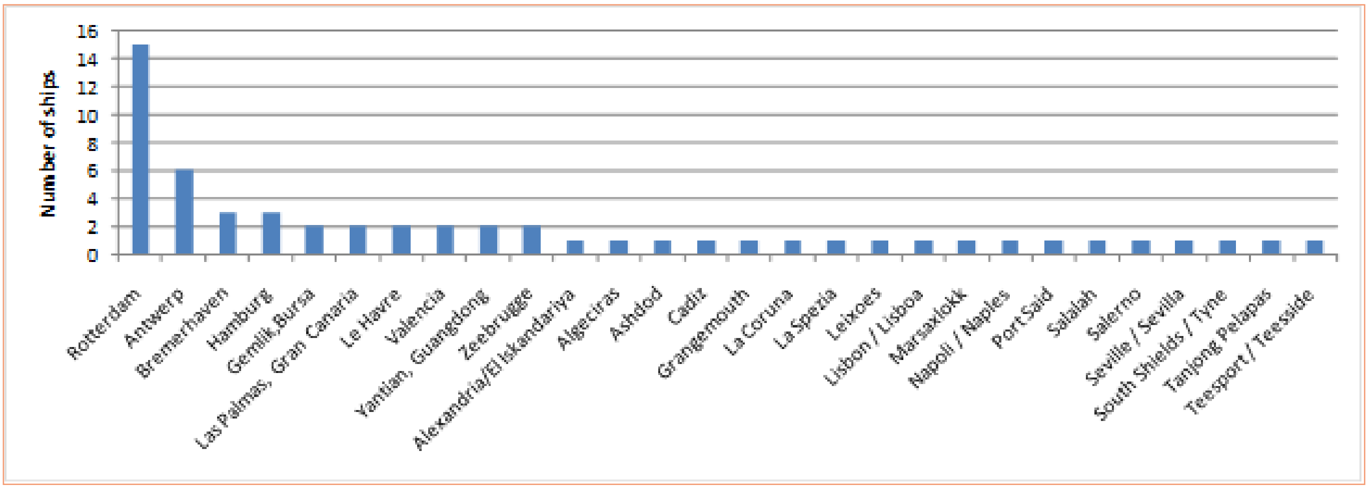


Figure 39. Last port of call for vessels arriving at Felixstowe Port between 13 and 19 May 2011.

The same ships that enter Felixstowe, shown in Figure 39, then leave the port of Felixstowe for their next port of call. Figure 40 shows that for the sample period between 13 and 19 May 2011, vessels that were scheduled to leave Felixstowe were destined primarily for ports in northern Europe, with Rotterdam being the most frequent next port of call for vessels leaving Felixstowe port. This is followed closely by Antwerp, Bremerhaven and Hamburg.

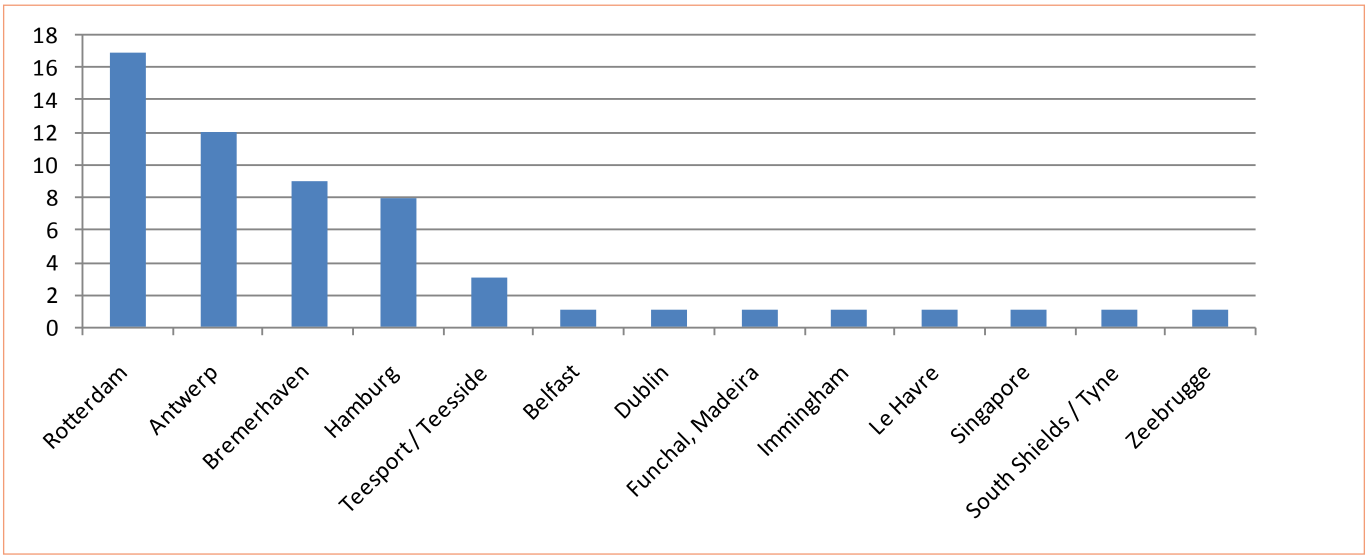


Figure 40. Next port of call for vessels leaving Felixstowe Port between 13 and 19 May 2011

Following on from this analysis we also analysed data on the 'strings' operated by the major shipping lines with ports of call in Europe with a view to gauging implied levels of transhipment arising from these network structures

Combining the analysis on transhipment in this WP with both the apportionment and emissions calculations in the preceding one (WP3-4) and with the micro-level analysis of supply chains in the next (WP3-6), we were able to illustrate typical emissions profiles for direct routed versus transhipped containers:

- Container shipped direct Middle East – Felixstowe: 3,493 kg CO2e
- Container shipped Middle East – Antwerp: 3,558 kg CO2e, with the various connecting RoRo and LoLo services from there generating emissions ranging from 382 to 3,435 kg CO2e.

It should also be noted that an added dimension is that the transhipment activity itself (unloading from one vessel and loading onto another) will also generate extra carbon emissions. We estimate that container handling at a port accounts for 35kgCO2e per TEU on average; obviously this figure is small in the context of an end-to-end carbon footprint, but it is not an insignificant figure either.

The above profiles of course do not represent the entire end-to-end emissions as road/rail journeys to and from ports need also to be considered (the inland location of freight origin/destination is thus a key issue in the total emissions calculation); the next WP (3-6) on supply chain mapping discusses and illustrates this further.

Another aspect to consider with regard to liner networks is what is the cost trade-off between operating many smaller vessels on multiple point-to-point routes versus operating larger vessels and associated feeder vessels on hub-and-spoke networks? Presumably at some point diseconomies of scale 'kick in' as vessels operating between the hubs get bigger and thus require increased feeder vessel capacity. Another dimension to this is if transit time increases with transhipment (it usually does, but interestingly not always) then the owners of the cargo suffer an opportunity cost penalty as a result of the cargo being in transit for a longer period.

WP3-6 Map supply chains for different types of containerised products and estimate the share of maritime related CO_2 emissions (containers only) [in conjunction with WP4]

Shipping is a derived demand: it exists not for itself but in response to demand from consignors for the transport of freight to consignees. Transport logistics systems, of which shipping is a key component, respond to trade demands and help to 'lubricate' the global economy by providing nodes and links (ports, distribution centres, transport services, etc.) to facilitate the demands for product movement. Transportation, and particularly shipping, thus plays a critical role in the global economy and as such is one of the key enablers of globalisation. In order then to understand the role and activity of shipping it is necessary to also consider the place of shipping within the wider transport system, and in turn to understand what drives the demand for international freight transport. This demand for international freight transport occurs within 'end-to-end' supply chains linking sources of production with the ultimate consumer. Shipping and ports constitute important links and nodes within many supply chains, both in terms of their costs and their performance. When seeking to mitigate the (growing) CO_2 footprint associated with shipping activity, we need then to understand the fit between shipping and the wider supply chains and logistics systems within which shipping operates.

Dr Rigot-Muller and Professor Mangan completed training on the Arena simulation software. Three companies were recruited and their supply chains analysed:

- **Company 1:** A logistics provider and its retail partner, both regarded as best-in-class companies. They gave us significant access to data on inbound product flows from both Turkey and Portugal and the potential (carbon savings) from modal shift was analysed.
- **Company 2:** The EMEA business unit of a company in the specialist painting/chemical products sector. The analysis covered all outbound flows from the production facility in the north of the UK towards warehouse facilities, mainly in continental Europe but also in the USA, China, Singapore, Australia, India and Brazil.
- **Company 3:** A major UK distributor of plastic products. The analysis concerned data on sourcing from different overseas suppliers, storage in the central warehouse in the East Midlands and shipping to more than 600 delivery points in the UK.

Publications detailing the analysis and its results include: Mangan *et al*. (2012), Lalwani *et al*. (2012) and Rigot-Muller *et al*. (2013). For Company 2, emissions towards several destinations were calculated and two alternative routes to southern Europe were compared, using several transport modes (road, RoRo (roll-on roll-off), rail and maritime).

For Company 3, several alternative realistic routes towards the UK were analysed and the optimal route minimising total carbon emissions was identified and tested in real conditions. An adapted Value Stream Mapping (VSM) approach was used to map carbon footprint and calculate emissions; in addition AIS data provided information for vessel specification, allowing the use of more accurate emission factors for each shipping leg. The analyses demonstrated that end-to-end logistics carbon emissions can be reduced by between 14% and 21% through direct deliveries (to Felixstowe and Southampton) when compared to deliveries with transhipment and warehousing (in Antwerp). For distant destinations the maritime leg of the supply chain is the main contributor to the total emissions. The feasibility of the optimal routes was demonstrated with real-life data and is illustrated in Figure 41 and Figure 42. It is notable that one of the main apportionment approaches (that of Defra in the UK) generates higher carbon footprints for routes using Ro-Pax vessels, making those suboptimal. This raises (again) the question as to what is the correct apportionment method to use in supply chain mapping, as this will influence the results obtained.

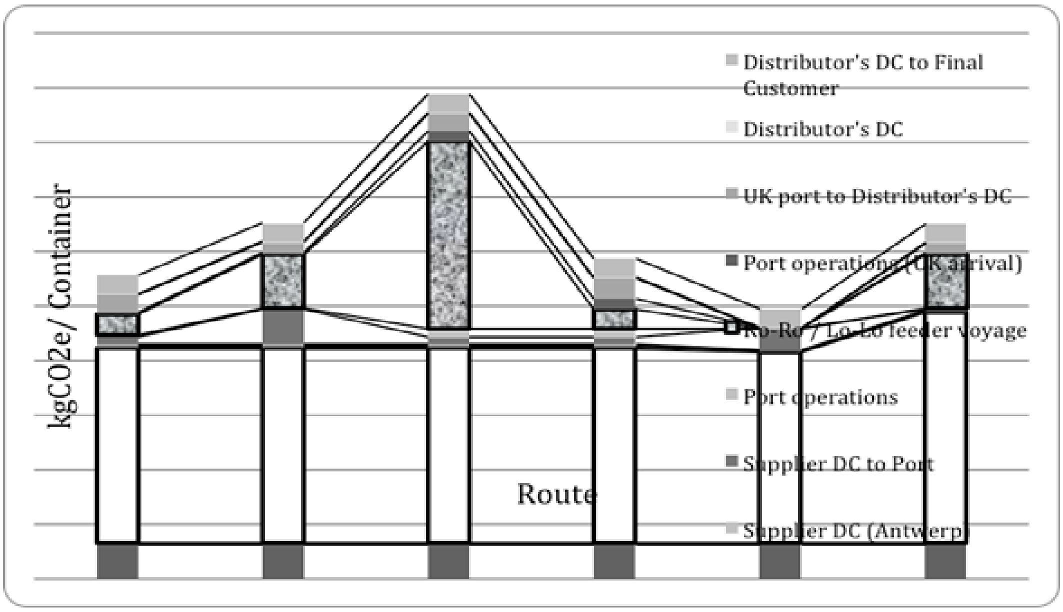


Figure 41. End-to end CO_2 emissions for different routes of palletised products

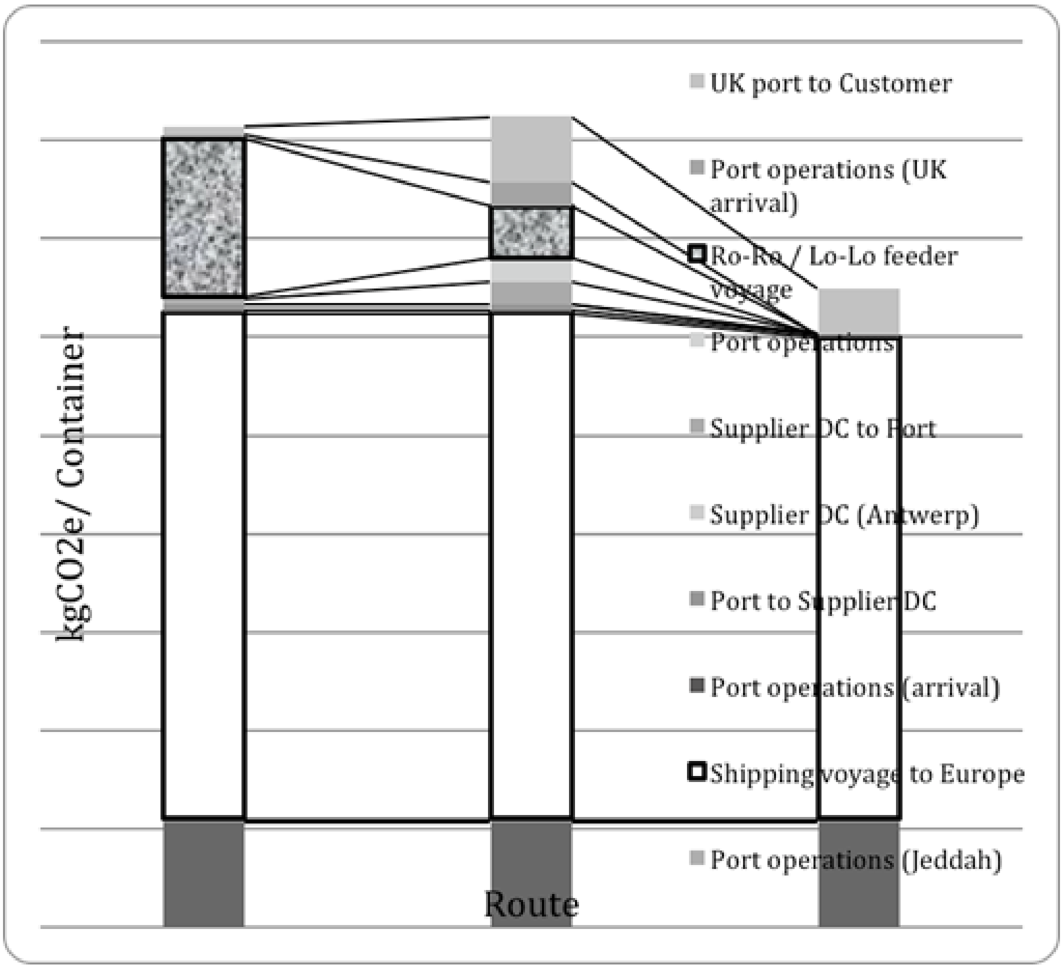


Figure 42. End-to-end CO_2 emissions for different routes of bulk products

We are still engaged with Company 1 (the logistics provider) with whom we (including Dr Tristan Smith from UCL) organised a joint workshop ('Moving towards sustainable logistics') in October 2012 and to which they invited some of their key clients (it is notable too that the logistics provider, one of the largest in the sector, also had both their 'Head of Green Logistics' and their 'Global Head of Sustainability' attend the workshop). With regard to logistics and low carbon shipping, some of the many and diverse issues participants raised at the workshop included questions around reliability and transparency of information (speed/reliability/price), whether cost of carbon can be absorbed or passed on along the supply chain, direct services versus transhipments, and the perceived impact of the London Gateway port and related infrastructure project. There was a consensus among participants that within retailers and other consignees the role of the 'product buyer' is key: they need to be 'educated' around the impact their sourcing decisions have on logistics costs.

Participants also discussed slow steaming, and while they noted its obvious environmental benefits, they were quick to point out that industry values costs and speed differently. As well as cost and speed, the workshop participants also noted that another dimension is equally important: reliability. They were emphatic too (many were clients of the various major container shipping lines) that passing transport cost increases on to customers is simply no longer an option. It was also observed that perhaps finally the link between product quality and transit speed has been broken: one participant dryly noted that an apple can be refrigerated for six months with its product quality remaining unchanged! The question for many buyers is no longer 'how fast?', but 'how reliable?', with issues of long lead times, stretched supply chains and product availability all coming to the fore.

As part of our analysis of the supply chain of one of Company 1's key retail clients we conducted a routing analysis on one of their inbound product flows from Portugal. Currently goods are delivered using road transport and consolidating cargo through milk runs. After reviewing suppliers' locations, volumes, potential ports of origin and destination, we came up with a solution that reduced the carbon impact for the same route by over 50%, by switching more freight from road to sea and ensuring cargo consolidation at origin. This illustrates the general consensus that, ceteris paribus, significant supply-chain-wide CO_2 savings can be made by shifting more product from other modes to the maritime mode.

Key Findings and Their Relevance to Academia, Industry and Policy Makers

As noted above, we believe that our work around ports, in terms of the various initiatives and calculation of their carbon emissions, is the first comprehensive review of port-related sustainability issues in the UK and should be of interest to all stakeholders, having to date received very little attention in the academic literature.

Our work on mapping the shipping network, measuring transhipment, and seeking to calculate UK-centric maritime CO_2 emissions, is relevant to all stakeholders and will serve as a benchmark for future analyses and policy initiatives.

Our third area of work, supply chain mapping, has already been of significant interest to our partner companies, and contributes to the understanding of the topic of maritime CO_2 emissions in the context of the wider supply chain, a topic which will be of growing interest.

Finally, our overarching efforts to connect up all of our work and insights around logistics with future ship designs is a key output of our three years' work on WP3, and represents our considered view as to how logistics and ship designs will intersect going forward, a topic of obvious interest and importance to all stakeholders.

Dissemination

The various journal papers, briefing papers and conference papers that were produced by WP3 are detailed below. Work Packages 3 & 4 also hosted the LCS 2012 conference and as part of this conference we had a track dedicated to maritime logistics, which included presentations from Damco, Dubai Ports World (DPW) and Heineken. The work is highlighted in the prestigious UNCTAD Transport Newsletter (No.53, Quarter 1 2012).

In addition, Paul Stott conducted research to review the potential gains in efficiency that may be facilitated by the expansion of the Panama Canal, and thereby the relaxation of the panamax constraint on ship design. This is the most significant change in ship routing in the past 100 years and the potential gains in ship design efficiency are significant. This was the first time that the effect of the expansion had been examined from the ship design standpoint rather than the trade routing standpoint, and the two were found to be significantly de-coupled: that is to say that the effect on ship design is not related specifically to the change in trades that may develop following the opening of the expanded canal. This is unusual in that ship design is normally derived from trade requirements and this is an important principle in naval architecture. In the case of panamax beam, the constraint is generally adopted at a certain ship size in case the ship ever needs to transit the canal, not necessarily because it intends to do so. The implications for the fleet are therefore much wider than being simply related to changing trade patterns through the Canal. It has also been possible, therefore, to study the change in design without knowing what changes in trade patterns will result. Two papers (Stott and Wright, 2011; Stott, 2012) resulted from this work, along with wide take-up by the press (including an interview on BBC Radio 4) and thereby good opportunities for the dissemination of work by the LCS group.

Journal papers

Gibbs, D., Rigot-Muller, P., Mangan, J., and Lalwani, C. (2014) The role of sea ports in end-to-end maritime transport chain emissions. Energy Policy 64 (337–348).

Rigot-Muller P, Lalwani C, Mangan J, Gregory O, Gibbs D (2013). Optimizing end-to-end maritime supply chains: a carbon footprint perspective. *International Journal of Logistics Management,* 24(3), 407-425.

Briefing Papers

Gibbs, D., Rigot-Muller, P., Mangan, J., and Lalwani, C. (2012) Ports as Drivers for a Sustainable Maritime Transport Sector. LCS 2012

Mangan, J., Bennett, M., Lalwani, C., and Rigot-Muller, P. (2011) Mapping Shipping Activity in the UK. LCS 2011

Conferences

Bennett, M., Dinwoodie, J., and Mangan, J. (2011) Origin and destination of maritime container flows to and from the United Kingdom. ICMMA 2011 (Plymouth, UK)

Mangan, J., Bennett, M., Lalwani, C., Dinwoodie, J., and Gibbs, D. (2010) Logistics considerations in a systems approach to low carbon shipping. LRN 2010 (Harrogate, UK)

Lalwani, C., Mangan, J., Gibbs, D., and Rigot-Muller, P.(2012) Optimizing end-to-end maritime supply chains: a carbon footprint perspective. ISL 2012

Mangan, J., Lalwani, C., Gibbs, D., Feng, M., and Karamperidis, S. (2012) The relationship between transport logistics, future ship design and whole system efficiency. LCS 2012 (Newcastle, UK)

Mangan, J., Lalwani, C., Gibbs, D., Rigot-Muller, P., and Bennett, M. (2011) Logistics and Low Carbon Shipping. LCS 2011 (Strathclyde, UK)

Mangan, J., Lalwani, C., Rigot-Muller, P., Gibbs., D., and Dinwoodie, J. (2012) Improving the environmental performance of maritime transport in global supply chains. RIRL 2012

Rigot-Muller, P., Mangan, J., Lalwani, C., and Dinwoodie, J. (2012) Assessing Emissions of UK International Maritime Traffic. LCS 2012 (Newcastle, UK)

Rigot-Muller, P., Mangan, J., Lalwani, C., and Dinwoodie, J. (2012) Mapping UK international seaborne trade and traffic. LCS 2012 (Newcastle, UK)

Rigot-Muller, P., Mangan, J., Lalwani, C., and Gibbs, D. (2011) Logistics and Low Carbon Shipping. ENSUS 2011 (Newcastle, UK

References

AEA Energy and Environment (2008) Greenhouse Gas Emissions From Shipping: Trends, Projections and Abatement Potential, Final Report to the Committee on Climate Change, ED43808, Issue 4.

Buhaug, Ø., Corbett, J.J., Endresen, Ø., Eyring, V., Faber, J., Hanayama, S., Lee, D.S., Lee, D., Lindstad, H., Markowska, A.Z., Mjelde, A., Nelissen, D., Nilsen, J., Pålsson, C., Winebrake, J.J., Wu, W.–Q., Yoshida, K. (2009) *Second IMO GHG study 2009.* London: International Maritime Organization (IMO).

Committee on Climate Change (2011) Review of UK shipping emissions: Supporting analysis. Committee on Climate Change: London.

Gibbs, D., Rigot-Muller, P., Mangan, J. and Lalwani, C. (2012) Ports as drivers for a sustainable maritime sector. Low Carbon Shipping Consortium WP3 Briefing Paper.

Gilbert, P., Bows, A., Starkey, R. (2010) Shipping and climate change: Scope for unilateral action. Tyndall Centre for Climate Change Research, The University of Manchester: Manchester.

Lalwani, C., Mangan, J., Gibbs, D. and Rigot-Muller, P. (2012) Optimizing end-to-end maritime supply chains: a carbon footprint perspective. ISL Conference, July 2012.

Mangan, J., Bennett, M., Lalwani, C., Dinwoodie, J., Gibbs, D. and Smith, T.W.P. (2010) Logistics considerations in a systems approach to low carbon shipping. Logistics Research Network (LRN) conference, Harrogate.

Mangan, J., Bennett, M., Lalwani, C. and Rigot-Muller, P. (2011) Mapping shipping activity in the UK. Low Carbon Shipping Consortium WP3 Briefing Paper.

Mangan, J., Lalwani, C., Rigot-Muller, P., Gibbs, D. and Dinwoodie, J. (2012)

Improving the environmental performance of maritime transport in global supply chains. RIRL Conference August 2012.

Qi and Song (2012) Minimizing fuel emissions by optimizing vessel schedules in liner shipping with uncertain port times. *Transportation Research E*, 48, 863-880.

Rigot-Muller, P., Mangan, J., Lalwani, C. and Dinwoodie, J. (2012a) Assessing emissions of UK international maritime traffic. LCS 2012

Rigot-Muller, P., Mangan, J., Lalwani, C. and Dinwoodie, J. (2012b) Mapping UK international seaborne trade and traffic. LCS 2012.

Rigot-Muller, P., Lalwani, C., Mangan, J., Gregory, O. and Gibbs, D. (forthcoming, late 2013) Optimizing end-to-end maritime supply chains: a carbon footprint perspective, International Journal of Logistics Management.

Stott, P. and Wright, P. (2011) Opportunities for improved efficiency and reduced CO_2 emissions in dry bulk shipping stemming from the relaxation of the panamax beam constraint. *Transactions of the Royal Institution of Naval Architects Part A: International Journal of Maritime Engineering;* 153: 215-30

Stott, P. (2012) New panamax and its implications for ship design and efficiency. LCS 2012

WORK PACKAGE 4

LOW CARBON SHIPPING ECONOMICS

Led by Professor Dinwoodie and Ms Melanie Landamore, with input from Professor Birmingham, Mr Martin Gibson, Ms Nasima Chowdhury, Dr Sarah Tuck and Captain Paul Wright.

WP4 – LOW CARBON SHIPPING ECONOMICS

Led by Professor Dinwoodie and Ms Melanie Landamore, with input from Professor Birmingham, Mr Martin Gibson, Ms Nasima Chowdhury, Dr Sarah Tuck and Captain Paul Wright.

Overview

This WP included contributions from staff at Newcastle University and Plymouth University and was split over two main tasks: Task 4.1 considered the cost of the ship as a system, and in particular, the technologies available to reduce its emissions and their environmental, social and economic cost-benefit; and Task 4.2 undertook studies to validate and expand on controversial issues concerning shipping cycles, and macro and micro economic models which considered the equilibrium between supply and demand for shipping resources.

Main Research Focus

The research questions WP4 predominantly considered can be summarised as:

- to consider the economics and cost-benefit of the application of low carbon methodologies and technologies to ships and shipping; and
- to better understand the economic climate within which shipping operates, including the cyclical nature of the shipping market.

The overarching commercial aim of the shipping industry is to satisfy freight and passenger transport demands and to meet environmental objectives, at maximum profit. Consequently, one must first understand how shipping costs will be affected by developments in technology, ship design and operation. This information can then be used to look at the economics of shipping markets – particularly under future fuel price and fiscal scenarios. Both conventional and triple bottom line ('people, planet, profit') approaches to the assessment of whole life ship costs were considered.

Main Outputs and Activities

Task 4.1: Economic and Environmental Costs of Ships

The main research focus of Task 4.1 was the economic and environmental costing and cost-benefit analysis of different approaches to reducing the contribution of shipping to global warming, and general environmental impact.

A baseline cost model for ship new build price, and through life operational costs was developed; this was used to analyse the economic cost implications (capital expenditure and through life operational cost) of the large set of technologies being studied in WP 2, and formed a key input to the GloTraM model developed in WP1. The other focus under Task 4.1 was the relative environmental costs of shipping, and particularly the impact of considering more than a simple 'carbon' measure of the CO_2 emitted, directly calculated from fuel consumption. The intention is to demonstrate the relative potential impact of decisions and scenarios on ships and shipping, rather than to predict the absolute cost or benefit available to a specific ship, owner or operator.

When considering operational emissions of existing shipping it is common to discount the life cycle impacts of the ship entirely, as they generally contribute a relatively small percentage (often less than 10%) to the overall harmful impacts, particularly if focusing on Global Warming Potential (GWP). They are also often less visible to those concerned with transport policy, and overlap into global construction impacts. However, if shipping is to achieve its share of the 80% GWP reduction deemed necessary to avoid unsustainable climate change, then significant reductions in either operational emissions or demand for shipping must be achieved. Current models predict that demand for shipping will not drastically reduce in the short term, and therefore significant operational efficiency gains must be assumed. There is therefore a need for models that consider the impact of the whole ship, for two major reasons:

- emissions from shipping may no longer be dominated by operational emissions directly related to the type and quantity of fuel burnt;
- actions to reduce these emissions, such as slow steaming, and the uptake of more fuel-efficient designs (whether new build or retrofit) will cause the proportion of GWP impact embodied within the ship itself to increase further.

In response to this, a model was developed which estimated the whole lifecycle emissions of a ship, rather than just the operational emissions. Whilst the fuel-related operational emissions of a standard cargo ship operating today dwarf the impacts from other lifecycle stages, this may not be true for potential future designs, particularly in a very low carbon economy scenario. By varying inputs, such as fuel type and ship speed, and applying abatement technologies to a set of standardised ship average characteristics, as well as to real ships as a case study, the effect on lifecycle emissions, and the share of them attributable to fuel-based emissions, can be assessed.

Emission reduction scenarios are primarily presented as comparative: the average baseline ship figures used will not be representative for the majority of individual ships, and so description of a reduction as absolute would be misleading. Full lifecycle analysis of individual ship systems can demonstrate absolute savings for that particular system: the method employed here was to consider the overall relative reductions available and likely cost implications for a range of ship types and sizes.

The cost-benefit analysis of technological approaches to reducing operational CO_2 emissions (from combustion of fuel) via fuel savings was closely integrated with WP1 using the GloTraM model, and so is reported there. Validation of, and expansion upon, these results within WP4 was not possible within the project timeframe but will be taken forward in future work. These results present the through life GHG reduction and environmental score models for shipping, incorporating averaged model estimates of operational fuel savings for the various abatement technologies, and other potential routes to impact, for comparison.

All cost and emission scenario analysis carried out within Task 4.1, and reported here, is comparative rather than absolute. The intention is to demonstrate the relative potential impact of decisions and scenarios on ships and shipping, rather than to predict the absolute cost or benefit available to a specific ship, owner or operator.

Task 4.2: Economic Modelling of Shipping and Shipping Cycles

Because the macro-economic modelling of shipping could not be divorced from technological, regulatory and ship design issues, most issues concerning the demand for shipping were closely integrated with studies in WP1. Work Package 4 undertook supplementary studies to validate and expand on controversial issues concerning shipping cycles and macro and micro economic models to determine from constituent components the equilibrium between supply and demand for shipping resources. The need to understand maritime practitioners' perceptions of the likely future demand for shipping promulgated the setting up of two Delphi surveys, which engaged international panellists with long-term industrial commitment. One survey focused on wet bulk demand for shipping and another on dry bulk demand. In addition, a top-down approach was used to assess the impact of bunker fuel price changes on spot freight rates for shipping coal, by estimating relevant elasticities from Clarksons SIN database. This data has implications for the deployment of market-based emission control measures, such as a bunker fuel levy. Some analysis of publicly reported practitioner attitudes towards slow steaming at different stages in the business cycle was also undertaken.

What are The Key Findings and What is Their Relevance to Commercial and Policy Issues?

Despite variation in individual ship sizes and classes, operational emissions from ships utilising fossil fuels (including LNG) contribute 90-99% of total greenhouse gas impact at 2011 average service speeds. At 50% lower speed, however, the range of operational emission contribution (total emissions) is between 56% (for a VLCC) to 82% (for a handymax container ship). At full speed these were 91% and 97% respectively.

The consideration of whole life emissions reduces the effect of the improvement gained from CRTs (carbon reducing technologies) by 1-2%, compared to consideration of operational emissions only.

A measure of global environmental impact (ReCiPe method) shows close agreement with a global warming potential method (IPCC 100 year GWP) for emissions from ships and shipping overall, despite small variations in category contributions, meaning that climate change impact can be considered to be the key emission category for shipping, and a proxy for whole environment impact without risking unintended consequences from a significant increase in other impact categories.

Modelling of industry-wide take-up of measures to mitigate operational CO_2 allows for identification of routes to global efficiency gains: however, wider impacts from the build, end-of-life, and maintenance of ships can become significant when action is taken to reduce fuel consumption.

A significant proportion of the mitigating actions available to shipbuilding to reduce environmental impact are external to the shipyards themselves, related to the production of steel, and secondly the generation of electricity. Closed loop recycling (CLR) can deliver reductions of 13-15% embodied emissions. On a typical ship today this equates to a reduction of only 1-3% in whole lifecycle emissions.

The whole life cost-benefit ($/t.CO2e$_{avoided}$; Table 7) of a majority of CRTs demonstrates a reduction in cost as well as in lifecycle GHG emissions.

Early scrapping of inefficient ships is a frequently observed consequence of an increase in economic imperative to reduce fuel use through a carbon levy on fuel, or similar emissions trading scheme. The impact of scrapping an inefficient ship before the end of its useful life can be significant; scrapping a ship after only a decade of operation may triple the relative impact of emissions from the construction and end-of-life phases (up to 26%). A carbon levy on shipbuilding emissions could introduce a new build price premium of up to 11.8%.

A number of key findings have come out of the baseline ship impact study and are listed below.

- The contribution from build, maintenance and end-of-life (BME) emissions and from operational emissions varies for different ship classes, but generally impact is dominated by the operation phase: BME emissions for the baseline ships vary between 1 and 10% and are more significant on very large and very small ships.

- In the scenarios analysed, the relative impact from either method remains broadly commensurate for emissions from ships and/or shipping; therefore climate change impact can be considered to be the key emission category for shipping without risking unintended consequences from a significant increase in another impact category, such as one related to human health or resource depletion.
- The build phase emissions from shipbuilding are generally dominated by steel and steelwork. The impact from the steel is around 80% for all ship classes with the exception of gas carriers; the stainless steel (or similar) and insulation content of the pressurised tanks contributes around 20% of impact (for ~10% lightweight).
- ReCiPe method whole life emissions show a significantly lower proportion of impact from electricity use, but total build phase emissions remain equivalent. In comparison with operational emissions, the effect is statistically insignificant.
- For the majority of ship carbon abatement technologies considered, the GHG emission savings from the reduction in fuel consumption are dominant for HFO, MDO, or LNG. Modelling of industry-wide take-up of measures to mitigate operational CO_2 allows for identification of routes to global efficiency gains: however, wider impacts from the build, end-of-life, and maintenance of ships can become significant when action is taken to reduce fuel consumption.

GWP and ReCiPe impact baselines agree closely for all abatement technology whole life impacts assessed. Whilst the significant additional steelwork or other materials required, for sails, for example, will increase the BME emissions phase, reduction of impact is still closely linked to operational emissions. Generally, the impact of the consideration of whole life emissions will reduce the available gains by something in the order of 1% (Table 7). The only significant contributors to increasing the build and end-of-life phase GWP emissions of a ship occur when a significant amount of additional steelwork is required (e.g. sails and contra-rotating propellers [CRP]), suggesting that even for novel designs, the climate change impact of the shipbuilding process will continue to be dominated by steel use and associated processing. Increased take-up of very low CO_2 fuels (measured at point of use) such as hydrogen, biofuels or nuclear power will refocus attention on the build phase of the ship, including any

	NOE	Total	
		high	Low
Contra-rotating Propellers	3.0%	2.9%	2.5%
Vane wheel	3.6%	3.4%	3.1%
Prop section optimisation	2.0%	1.9%	1.7%
Ducted Propeller	5.0%	4.8%	2.0%
pre-swirl duct	2- 4%	3.9%	1.1%
Propeller upgrade (nozzle)	2- 10%	9.7%	1.6%
Propeller boss cap fins	2.0%	1.9%	1.6%
Asymmetric Rudder	2.0%	1.9%	1.6%
Propeller rudder bulb	2.0%	1.9%	1.6%
waste heat recovery	3- 29%	28.0%	3.0%
Sails	8- 25%	23.0%	7.0%
Sails +10% speed red.n	21- 34%	31.0%	19.0%
Sails +20% speed red.n	31- 48%	42.0%	27.0%
Wind engine	2.7- 24%	21.7%	2.1%
Wind kite	3.8- 51%	49.0%	3.5%
Covering hull openings	0.9%	0.9%	0.6%
Optimisation of dimensions (med speed)	3.0%	2.8%	2.1%
Other Post Swirl Gadgets	1.6%	1.5%	1.2%
Main Engine Tuning Phase2	7.0%	6.8%	6.1%
Solar Power	0- 0.07%	0.03%	0%

Table 7: All whole life costed abatement technologies with relative range of impact of whole life emissions versus operational emissions

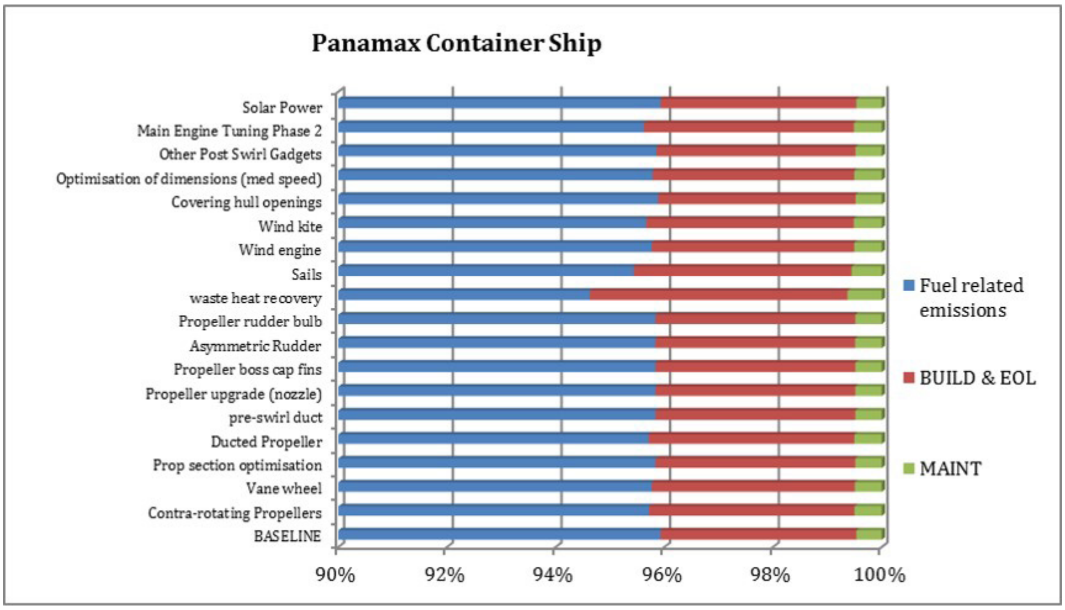


Figure 43: Relative phase-delineated impact of emission reduction potential of abatement technologies applied to a panamax container ship

abatement technologies. It is highly likely that the small savings achievable via many of the technologies could become carbon abatement negative if a zero or near zero emission fuel were used, although they may well remain economically viable as a fuel-saving device.

The reductions available from the use of wind-assisted devices, particularly in conjunction with a reduction in service speed, are significant (for example, see Table 7): a small liquid bulk tanker fitted with sails and operating at 20% below 2011 average service speed may see a reduction of operational emissions (and fuel consumption) in the order of 48%. In this instance the impact of other through life emissions could be 21% of total emissions. A calculation that focused only on operational emissions would significantly overestimate the positive impact of this system on reduction of climate change impact.

Reduction in service speed alone significantly affects the impact phase contributions. For the baseline ships, a reduction in service speed of 10% corresponded with a 2-3% increase in contribution from BME phases versus operation phase (for both ReCiPe and IPCC 2007 100-year GWP methods). As ships go more slowly, the impact of through life emissions will become more significant. At 50% lower speed, the range of operational emission contribution (total emissions) is between 56% (for a VLCC) and 82% (for a handymax container ship), compared with 91% and 97% respectively at full speed.

The use of HFO or MDO has little impact on the overall GHG emissions for a given ship: the operational emissions if MDO is used are around 4% lower, and the contribution of BME phase emissions is 3-11% for either fuel. Applying the total impact (ReCiPe method), BME phase emissions remain around 3-11% of the total, and HFO BME contribution is reduced at 2-10%. The broader environmental impacts of residual fuel (HFO) appear to be slightly better modelled by the ReCiPe method, although they are not statistically significantly. LNG as a fuel appears to reduce emissions significantly (10-12% below HFO baseline), even where the through life and whole environmental impact emissions of pressure tank manufacture and reduced ship capacity are considered. The variation in percentage of emissions from the BME phases is slightly larger than for MDO or HFO (14% for a handymax tanker, to 4% for a handysize container vessel or panamax bulk carrier).

A significant proportion of the mitigating actions available to shipbuilding to reduce environmental impact are external to the shipyards themselves, related to the production of steel, and, secondly, the generation of electricity. Closed loop recycling (CLR) aims to recover as much steel as possible from the ship at end-of-life: typically a 13-15% reduction in GWP build impact category contribution from low-alloyed steel production is available if closed loop recycling is employed (17% for LNG Carrier). The reduction in ReCiPe impact is slightly less: 10-12% (15% for LNG carriers). Overall, these reductions typically equate to a 1-3% reduction in whole lifecycle emissions against a current baseline ship.

The whole life cost-benefit ($\$/t.CO2e_{avoided}$; Table 8) of a number of abatement options compares the lifecycle economic and environmental (IPCC GWP method t.CO2e.) costs. The majority of technologies presented demonstrate a reduction in cost as well as in lifecycle GHG emissions.

Panamax Container	Operational fuel saving (%)		Aux fuel saving (%)	Abatement potential ktCO2.e		Abatement COST $/t.CO2e	
	Min	Max		Min	max	min	max
Contra-rotating Propellers	3	5	-	30		$ 239	
Vane wheel	3.6	5	-	38	52	$ -148	$ -78
Prop section optimisation	2	-	-	21		$ -152	
Ducted Propeller	5	-	-	52		$ -154	
pre-swirl duct	2	4	-	21	42	$ -136	$ -74
Propeller upgrade (nozzle)	2	10	-	21	105	$ -65	$ -66
Propeller boss cap fins	2	-	-	21		$ -142	
Asymmetric Rudder	2	-	-	21		$ -156	
Propeller rudder bulb	2	-	-	21		$ -141	
Waste heat recovery	0.04	-	100	262		$ -164	
Sails	9	-	-	91		$ 18	
Wind engine	3.4	-	-	35		$ 74	
Wind kite	4.00	6.67	-	62		$ -154	
Covering hull openings	0.9	-	-	9		$ -158	
Optimisation of dimensions (med speed)	3	-	-	31		$ -130	
Other Post Swirl Gadgets	1.6	-	-	17		$ -131	
Main Engine Tuning Phase2	7	-	-	73		$ -54	
Solar Power	-	-	0.14	0		$ 443	

Table 8: whole life GWP impact abatement potential of selected technologies on a panamax container ship at present value [ship lifespan 30 years; fuel cost $500/tonne; interest rate 5%]

Applying the current 2010 carbon price of $20/tonne would make sails a cost negative option for reducing emissions, assuming the calculated 9% efficiency savings could be realised. If the carbon price were $40/tonne, then the cost per tonne $\mathrm{CO_2}$e emitted to implement the wind engine system (Flettner rotors) would be $34/t$\mathrm{CO_2}$.e. At $100/tonne (high 2030), even if fuel price were to remain at $500/tonne, the wind engine system would become cost-positive. The abatement cost associated with installing a contra-rotating propeller system would also reduce to $139/ tonne $\mathrm{CO_2}$.e. If the fuel price is set at $1496/tonne (US EIA Annual Energy Outlook 2010 Distillate Fuel Reference Scenario Price for 2035), only solar power remains a cost-plus consideration for abatement of CO2e: in addition, the current assumed level of solar power available to a container ship (deckhouse only) means that actual $\mathrm{CO_2}$e abated is effectively zero.

The cost-effectiveness as measured by operational efficiency (g$\mathrm{CO_2}$ emitted per tonne.nm from fuel use) of the options considered by Low Carbon Shipping: A Systems Approach in terms of likely market take-up under future fuel price and fiscal scenarios is reported elsewhere in the project, primarily in WP1, as this was modelled using GloTraM. Therefore, given the focus of industry and policymakers on fuel efficiency and operational (fuel) emissions, some of the key outputs of this work, particularly the identification of economic costs of abatement measures, are reported elsewhere. However, the analysis carried out of the whole life GHG emissions, non-dimensionalised environmental impact scores (ReCiPe model) and through life cost-benefit modelling, utilising these analyses, provides some important context.

Application of economic incentives to attempt to reduce environmental impact from shipping, given existing regulations concerning NOx and SOx emissions, as a fuel levy or voyage $\mathrm{CO_2}$ levy, are appropriate in the short term, considering the current makeup of the global fleet and the close correlation of GWP and total environmental impact for shipping demonstrated here. Early scrapping of inefficient ships is a frequently observed consequence of an increase in economic imperative to reduce fuel use through a carbon levy on fuel, or similar emissions trading scheme The impact of scrapping an inefficient ship before the end of its useful life can be significant: scrapping a panamax container ship after 20 years' operation increases the impact from the shipbuilding phase by 1-2%; if the ship is scrapped after only 10 years' operation, then 10-11% of its lifetime environmental impact will have come from the construction, maintenance and end-of-life phases, compared with 3-4% if the same ship is operated for 30 years. For a handymax tanker, the whole life emissions are 12-13% higher than those predicted by assessment of the operational efficiency after 30 years' operation, but 23-26% if scrapped after only 10 years. The variation between baseline and early scrapping BME % contributions is relatively constant across ship classes. A carbon levy on shipbuilding emissions could introduce a new build price premium of up to 11.8%.

Shipping, like all modes of transport, is a derived demand, so in order to understand the demand for shipping we need to understand the underlying drivers of this demand. Maritime professionals' expectations of trends in dry bulk shipping flows to 2050 highlighted drivers including Arctic ice melt, canal upgrades, piracy and mode splits. Globally, expected doubling of raw materials shipments to Western economies and quadrupling elsewhere will be partially offset by expectations of shorter hauls. Moderate annual expected tonnage growth globally compares with rapid annual growth in coal shipments, although more localised and multi-sourcing will shorten global coal hauls.

The impact of bunker fuel price changes on spot freight rates for shipping coal analysed using monthly time series revealed a breakpoint in late 2004, defining two distinct phases from 1991-2004 and 2005-2012. Ordinary least squares modelling revealed low elasticities in a relatively stable market pre-2005 but high elasticities in a volatile market post-2005. Coking coal freight rates are more responsive to bunker prices than steam coal markets. In a volatile market, market-based measures to reduce such emissions, which might include a bunker fuel levy, have greater impacts on freight rates.

Perceptions of established practitioners and younger maritime specialists of changing patterns of maritime oil freight flows to 2050 coincided and were conservative. Local sourcing, new Arctic seaways and fossil fuel intolerance will tend to reduce oil freight work but perceptions of ship re-routing to avoid, for example, Emission Control Areas and piracy, would tend to lengthen hauls. In advanced industrial nations, reducing energy intensities and diminishing social tolerance of fossil fuels imply gradually reducing maritime oil shipments. Achieving radical national commitments to carbon emissions reductions will necessitate specialist education for naturally conservative maritime professionals and vigorous oil import reduction policies to curtail domestic demand for oil shipments.

Sustainable approaches are becoming the norm throughout industry, and shipping can be no exception. In 2009, UNCTAD's Expert Meeting on Maritime Transport and the Climate Change Challenge highlighted that timeframe was a real concern:

Current trends in terms of energy consumption and carbon path suggested that if no action were taken within the following two years … the world would forever miss the opportunity to stabilise emissions at "manageable" levels [and] a global and concerted solution was urgently required. … [N]egotiations towards regulation of CO_2 emissions from international shipping should be pursued with all due speed.

The analysis of predicted shipping demand is clear in its assessment that we cannot rely on a reduction in demand to enable shipping to meet its share of the required 80% reduction in GHG emissions by 2050 required under the UK Climate Change Act 2008. Although international shipping (and air travel) is not yet included in the calculation, apportionment of ship emissions is under consideration, and will be implemented. Morally, if not yet legally, the same reduction targets must be assumed also to apply to ships and shipping.

While reduction of operational emissions via fuel substitution and fuel efficiency gains appear likely to dominate the landscape of mitigation actions for some time, particularly in the context of likely implementation of carbon fuel levies, greater recognition of the need for sustainable business practices and acknowledgement of whole life impact means that as fuel emissions are reduced, the impact of upstream ship emissions will become significant. A composite approach is most likely to occur in the near term, and this will be influenced by changes in policy and market factors such as fuel price, and demand driving spot and charter rates. The potential abatement option mix selected will vary for different ship types, sizes, cargoes and routes, and has been modelled by GloTraM. WP1 reports the outcomes of this, under the application of a carbon levy, as well as a business-as-usual approach: the added incentive to reduce emissions is the fuel savings gained.

In a very low carbon future scenario, the impacts beyond GHGs will become significant and the market could prove receptive to a system recognising the whole life wider environmental impact, potentially altering the cost-benefit decision backdrop so that either through life environmental impact as a whole or just GHG through life emissions, are routinely considered and the emission of pollutants (all or GHG only) becomes unethical and widely condemned. This work has demonstrated that whilst consideration of through life emissions is important, in many instances a scaling ratio with operational emissions can be applied. The dual analysis of the whole environment impact (ReCiPe) method and the GWP method has demonstrated that for shipping and shipbuilding, global warming impact is often dominant and is likely to remain so whilst the greatest contributors to emissions are fossil fuels and steel. Upstream emissions from shipbuilding have the potential to become significant in a very low carbon future scenario, particularly where the uptake of low carbon fuels is high. Increased uptake of very low CO_2 fuels (measured at point of use), such as hydrogen, biofuels or nuclear power will refocus attention on the build phase of the ship, including any abatement technologies.

The published GloTraM model allows actors throughout the shipping industry and policymakers to understand the impact and cost of measures to mitigate carbon emissions from shipping. Modelling of the through life environmental impact of shipping and its available carbon mitigation measures, and their associated environmental and economic cost equally informs policy makers at all levels (UK government, EU, IMO, UNFCCC) and stakeholders throughout the shipping industry of the global cost-benefit balance inherent within shipping's attempts to mitigate carbon emissions. Assessment of balanced environmental impact highlights not only opportunities to reduce shipping's global impact, but also unintended consequences of efforts to mitigate fuel combustion-derived emissions.

What further work is there and what key challenges remain?

It was beyond the scope of the study to consider options for reducing the environmental impact of baseline shipbuilding processes, for example lower energy welding, cutting, or blasting of steel. However, savings available from improvements to the steel-making process, and increased use of recycled steel, as well as reduction of shipyard energy demand through process improvement offer the opportunity to further reduce the emissions from shipbuilding, and therefore from shipping. Improvements in onshore electricity generation, and increased use of renewable energy, would afford the opportunity to further reduce emissions from shipbuilding, and also from port operations, but this was another area which fell outside the scope of this study. Route-specific modelling that applied the ShipLCA cost-benefit model to an existing ship or trade would necessitate the addition of a port costs and impacts module, which was outside of the scope of this study.

Due to time and scheduling constraints, it was not possible to carry out the validation of the final GloTraM model against the environmental impacts and cost-benefit models developed in WP4. Comparison of the abatement technologies in particular, therefore, had to use simplified models of ship emissions at sea for final validation, rather than the more complex ship-specific models developed by WP2. The results form the basis of a tool for the comparison of available reductions rather than for absolute cost prediction; this is consistent with the experimental early adoption nature of full cost accounting methodologies. Detailed comparison of the abatement cost of all the technologies considered to update models such as the IMO 2nd GHG study Marginal Abatement Cost Curves has not been included, as it was not possible within an appropriate timeframe to access the detailed abatement potential models developed in WP2, and the GloTraM model and SIM based on them. Consequently, there is further work to be addressed future projects, such as the EPSRC-funded Shipping in Changing Climates.

Future research focusing specifically on shipbuilding should investigate the industry-transport system link and the dual role of shipping in the steel markets explicitly. The primary ongoing work from this study will be to bring together the complex modelling of predicted achieved operational emissions (fuel consumption-based), from existing ships and routes, as well as future demand-derived trade patterns developed by the other WPs, in GloTraM with these through life impact models, to assess the true impact of efforts to reduce shipping's CO_2 footprint on a global scale, and the likely associated costs and opportunities.

The technological near-market focus of the ***Low Carbon Shipping: A Systems Approach*** work meant that the step-change industry shifts likely to be associated with a very low carbon future energy scenario have not been assessed to the same level of detail as those more aligned with a 'slow and steady' scenario. In answering the major research question 'What is the likely future demand for shipping?', the impact of these various predicted scenarios on global shipping has been considered and potential reactions of the industry discussed. Detailed assessment of the technological, regulatory and operational outcomes under such a scenario, and their impact upon the economic realities of the industry, remain a major challenge, outside of the scope of LCS, which is being carried forward into the ***Shipping in Changing Climates*** project.

Key Outputs

The main outputs from this WP include a number of journal and conference publications, which are listed, with corresponding abstracts, in the References section below.

A number of internal reports were produced during the course of work under WP4, including the following titles:

- ECA Methodology
- Ship LCA model for the assessment of whole life ship emissions and cost-benefit analysis
- Technology costs appendix
- Abatement technology environmental costs
- Case study: Kite LCA and speed optimisation, short sea container route.

Journal articles

Title	Journal	Link (if applicable)
Optimizing end-to-end maritime supply chains: a carbon footprint perspective	International Journal of Logistics Management 2013	In press
Moments, motivations, slow steaming and shipping's carbon emissions	Carbon Management 3(6) 529-531	http://www.future-science.com/doi/pdf/10.4155/cmt.12.60
Dry Bulk Shipping Flows To 2050: a Delphi Approach	Technological Forecasting and Social Change*	

Abstract: This paper aims to report expectations of trends in dry bulk shipping flows to 2050, the ship type which generates the second highest total volume of carbon emissions. Expectations have implications for formulating polices to manage global trade and shipping emissions. Established Delphi survey techniques achieved consensus in a novel long-term industrial context amongst international panelists with long-term industrial commitment, highlighting trends in drivers including Arctic ice melt, canal upgrades, piracy and mode splits. Globally, expected doubling of raw materials shipments to Western economies and quadrupling elsewhere will be partially offset by expectations of shorter hauls. Moderate annual expected tonnage growth globally compares with rapid annual growth in coal shipments, although more localized and multi-sourcing will shorten global coal hauls. After 2030, ocean routing is expected to slightly shorten global hauls.

The Potential Impact of Bunker Fuel Price Changes on Coal Spot Freight Rate tbc

Abstract: This paper aims to assess the impact of bunker fuel price changes on spot freight rates for shipping coal, by estimating relevant elasticities using a top down approach. Earlier work has shunned coal markets which offer an interesting case study of dry bulk shipping market operations and have important implications for managing international shipping. Analysis of monthly time series data drawn from Clarkson's Shipping Information Network revealed a breakpoint in late 2004 defining two distinct phases from 1991-2004 and 2005-2012.

Maritime oil freight flows to 2050: Delphi perceptions of maritime specialist	Energy Policy 63(2013) 553-561	In press

Abstract: This paper aims to synthesise maritime specialists' perceptions of changing patterns of maritime oil freight flows to 2050. Debate spans published maritime oil flows globally, diverse drivers of future flows including economic growth, shipping market changes and haul lengths. A classic Delphi study to explore the perceptions of likely trends and flows to 2050 recruited a panel of early career and established maritime specialists, many with long term career commitments to this industry. Underpinned by market volatility and legislative uncertainty, the perceptions of both groups coincided and were conservative.

What is the likely future demand for Shipping? tbc

Abstract: A key driver for future emissions from the sector must be the demand for shipping – both local and global. Predictions of shipping flows underpin forecasts of their likely environmental impacts, and policy debates to develop technologies and operational strategies to manage and regulate emissions. To evaluate policy strategies designed to deliver low carbon shipping requires realistic forecasts of future movements of different types of ships. This paper focuses on the socio-economic drivers, and particularly those with a Low Carbon future perspective. This paper summarises analyses of patterns of wet and dry bulk flows involving the UK, and forecast flows to 2050. Drivers of future shipping flows include economic growth, market changes, haul lengths and energy demands. Container flows, and drivers related to supply chain optimisation, port configuration and choice, technological development, ship operations, and policy and regulation are also discussed.

Wider Environmental Costs and Impacts of Shipping tbc

Abstract: The current global debate on the environmental impact of shipping is predicated upon either the local/air quality implications of Ships' emissions of NOx, SOx and PM, or the global effect of the emission of CO_2 from the funnel; whether focussing locally or globally, it is primarily concerned with only the emissions generated within the ships' own engine room whilst at sea. However a ship does not operate within a vacuum, as well as other emissions to its environment whilst in use (for example from coatings), a ship must be built, often using non-renewable resources and energy, repaired and ultimately dismantled or recycled.

Conference Papers

Low Carbon Shipping- A Systems Approach: Conceptualising a full cost environmental model for sustainable shipping PRADS 2010

Abstract: This paper identifies and discusses some of the methodological challenges facing the development of a model for environment-focused full cost accounting with an international shipping context, within the UK EPSRC-funded project Low Carbon Shipping – A Systems Approach. The focus is on forming the framework within which a simplified system for assessing the sustainability of shipping, which still reflects all the most important facets of the industry. For what is a new thought experiment in the greenhouse gas management of the shipping industry, this study introduces the con-text, reviews the relevant literature and then discusses the methodological approach that might be adopted and utilised.

Optimizing end-to-end maritime supply chains: a carbon footprint perspective	ISL17 2012	http://eprint.ncl.ac.uk/pub_details2.aspx?pub_id=190837

Low Carbon Shipping: Oil Tanker Movements involving the UK	IAME2011	

Abstract: Carbon emissions from international shipping have only recently become a source of global concern. This paper reports on shipping economics inputs to Work Package 4 of the UK Engineering and Physical Science Research Council funded Low Carbon Shipping: A Systems Approach project. This work is developing the first holistic model of shipping to guide the development of technologies and operational strategies for the reduction of shipping's CO_2 emissions, engaging major industrial partners and UK universities at University College London, Newcastle, Plymouth, Hull and Strathclyde. Because oil tankers have been identified as the largest single source of CO2 emissions in the shipping sector, this paper aims to synthesise changing patterns and forecasts of oil tanker movements principally involving the UK, and hypothesises evolutionary changes. Changing global patterns of oil movements are reported which depend on the world demand for shipping crude oil and oil products, the world oil tanker fleet and are stimulated by regional surpluses and deficits which define tanker loading and discharge areas.

Low Carbon Shipping: Forecasting Oil Tanker Movements involving the UK	ICMMA 2011	www.icmma.info

Abstract: Carbon emissions from international shipping have only recently become a source of global concern. This paper reports shipping economics inputs to work package (WP) 4 of the UK Engineering and Physical Research Council (EPSRC) funded Low Carbon Shipping: A systems approach project.

Low Carbon Shipping: dry bulk movements involving the UK	LRN2011	Copyright

Abstract: Increasing global concern regarding carbon emissions from international shipping is focused on the most polluting ships. This paper queries the extent to which dry bulk movements, the second most polluting ship-type, impact the UK currently and are likely to do so to 2050. WP4 is researching the economics of shipping markets, which exhibit unique characteristics such as regular boom-bust cycles and their impact on future requirements and market structure.

Slow steaming and low carbon shipping: revolution or recession?	LRN 2010	Copyright

Abstract: Until recently, carbon emissions from international shipping were largely overlooked, but they are now of global concern. This paper outlines the shipping economics input to work package (WP) 4 of the UK Engineering and Physical Sciences Research Council (EPSRC) funded Low Carbon Shipping: A systems approach project. This project will present the first holistic model of shipping which will in turn guide the development of technologies and operational strategies for the reduction of shipping's CO_2 emissions, engaging major industrial partners and UK universities. This paper questions whether apparent recent reductions in carbon emissions attributable to slow steaming and other measures reflect a revolution in practitioners' attitudes or merely a behavioural response to the impacts of fuel price rises and global recession, and hence whether they are likely to endure.

Sustainable shipping – a way forward? developing economic imperatives in an international market	LCS 2011	

Abstract: Sustainable approaches are becoming the norm throughout industry, and shipping can be no exception. In 2009 UNCTAD's Expert Meeting on Maritime Transport and the Climate Change Challenge highlighted that timeframe was a real concern. The concept of a sustainable industry or economy is an interesting one; oil is the major energy source powering the global economy and supplying 95% of the total energy fuelling world transport. Maritime transport relies heavily on oil for propulsion, and is not yet in a position to adopt effective energy substitutes, however, fossil fuel reserves are finite.

The Potential Impact of a Levy on Bunker Fuels on Dry Bulk Spot Freight Rates	9th International Conference on Logistics and Sustainable Transport	http://iclst.fl.uni-mb.si/

Abstract: The objective of this paper is to assess the effect of bunker fuel prices on spot dry bulk freight rates, principally coal. The study will also examine how the effects of a carbon tax on bunker fuels will affect spot freight rates for these dry bulk markets. The paper analyses and models the elasticities of spot freight rates with respect to bunker fuel prices from a top down approach, and probes some of the assumptions regarding market structure and competition on routes.

What is the Future Demand for Shipping?	LCS 2012	http://conferences.ncl.ac.uk/lcs2012/

Abstract: Within the context of Low Carbon Shipping, a key driver for future emissions from the sector must be the demand for shipping – both local and global. Predictions of shipping flows underpin forecasts of their likely environmental impacts, and policy debates to develop technologies and operational strategies to manage and regulate emissions. To evaluate policy strategies designed to deliver low carbon shipping requires realistic forecasts of future movements of different types of ships.

Oil Tanker Flows Involving the UK to 2050: A Delphi Survey	LCS 2012	http://conferences.ncl.ac.uk/lcs2012/

Abstract: Predictions of shipping movements underpin forecasts of their likely environmental impacts, and policy debates to develop technologies and operational strategies to manage and regulate emissions. This paper aims to analyse patterns of oil tanker flows, the most polluting type of ship, as they involve the UK and by synthesising experts' opinions, to forecast them to 2050.

Dry Bulk Shipping Movements to 2050: a Delphi Study	LRN 2012	Copyright

Abstract: Predictions of global shipping movements to 2050 underpin forecasts of their likely environmental impacts, and hence policy debates designed to develop technologies and operational strategies to manage and regulate emissions. This paper reports a Delphi survey which aimed to predict likely trends in dry bulk movements, the second most polluting ship-type, to 2030 and to 2050. Secondary data sources including UK government, supranational and private statistical sources such as Clarkson's Shipping Information Network were deployed to identify baseline dry bulk movements in 2010. Based on drivers of future shipping movements such as Arctic ice melt, an upgraded Suez canal, piracy, resourcing and changed mode splits identified in trade press articles and academic opinions, an instrument was devised to test for consensus regarding future market trends.

Origin and Destination of maritime container flows to and from the United Kingdom	ICMMA 2011	Mark Bennett	www.icmma.info
Sustainable shipping – a way forward? developing economic imperatives in an international market	ENSUS 2011		http://ensus-newcastle.ncl.ac.uk/

Abstract: Sustainable approaches are becoming the norm throughout industry, and shipping can be no exception. In 2009 UNCTAD's Expert Meeting on Maritime Transport and the Climate Change Challenge highlighted that timeframe was a real concern. The concept of a sustainable industry or economy is an interesting one; oil is the major energy source powering the global economy and supplying 95% of the total energy fuelling world transport. Maritime transport relies heavily on oil for propulsion, and is not yet in a position to adopt effective energy substitutes, however, fossil fuel reserves are finite.

What is the likely future demand for Shipping?	LCS 2013*	http://www.lowcarbonshipping.co.uk

Abstract: A key driver for future emissions from the sector must be the demand for shipping – both local and global. Predictions of shipping flows underpin forecasts of their likely environmental impacts, and policy debates to develop technologies and operational strategies to manage and regulate emissions. To evaluate policy strategies designed to deliver low carbon shipping requires realistic forecasts of future movements of different types of ships. This paper focuses on the socio-economic drivers, and particularly those with a Low Carbon future perspective. This paper summarises analyses of patterns of wet and dry bulk flows involving the UK, and forecast flows to 2050.

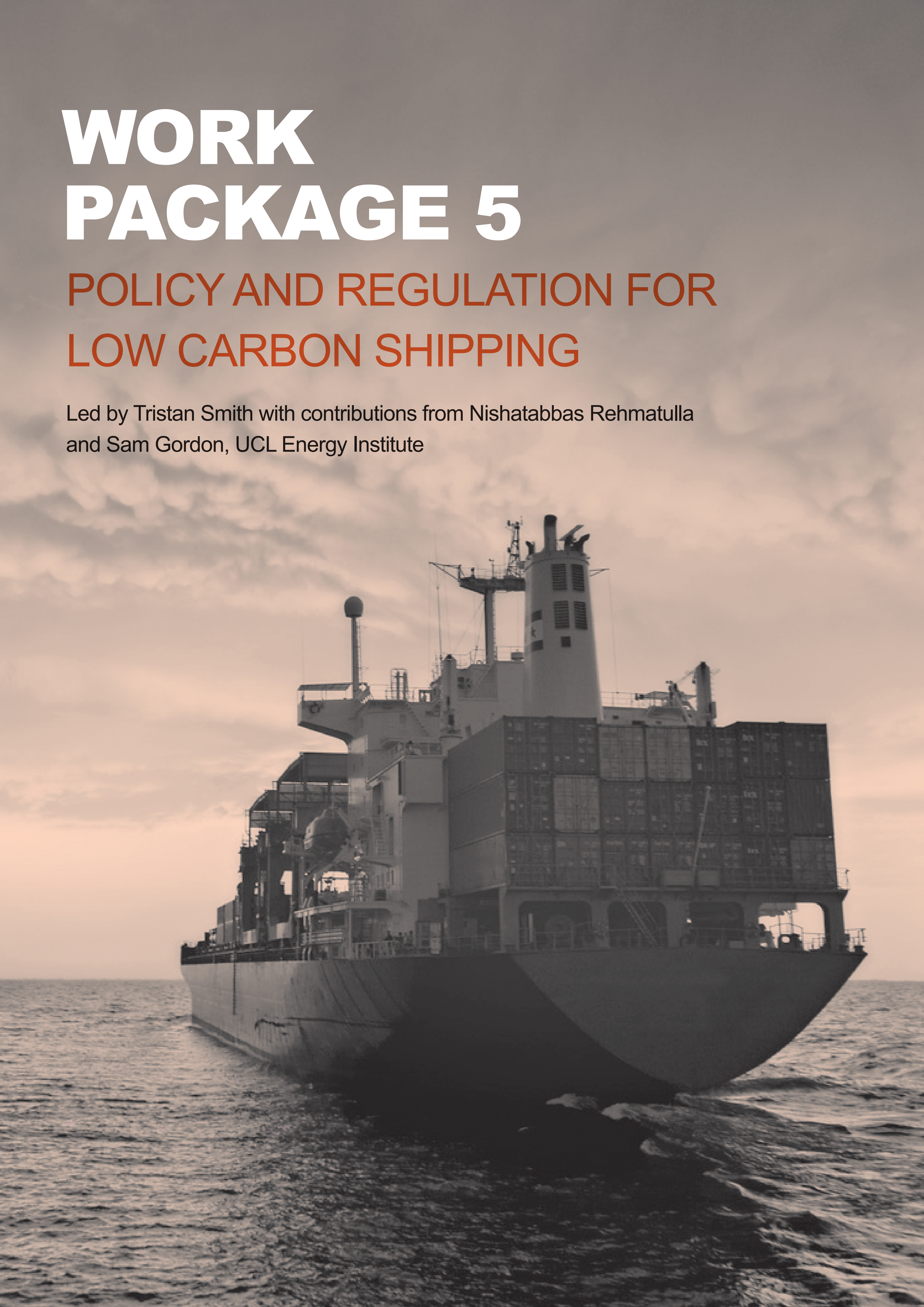
Wider Environmental Costs and Impacts of Shipping	LCS 2013*	http://www.lowcarbonshipping.co.uk

Abstract: The current global debate on the environmental impact of shipping is predicated upon either the local/ air quality implications of Ships' emissions of NOx, SOx and PM, or the global effect of the emission of CO_2 from the funnel; whether focussing locally or globally, it is primarily concerned with only the emissions generated within the ships' own engine room whilst at sea. However a ship does not operate within a vacuum, as well as other emissions to its environment whilst in use (for example from coatings), a ship must be built, often using non-renewable resources and energy, repaired and ultimately dismantled or recycled.

WORK PACKAGE 5

POLICY AND REGULATION FOR LOW CARBON SHIPPING

Led by Tristan Smith with contributions from Nishatabbas Rehmatulla and Sam Gordon, UCL Energy Institute



WP5 – POLICY AND REGULATION FOR LOW CARBON SHIPPING

Led by Tristan Smith with contributions from Nishatabbas Rehmatulla and Sam Gordon, UCL Energy Institute

Overview

WP5 is focused on the policy issues for the shipping industry, and in particular what the different regulatory options might look like, how they would impact the shipping industry and how emissions might be apportioned. The WP has also explored the market barriers and failures in the industry (particularly the principal agent or 'split incentive' problem), in order to understand whether this might impede industry adoption of low carbon technical and operational interventions.

Main Research Focus/Activity

Of the five RCUK research questions, this work package is focused on providing insight to:

- What are the implementation barriers to low carbon shipping?
- What is an appropriate measurement and apportionment strategy?

WP5 is also providing input to WP1's modelling with respect to generating foreseeable policy scenarios and interpreting the results.

Both in support of these objectives and as an independent check, Nishatabbas Rehmatulla's PhD thesis has examined the following questions in greater detail:

- How does the principal agent problem in the wet bulk, dry bulk and container sector limit the adoption of energy efficient operational measures?
- What is the relative importance of the different types of market barrier/failure for the adoption of operational measures?
- How do the similarities and differences of the key charterparty clauses influence operational efficiency of a ship?

Main Outputs and Activities

Stakeholder interactions, incentivisation and barriers

The first step in the research process for this WP was to build up a picture of the stakeholders: a mapping of the stakeholder space (Figure 44).

Following further investigation into the specifics of commercial transactions between some of the key stakeholders, this map was refined in order to identify the stakeholder connections at particular risk of split-incentives that might result in market failures (Rehmatulla 2011). Four of the interactions that were further investigated in this study are shown in Figure 45. Of these, Scenarios 2, 3 and 4 were thought to be at significant risk of principal agent related market failures.

A of nearly 150 ship owners, charterers and ship management companies was undertaken to ascertain how they perceived market barriers, establishing their uptake and attitudes towards a variety of operational energy efficiency interventions (weather routing, hull scrubbing, slow steaming, etc.). The design of the survey and full results are available in (Rehmatulla 2012). Figure 46 shows the operational efficiency interventions that the survey respondents believed to have significant potential, including three agreed

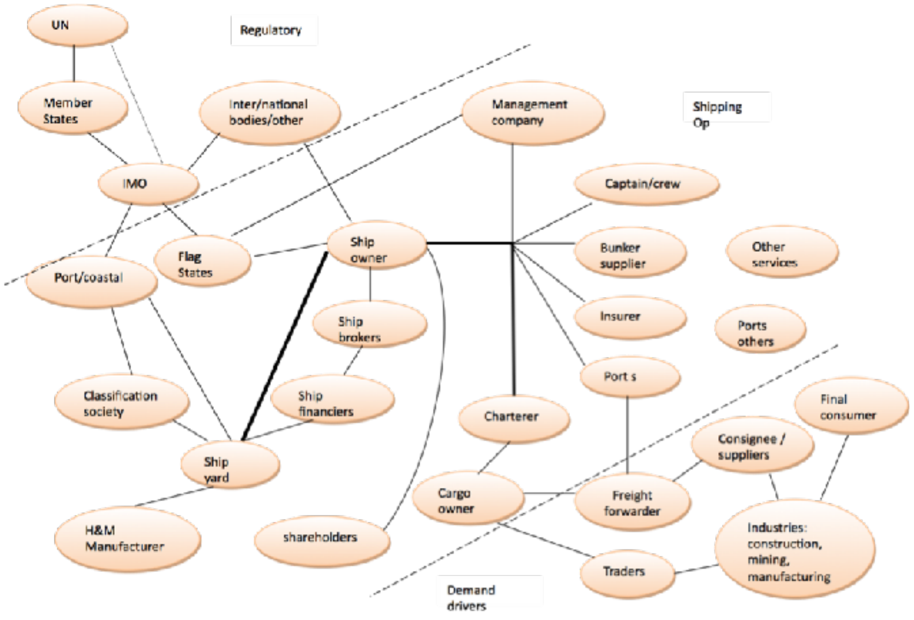


Figure 44: Stakeholders in the shipping industry and their interactions

upon by approximately 70% of respondents: fuel consumption monitoring, general speed reduction, and weather routing. This finding is useful in confirming that there are a number of interventions that a large majority believe to have potential, as this refutes the oft-repeated concept that 'nothing can be done' and all potential improvements are already fully embedded in the industry. Of more direct application to the subject of market barriers and failures is Figure 47, which identifies a number of reasons why some interventions were not seen as having high potential. The most regular explanations included: lack of reliable information on cost and savings; difficulty of implementation under some charterparties and lack of direct control over operation. Both the informational barriers and the consequences of certain charterparty clauses have been referred to by many others (Faber et al., 2011) and are the subject of ongoing discussion in the policy space (Maddox 2012, and ongoing activities at both Carbon War Room and the Sustainable Shipping Initiative). This work therefore presented useful evidence to support those discussions, as well as defining the direction for further research into the specifics of the most common charterparties used both for time charter and voyage charter. The corresponding detailed analysis can be found in (Rehmatulla 2013).

The subject of market barriers, their characterisation in the shipping industry, and their impact on the potential of the industry to transition to lower carbon emissions, are described in greater detail in Rehmatulla and Smith 2012.

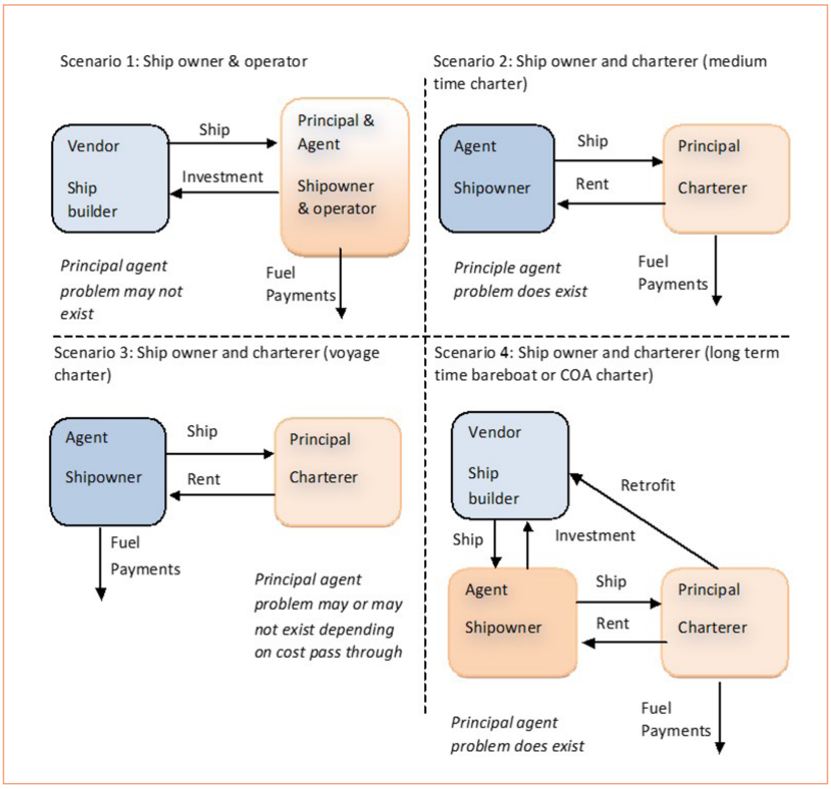


Figure 45: Key stakeholder interactions and their transactions

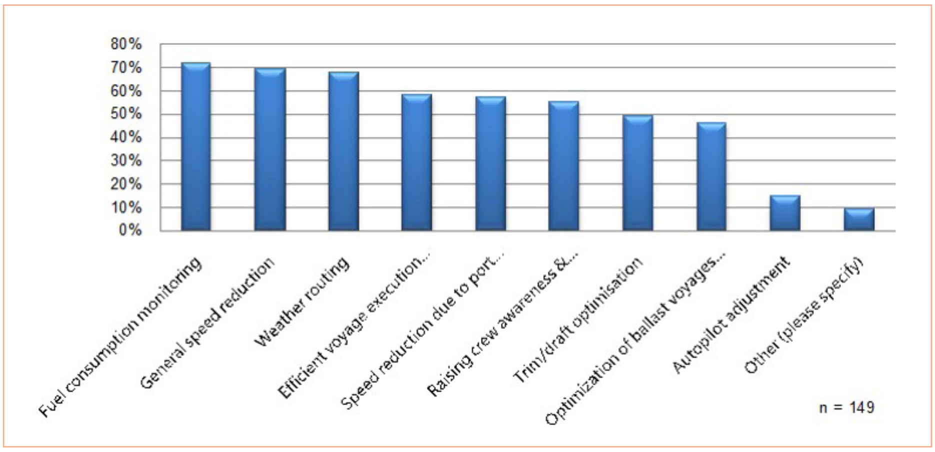


Figure 46: Operational measures believed to be of highest potential in CO_2 reduction

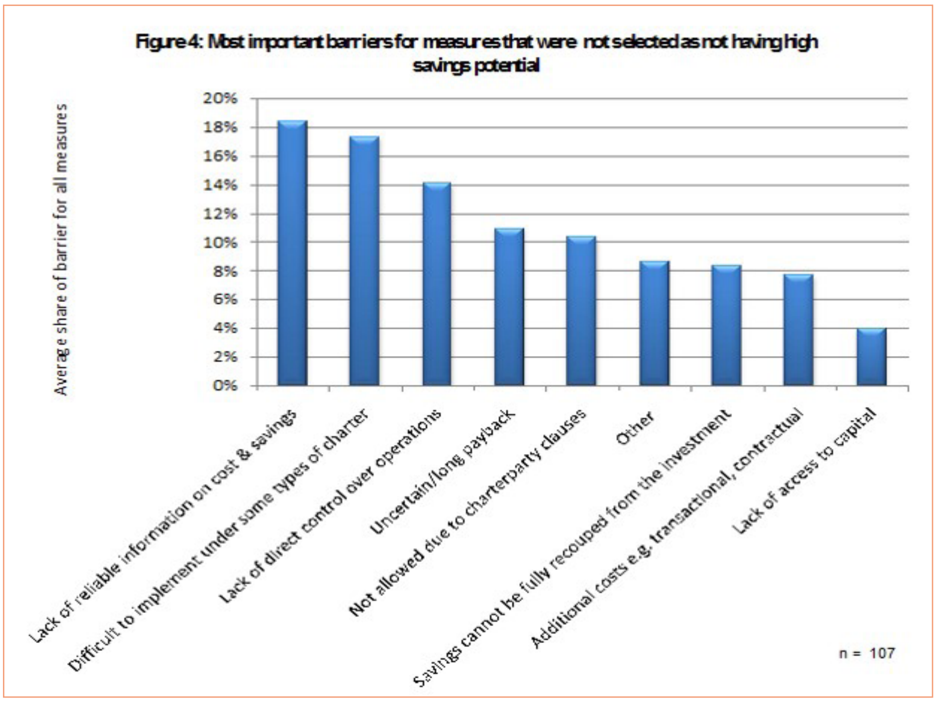


Figure 47: Most important barriers for measures that were not selected as not having high savings potential

Prices and energy efficiency

Building on the analysis of perceived barriers, a further piece of work was undertaken to attempt to observe the extent to which barriers could be detected in price data. This took the perspective that if market barriers were not present, then more efficient ships should be achieving higher prices than average in the different markets e.g. new build, second-hand and the time charter day rates. The model that was applied to estimate how efficiency was represented in prices in the different markets can be seen in Figure 48.

The analysis was undertaken using data from both Clarksons World Fleet Register (on ship technical characteristics) and Clarksons Ship Intelligence Network (on prices for ship sales and fixtures). A full account of this work can be found in (Smith et al. 2013). The findings confirmed anecdotal evidence from the industry press that energy efficiency is indeed currently reflected in the time charter rates, particularly in recently built vessels, but our quantitative analysis shows that the influence of energy efficiency on prices is limited. Evidence that new build prices incorporate an energy efficiency premium is less strong, with the exception of the container sector.

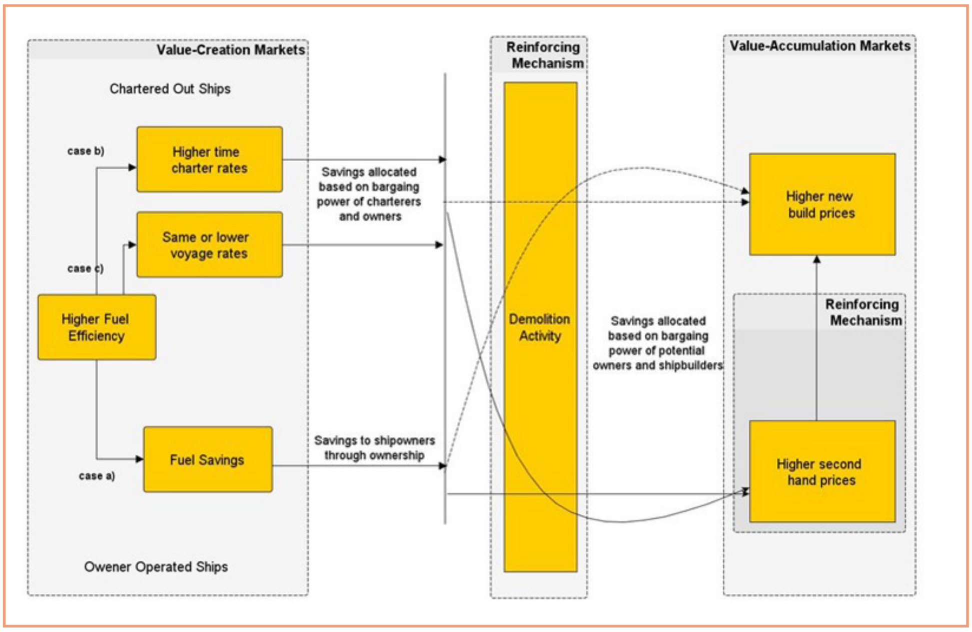


Figure 48: Logic of the value chain discussed in this study

It is possible that the above findings reflect the fact that while the new build data is for the same, post-financial crisis period as the data for other markets, new build prices are negotiated at the beginning of the build process so could demonstrate a lag of around three years, enough to recreate a different, 'pre-crisis', dynamic in the shipping markets. Our findings showed some strong support for the existence of a premium in the second-hand market. Confirming anecdotal evidence from the industry press, we discovered that energy efficiency is an important factor in the selection of ships to be demolished (less efficient ships are scrapped in preference to efficient ships).

With regard to the sectors assessed in the study (tankers, bulkers and container ships), the container sector appears to be the most price-sensitive to energy efficiency. This is demonstrated by the existence of a premium both in the case of time charter rates and new build prices, although perhaps this is to be expected for a sector with proportionately higher fuel costs to begin with owing to the higher speeds of its services.

This analysis shows that incentives for the adoption of new, more efficient, ships may occur differently across sectors and that to ensure that policy and incentives are tailored and applied in such a way as to maximise their cost-effectiveness, more research is needed to understand these differences. Our findings in relation to the second-hand market are encouraging in terms of the economic viability of retrofitting activity, as they imply that there is a clear price incentive for initiatives that increase the efficiency of the current fleet.

Relative to the magnitude of the cost savings of energy efficiency, our quantitative analysis points to a limited impact on the prices of the sectors and markets analysed in this study. Consistent with the discussion in the literature, our results may be attributed to the existence of market barriers or failures in the adoption of energy efficiency. Specifically, given the challenge of obtaining quality data on the technical performance of the existing fleet, it is likely that this analysis corroborates the suggestion of an information barrier related to the measurement of the efficiency of the ships being chartered or bought.

As incorporation of energy efficiency in market prices is supportive of measures aimed at reducing energy consumption and therefore carbon emissions, our findings imply the need for policies tackling any barrier to the stronger representation of energy efficiency in the market prices. Such polices could take the shape of standards for measuring energy efficiency in operational settings, mandatory publication of information, and the establishment of databases documenting the performance of vessels across time and in different weather conditions.

EU GHG policy

Most recently, the EU has been exploring the implementation of a Monitoring, Reporting and Verification (MRV) system. Prior to this policy development, DG Clima carried out a number of pieces of work in order to identify the potential for unilateral action on shipping GHG using a market based measure (MBM) for example an emissions trading scheme (ETS) (CE Delft (2009)).

Aviation, at least in EU ETS terms, is further ahead than shipping in terms of its inclusion in international regulation. GHG regulation for both aviation and shipping has been a subject of topical discussion and a report was produced in early 2012 (Gordon and Smith 2012) outlining, at that stage of their respective policy developments, what parallels and differences could be observed and what indication these might give of the potential for the inclusion of shipping in the EU ETS system.

IMO GHG policy

As outlined in the Introduction to this report, the main focus for the investigation of possible future policy scenarios has been global regulation of shipping's GHG emissions, proposals for which have been led by the UN agency, the IMO.

Policy requires both an instrument (or instruments) and a targeted level of stringency. On GHG emission reduction policy, the level of stringency should reference the global mitigation strategy, as no one sector of the economy has the responsibility, nor should carry the burden, for anthropogenic climate change. Although there remains no clear guidance on the level of stringency of emissions reduction, or the target trajectory for the industry's evolution of future emissions, a number of instruments have been proposed. These started with EEDI and SEEMP, command and control policy mechanisms targeting energy efficiency improvements that will also incentivise emissions intensity improvements, and extend into a number of suggested Market Based Measures (MBMs).

During the course of this project, at MEPC 62, IMO adopted the EEDI and SEEMP regulations as amendments to MARPOL Annex VI. Whilst these regulations are expected to produce an effect on the emissions trajectory of the shipping industry, there is still a need for additional GHG regulation (IMO 2010).

Over the duration of this project, the IMO has debated and attempted to evaluate a number of MBM proposals (see submissions for agenda item 5 of MEPC meetings 60 to 65). Categorisation of these proposals proved contentious, but they could be divided into two broad categories:

- Price-signal-based instruments, which applied a cost per tonne of CO_2 emitted, or a levy on the bunker price
- Mandatory efficiency target instruments, some allowing for efficiency credits to be traded

Argument used by Airlines for America to challenge EU ETS inclusion	ECJ rationale for overturning claim	Potential argument used by shippers to challenge EU ETS	Potential EU rationale for overturning claim
Violates customary law in relation to sovereignty over national airspace	EU ETS only applies to airlines choosing to fly to EU airports, not all airports. US operators still have the choice to fly somewhere else.	Violates customary law in relation to sovereignty over national EEZ	EU ETS only applies to ships that choose to use EU ports, not all ships or all ports.
Violates customary law in relation to freedom of high seas	EU ETS only applies to airlines choosing to fly to EU airports, not all airports. US operators still have the choice to fly somewhere else.	Violates customary law in relation to freedom of high seas	EU ETS only applies to ships that choose to use EU ports, not all ships or all ports.
Violates 2007 Open Skies agreement between the US and EU	Once aircraft are in EU jurisdiction, EU legislators have the remit to decide what commercial activity they permit and under what conditions	Violates free trade agreements	Once ships are in EU jurisdiction, EU legislators have the remit to decide what commercial activity they permit and under what conditions
Inclusion represents a duty or tax	No requirement for how much fuel planes 'have' to use – a company might not make a loss, or even profit	Inclusion represents a duty or tax	No requirement on how much fuel ships 'have' to use – a company may not make a loss, or even profit
Inclusion will restrict air traffic	The EU ETS does not set a limit on emissions, so it is not a restriction on air traffic. Even if a limit was set, this is still acceptable, as it is a non-discriminatory environmental measure	Inclusion will restrict marine traffic	The EU ETS did not set a limit on emissions, so it is not a restriction on marine traffic. Even if a limit was set, this isn't an issue, as it is a non-discriminatory environmental measure
ICAO is better placed to deal with emissions	The ICAO has had 15 years to act, since the Kyoto Protocol, and hasn't put any legally binding instruments in place	IMO is better placed to deal with this	IMO instruments have not led to significant reductions in emissions

Table 9: Data describing the issues raised around aviation's inclusion in the EU ETS and how they might relate to the shipping industry

Whilst MEPC 61 Inf. 2 produced useful insight into the different mechanisms, with EEDI and its associated Technology Transfer Resolution (agreed at MEPC 65) dominating much of the debating time at MEPC 62 through to MEPC 65, little further progress was made in analysing, down-selecting or developing the detail of an MBM.

The Expert Group's study tested the cost of CO_2 abatement using each proposed measure, and the cost-effectiveness of each proposal. This allows for relative comparison of the measures, but does not provide any insight into the absolute costs of the regulation for a target trajectory, particularly as the cost abatement relationship has been suggested by many to be non-linear – meaning that the higher the level of targeted decarbonisation, the greater the cost per tonne of carbon abated becomes (IMO MEPC 61 Inf. 18).

Instead of assessing the relative merits of measures, WP5 selected one type of measure (the price signal based instruments) and used an implementation of it in GloTraM to assess what carbon price trajectory was required to reach a given prescribed emissions trajectory. Figure 49 explains how the calculation is performed. An initial guess of a carbon price scenario is provided as an input to GloTraM (along with prescribed exogenous data for transport demand, fuel price, technology and the cost and availability of alternative fuel). GloTraM is run simulating evolution of the industry over a given period (2010-2050) and calculating the resulting emissions trajectory. All other things being equal, a higher carbon price causes increased rate of uptake of energy efficiency technology and operational interventions (both new build and existing fleet). Depending on the definition of the measure within GloTraM, the revenues raised by the carbon price can also be used to purchase offsets in emissions outside of the shipping industry. The process in Figure 49 is repeated until the emissions trajectory achieved by the industry matches a given target trajectory

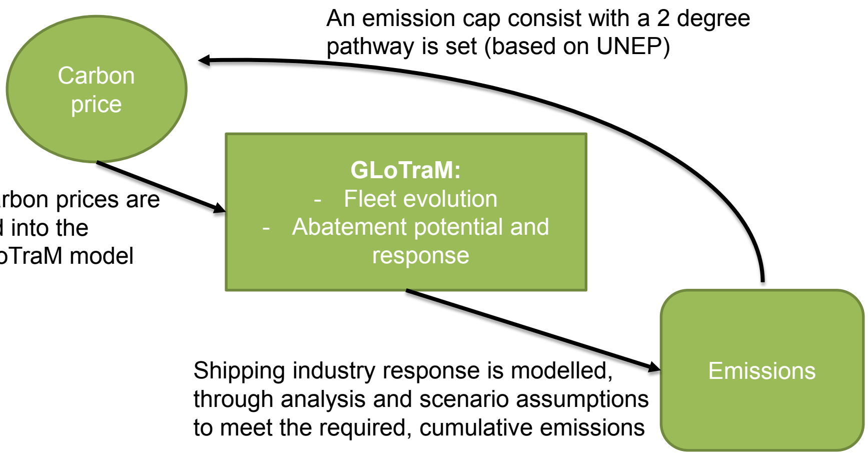


Figure 49: Deployment of GloTraM to calculate the carbon prices required to achieve different emissions targets

In the absence of an IMO-specified target trajectory of emissions, the work was carried out using the analysis and findings of UNEP's Bridging the Gap work (UNEP 2011). This calculated the difference between the expected trajectory of global anthropogenic CO_2 emissions, including policy commitments that have already been made, and the global trajectory of CO_2 emissions that needs to be achieved in order to ensure compliance with the Copenhagen Accord (UNFCCC 2009).

This process identifies a gap, which is allocated evenly across all industries that do not currently have policy in place (including shipping). Application of this approach to a derivation of shipping's targeted emissions can be found in (Smith et al. 2013), which describes the consequence of achieving this emissions trajectory under a range of policy design assumptions of shipping's emissions.

Overall emission reduction within a sector of the economy (e.g. shipping) can be either achieved by reducing emissions from the sector itself or by offsetting emissions through the use of carbon credits which generate reductions in other sectors of the economy.

There are rational grounds for doing this, for example because the marginal abatement cost may be cheaper in another sector and it is economically efficient to reduce the emissions at the lowest cost first (sometimes referred to as the 'low-hanging fruit'). Mechanisms for offsetting emissions at an international level are already well established, for example the Clean Development Mechanism (CDM), which is established under Article 12 of the Kyoto Protocol.

In order to simulate the opportunity of out-of-sector offsetting, the implementation of an MBM in GloTraM uses two carbon prices: one to represent the price of offsets purchased on the global market; and one for the price set in the shipping industry (e.g. through a market mechanism in the case of cap-and-trade, or through command and control in the case of a fuel levy). The flow of revenue raised by the carbon price to purchase out-of-sector offsets is modelled to occur if the carbon price within the shipping industry is greater than the carbon price out-of-sector (e.g. global carbon price). Whilst this out-of-sector offsetting might be economically efficient, it is viewed by some as a negative phenomenon as it might cause the sector to become the 'cash cow' of the low carbon economy (Lloyd's List 2012). For this reason, a limit can be placed on the total number of out-of-sector credits that can be purchased. If this limit is reached, then the shipping carbon price can rise above the out-of-sector carbon price.

Figure 51 shows the resulting trajectories of both the in-sector emissions (in blue) and the net (in-sector and out-of-sector offsets) emissions (in red) for a range of policy configuration scenarios. For each scenario, different assumptions are made:

- Scenario 1, no MBM
- Scenario 2, 3, 4, 2020 implementation of an MBM with X% out-of-sector and Y eJ bioenergy resource availability in 2050.
- Scenario 5, 2030 implementation of an MBM

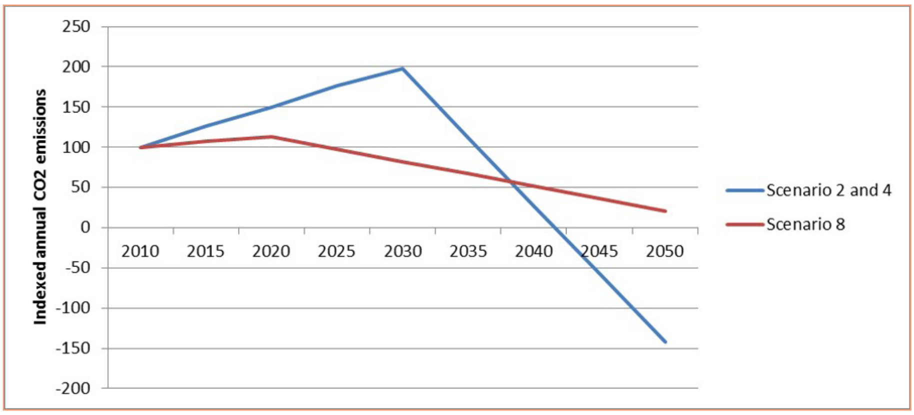


Figure 50: Emissions trajectories for the shipping industry (in sector and out of sector offsets) in a range of scenarios for a carbon price regulation's specification

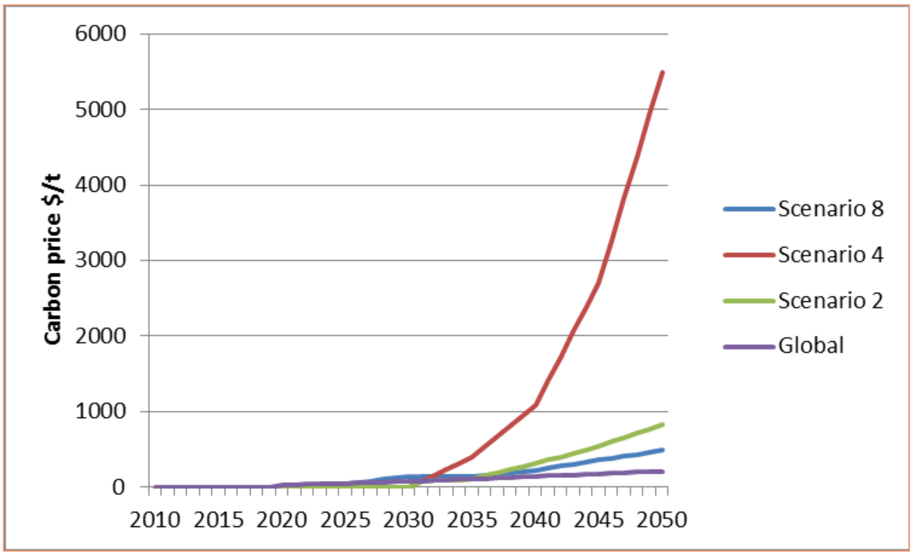


Figure 51: Scenarios of shipping carbon price 2010 to 2050

Every scenario shown in Figure 50 has a corresponding carbon price trajectory, shown in Figure 51, alongside the global carbon price scenario. While the outcomes are dependent on a large number of assumptions and forecasts of input parameters, which may turn out to be substantially different in practice, the results demonstrate a number of important findings, assuming that the cumulative emissions target for the industry (the stringency) remains consistent regardless of the scenario adopted:

- early adoption of a measure leads to a less dramatic carbon price trajectory;
- in all scenarios, a sizeable quantity of out-of-sector offsetting is required to reach the target trajectory;
- increasing the amount of out-of-sector offsetting permitted has a small impact on the amount of in-sector decarbonisation achieved, but a large (negative) impact on the carbon price that the industry experiences: this suggest there is no significant benefit either to the industry or society of overly constraining offsetting;
- bioenergy (biofuel and biogas) resources will have a beneficial impact on the sector's operational emissions, but apportioning an equitable share of the expected resource to the shipping industry will only have a modest beneficial impact on the emissions trajectory. To achieve a greater impact, either the industry needs to justify a requirement for a disproportional share of this resource, or a technology breakthrough that increases the resource available needs to be found; and
- to enact a policy of emission reductions in shipping consistent with the Copenhagen Accord is likely have a significant impact on the cost base of the industry, applying additional operational costs equal to, and in many cases exceeding, those associated with the fuel cost at current fuel prices.

An additional feature of this policy scenario is that, as well as generating revenue for out-of-sector offsetting, it will generate revenue that could be used for:

- administration of the measure (collection and management of revenues);
- providing a contribution to the GHG Green Fund;
- financing a rebate mechanism; and
- in-sector initiatives.

The rebate mechanism is a current proposal (MEPC 63/5/6) for how an MBM could ensure No Net Incidence, and helps to address some of the perceived conflict between UNFCCC principles and those of the IMO. As with each of the MBM, the rebate mechanism is still a proposal and the details of the implemented policy could be very different. It can be conceived, at least for modelling purposes, as a cost centre (e.g. a sink for some of the revenue raised). The implementation in GloTraM is described in greater detail in (Smith et al. 2013b). The quantities of revenue raised for the different cost-centres can be seen in Figure 52.

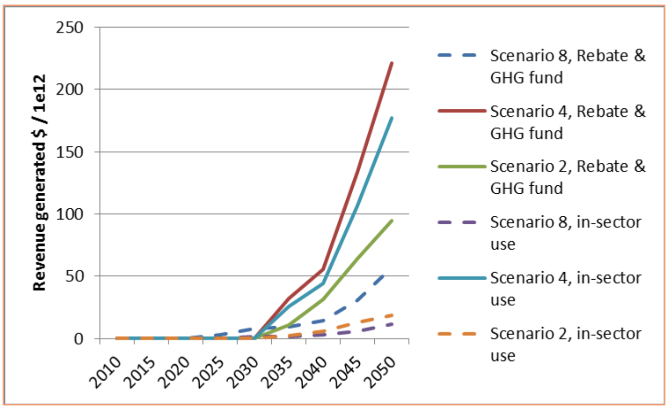


Figure 52: Different amounts of revenue raised (and its allocations) by a number of policy scenarios

The magnitude of the revenue raised for in-sector purposes even under the more modest policy scenarios this raises the question of how that revenue should be deployed, a subject that has only received limited attention to date. Potential uses include:

- recycling the revenue as carbon credits provided to shipping companies as grandfathered emissions allowances, in order to reduce the burden of the carbon price on the industry;
- subsidising energy efficiency technology investments or providing low cost finance; and/or
- investing in infrastructure (e.g. alternative fuels production and supply chain infrastructure).

Measurement and apportionment

Measurement refers to the estimation of emissions from the shipping industry and apportionment its allocation to different entities (e.g. firms, countries, regions). Whilst domestic shipping emissions are easily associated with the country in which their transport demand originates, the difficulty of fairly apportioning the emissions from 'international shipping' led to the allocation of their management as a 'whole' to the IMO, in the UNFCCC Kyoto Protocol. Measurement and apportionment are intrinsically linked, because the viability of different types of measurement system can affect the implementation of apportionment schemes. Some progress on the subject of measurement has been made at both the MEPC (IMO 2013) and the EU (EC 2013). For these reasons, the focus of the work in WP5 was placed on apportionment, albeit with assumptions and recommendations made for the most valuable measurement variables.

Applications of apportionment include:

- estimation of regional or national emissions for the purpose of unilateral measures, e.g. the EU's attempt to calculate its emissions and assess the cost-benefit of policy required to address them (AEA-Ricardo 2013); and
- estimation of the responsibility and the associated burden of different emissions policy solutions, e.g. for the consideration of the annex 1 / non-annex 1 split for use in instruments such as the Rebate Mechanism (IMO 2011).

Details of WP5's work on this subject is included in Smith and O'Keeffe 2012 and Smith *et al*. 2013b.

Key Findings and Their Relevance to Commercial and Policy Issues

Academia

- Market barriers literature is common to many industries. In each industry the context is slightly different but there are often structural commonalities. To date there has been very little literature published in the specific area of shipping industry market barriers.(Rehmatulla 2013) and associated publications will therefore not only contribute substantially to shipping specific literature, but could also produce opportunities for new interpretations of the principal agent problem.

Industry

- The survey work has been widely disseminated to industry, including to all the respondents to the survey.
- The stakeholder space map has been used by a number of companies, including B9 shipping and Rolls-Royce, to assist their own interpretation of the shipping ‘system’.
- The IMO reports have been used by a number of companies as concise summaries of the MEPC developments on GHG and how they might be relevant to their business.
- The observation and quantification of the split-incentive in the shipping industry, particularly the time-charter markets has been used both in the Sustainable Shipping Initiative’s “Save as You Sail” scheme design, and the work by the Carbon War Room on a “Self-Financing Fuel Saving Mechanism”.

Policy makers

- The survey work on uptake of operational energy efficiency is the most substantial survey of its kind and has been used and referenced by both sets of consultants reporting to DG Clima on the subject of EU unilateral action on shipping emissions.
- The work assessing the scenarios of carbon price that could be associated with achieving a trajectory of shipping’s emissions consistent with a two degree target has been presented at a side event at the 2013 UNFCCC COP meeting in Bonn. It is also being presented in a series of workshops with key industry stakeholders.

What Further Work is There and What Key Challenges Remain?

Two key pieces of work in this project provide evidence of further work needed to understand the operational efficiency of the existing fleet and the potential and mobilisation of its improvement. Figure 53, taken from (Smith et al. 2013), shows the estimated difference between the average operational efficiency and highest 10% and 5% operational efficiency for a number of different ship types. This analysis of operational data corroborates the survey of operational efficiency intervention take-up (Rehmatulla and Smith 2012), which implied that there is variability in the interventions applied according to the nature of the shipping firm (e.g. owner operator, time charterer, etc.), and the charterparty used. Further work could correlate the different levels of observed operational efficiency with specific shipping companies in order to characterise in detail both the causes of both the lower-end and higher-end operational efficiency performance. This characterisation could then be used to guide the development of focused policy to address the specifics of the observed market barriers, as well as ensure that the development of other policy (both GHG and non-GHG) does not create adverse unintended operational efficiency consequences.

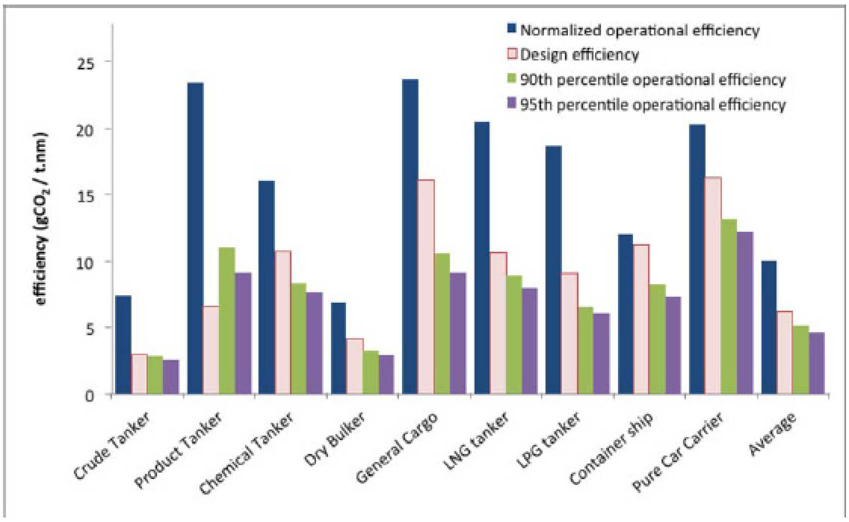


Figure 53: Operational, technical, 90th percentile, and 95th percentile energy efficiency

Longitudinal analysis

Due to the timescale of the Low Carbon Shipping project, the work has primarily focused on cross-sectional analysis of the efficiency of the fleet (predominantly in 2011). To improve understanding of the 'levers' and the influence that external drivers (policy, fuel price, freight rates, technology availability) have on the efficiency of shipping, more work to look at the evolution of parameters, including operational efficiency, over time (longitudinal analysis), is needed. As has been shown in many other industries, this would have applications both in the reduction of the 'efficiency gap' and also in the design of evidence-based policy that imposes minimal negative impacts on the industry.

Mandatory energy efficiency

Over the course of this project, the IMO's MBM discussion (MEPC 60 to 65) has continued to include both types of MBM (price-signal mechanisms and mandatory energy efficiency). GloTraM focused on assessing the impacts of the former, price-signal mechanisms. However, with the submission of (IMO 2013), the potential for a mandatory efficiency standard in the future remains high. The phased implementation proposed in this submission allows the time for further investigation using models, as well as experimentation and data analysis from a pilot implementation. This therefore warrants the development of functionality within GloTraM to assess, for the same exogenous input data, the impact of a mandatory efficiency measure, relative to the price-signal measure, in order provide a considered comparison.

Dissemination

Rehmatulla, N. (2011) Applying systems thinking approach for qualitative analysis of GHG emissions regulations in shipping. ICCMA 2011

Rehmatulla, N. (2013, forthcoming) Barriers in the shipping system. PhD Thesis, UCL London.

Rehmatulla, N. (2012) Barriers to uptake of energy efficient operational measures. Survey Report. UCL London.

Smith, T.W.P., O'Keeffe E. (2012) What is an appropriate measurement and apportionment strategy for international shipping? LCS 2012,

Smith T.W.P., O'Keeffe, E., Aldous, L., Agnolucci P. (2013a) Assessment of shipping's efficiency using Satellite AIS data. UCL Energy Institute. London.

Smith, T.W.P., O'Keeffe, E., Haji, S. (2013b) Quantifications of apportionment of CO_2 emissions from International Shipping. LCS 2013.

Rehmatulla N., Smith, T.W.P. (2012) Implementation Barriers to Low Carbon Shipping. LCS 2012

Smith, T.W.P., Barrett, M., Parker, S., O'Keeffe, E. (2011). Initial Estimates On Shipping's cost impacts and emissions for a range of policy options. LCS 2011

Gordon, S., Smith, T.W.P. (2012) Overview: Shipping versus aviation and the EU ETS. UCL. London.

References

Lloyd's List (2012) Shipping refuses to play cash cow in the war against climate change. Lloyd's List Intelligence.

EC (2013) Proposal for a regulation of the European parliament and of the council on the monitoring, reporting and verification of carbon dioxide emissions from maritime transport and emending regulation (EU) No 525/2013. 2013/0224 European Commission. Brussels.

UNEP. (2011). Bridging the Emissions Gap

Delft CE (2009) Technical support for European action to reducing Greenhouse Gas emissions from international maritime transport. CE Delft, Delft.

IMO MEPC 61/Inf. 2 (2010) Full report on the work undertaken by the expert group on feasibility study and impact assessment of possible market-based measures

IMO MEPC 63/5/6 (2011) Ensuring no net incidence on developing countries from a global maritime Market-Based Mechanism. IMO, London

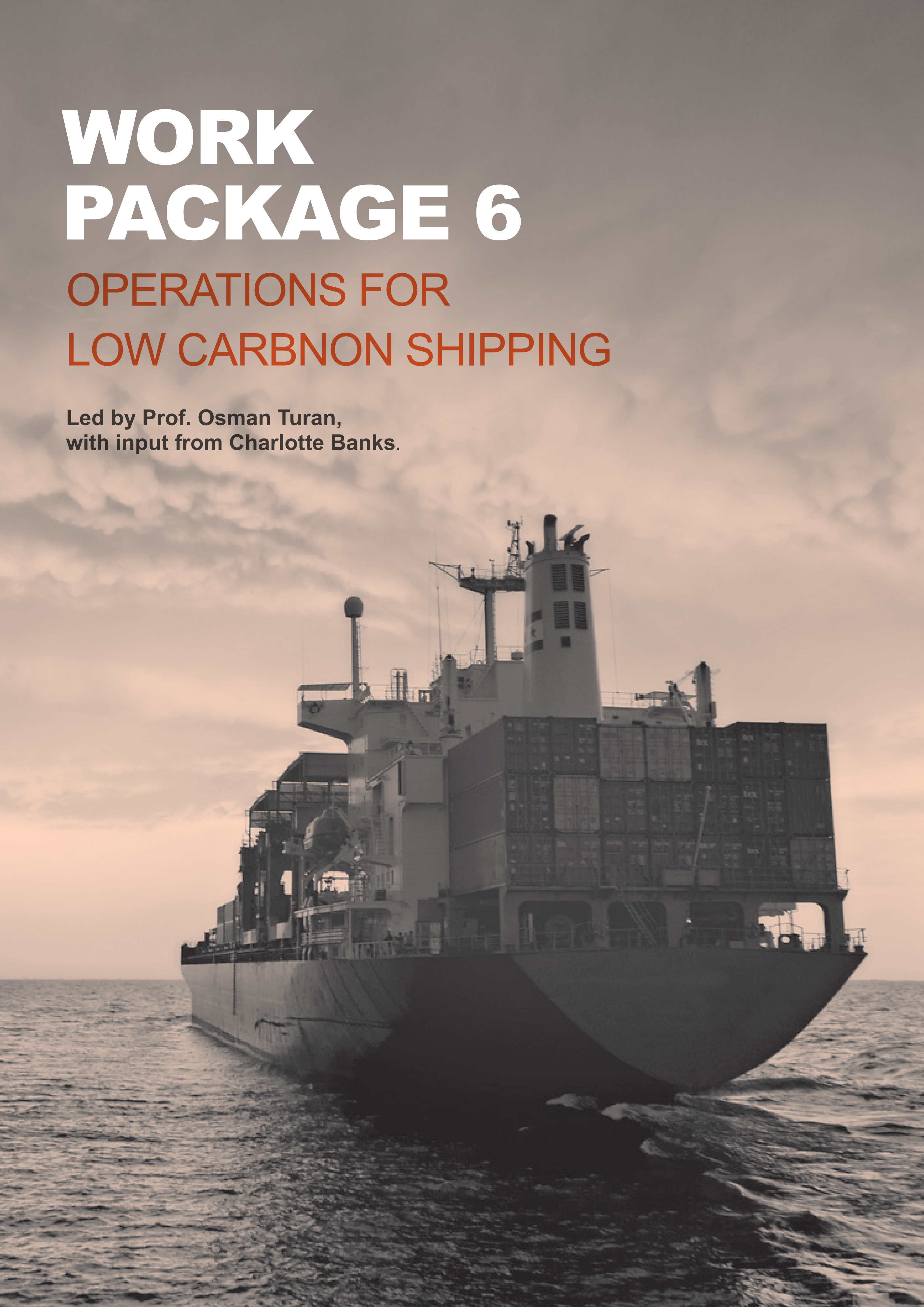
IMO MEPC 65/4/19 (2013) Proposal of the United States to enhance energy efficiency in international shipping. IMO, London.

Ricardo-AEA (2013) Support for the impact assessment of a proposal to address maritime transport greenhouse gas emissions. Ricardo-AEA Ltd. Didcot.

WORK PACKAGE 6

OPERATIONS FOR LOW CARBNON SHIPPING

Led by Prof. Osman Turan,
with input from Charlotte Banks.



WP6 – OPERATIONS FOR LOW CARBON SHIPPING

Led by Prof. Osman Turan, with input from Charlotte Banks.

Main Research Focus/Activity

The research focus of WP6 was to identify and address human factors that can be improved to increase the energy efficiency of ship operations, resulting in a reduction of carbon emissions emitted by shipping. The key areas identified to be addressed within WP6 include:

- Development of mission-specific education and training to increase the awareness, knowledge, skills and motivation of cadets and seafarers, hence improving their operational performance in terms of energy efficiency
- Development of Crew Resource Management (CRM) to increase the quality of team performance and vigilance for safe and efficient operation and navigation of ships
- Investigation of condition monitoring and onboard Real-Time Decision Support Systems (DSSs) to assist achievement of energy efficient ship operation
- Explore maintenance and repair strategies to maintain maximum ship operational performance

The research activities undertaken to explore the above key focus areas included: collection of real operational data; data storage and data analysis; a questionnaire analysis; performance modelling; and formulation of a performance monitoring tool.

WP6 focused around understanding the barriers related to the operations, practices and decisions made by seafarers and onshore personnel at a ship operation level.

Scope of the work (the boundaries of applicability)

In January 2013 the IMO made the addition of Maritime Energy Efficiency Regulations to chapter 4 of MARPOL Annex VI. This includes the Energy Efficiency Design Index, EEDI, and the Ship Energy Efficiency Management Plan, SEEMP. In the context of WP6 the EEDI is expected to incentivise the installation and use of new low carbon technologies and ship designs. This will require management: to consider good investment decisions in new technologies, and to update existing procedures and decisions to maximise the effectiveness of the new technologies. It will also require seafarers to operate the new technologies safely while realising maximum potential efficiency savings, and for onshore management to provide the support required to achieve this. Furthermore, the SEEMP requires an energy efficiency management plan to be implemented for each individual ship, detailing the activities that ship management, other onshore personnel and seafarers should undertake to achieve energy efficient ship operation. All of the points described, both for the EEDI and the SEEMP, require careful consideration of human factors: however it was not possible within the scope of this project to address these for all the different departments and personnel, both onboard and onshore.

The focus for WP6 was set to include the operations of seafarers (including cadets completing their initial maritime education) as well as the onshore management directly related to the integrated daily operation of a ship. There were several reasons for this:

- If seafarers do not have the awareness, knowledge skills and motivation to operate new technology and achieve the maximum energy efficiency potential savings, then the investment in the technology will not be realised. Furthermore, seafarers can increase operational energy efficiency by utilising existing machinery and equipment on board (i.e. without investment in new technologies). This requires application of the correct skills alongside the necessary support from onshore personnel.
- Focusing on providing education and training at a cadet level creates the development of awareness, knowledge, skills and motivation towards energy efficiency at the earliest stage possible, reducing the need to train seafarers once working on company time. Furthermore, noting that there is a growing trend for seafarers to spend less time working at sea before moving into onshore jobs, earlier training ensures personnel have the knowledge and motivation to integrate into their new job roles and responsibilities.
- The development of the EEDI and SEEMP has predominantly initiated the development of education (outside of the LCS project) at an operational and investment management level. This leaves an important gap that needs to be addressed by ensuring that seafarers and onshore personnel with day-to-day operational responsibilities also have the awareness, knowledge, skills and motivation required.

In exploring condition monitoring and maintenance strategies, the scope of WP6 focuses on two main areas:

- **Developing the framework** for voyage optimisation has included several tasks related to modelling ship performance. Not only will information generated by performance modelling support the framework for onboard real-time decision support systems, but it will also provide knowledge that can be used by seafarers when drawing up a voyage plan; appropriate education and training is required to deliver this awareness and knowledge, and develop skills.

- **Hull and propeller maintenance** was identified as an important energy-critical operational strategy with scope for improvement to increase energy efficiency. This WP has therefore focused on developing a model to monitor and predict ship performance and hence determine improved strategies for hull and propeller maintenance.

Main Outputs and Activities

The following papers (abstracts are listed below) have been published or are in preparation, based on the work carried out in WP6.

An approach to education and training of seafarers in low carbon – energy efficiency operations

The subject of low carbon–energy efficiency' has never been more important, with increasing worldwide concern about climate change and the pending enforcement of international maritime carbon policies and regulations. Implementation of operational measures alone offers significant potential for reducing carbon emissions from shipping. Currently there is no formalized education and training for maritime personnel in the area of energy efficiency with a focus on reducing ship carbon emissions. This paper considers the existing gap within the current maritime education and training system and addresses the potential benefits of providing a specific 'Low Carbon–Energy Efficiency' maritime education and training course on a large scale. Various approaches to course delivery are examined and a course framework is presented based on the most effective methods for knowledge transfer for increasing cadets' awareness, knowledge, skills and motivation in the area of energy efficiency. Appropriate course content is discussed, including consideration of the material required for theory-based learning, exercises, case-studies, simulator training and e-learning, and the subsequent assessment of each.

Self-learning Based Ship Onboard Decision Support System

Shipping contributes to about 3.3% of global carbon emissions, which equates to around 1,000 million tonnes of CO_2 emitted into the atmosphere each year. Action therefore needs to be taken to reduce this amount considerably within the coming years. This can be achieved immediately, cost-effectively and efficiently by increasing the energy efficiency of the ship's day-to-day operations. An onboard decision support tool to aid crew in making the correct energy efficient decisions will significantly contribute towards reducing emissions. Voyage optimization (route, heading, speed, propeller trim, etc.) and maintenance optimization of the main energy consuming systems on board are both considered within the proposed Decision Support System framework discussed within this paper. Automatic analytical methods, such as artificial intelligence, are developed for analysis of the historic and real-time monitoring of data and ship performance data. Predictive methods are also adopted for forecasting future ship performance. The construction of a unique system framework with an Energy Efficiency Knowledge Bank, which will provide innovative experience sharing based on the analysed data, is presented by utilising a distributed database management system (DDBMS). A numerical optimisation is required and the HCPSO and NSGA2 optimisation methods are considered for application. The Decision Support System is based on an in-house integrated fuzzy decision support method. A few essential attributes and their corresponding importance weightings are used to perform the decision support following the optimisation; thus providing crew members with clear and informative suggested best operational (voyage and maintenance) practices.

Seafarers' current awareness, knowledge, motivation and ideas towards low carbon – energy efficiency operations

There is increasing global concern regarding greenhouse gases, in particular carbon emissions and their detrimental effects to our earth's atmosphere; resulting in climate change. International and National pressure requires the shipping industry to play its role in reducing the 3.3% of total global carbon emission that it currently emits into the atmosphere. On the 1st January 2013 the IMO is expected to enforce mandatory measures to reduce shipping carbon emissions and these measures will directly and indirectly affect the daily operations of seafarers, onshore performance staff, and managerial personnel with influence over operational procedures. It is therefore imperative that these personnel have the awareness, knowledge, skills, and motivation necessary to successfully implement the operational changes that are needed. A questionnaire has been distributed to investigate seafarers' and onshore personnel's current levels of awareness, knowledge and motivation towards carbon emissions in general and towards shipping carbon emissions. The questionnaire also asked participants to contribute which level of personnel have the most influence over carbon changes and what are the most important operational improvements that can be made. 317 questionnaire responses were collected in total and the analysis of the results is discussed within this paper. The primary benefit of this study has been to support the development of a specific Low Carbon – Energy Efficiency maritime education and training program, by identifying target group needs and attitudes, and key areas for focus.

Understanding the operating profiles with an aim to improve energy efficient ship operations

On 1st January 2013 the IMO introduced Maritime Energy Efficiency Regulations in order to benchmark the energy efficiency of new ship designs and to create a framework for the management of energy efficient ship operations for all ships. It is necessary that energy efficiency improvements for design and operational performance reflect an understanding of the ship's operational profile, rather than its design condition alone. A ship design is typically carried out by optimising the hull form for a limited range of operating conditions, acknowledging that in recent years there have been significant advancements in the application of ship design optimisation processes, particularly with increasing computing capabilities. However, a vessel only operates in its design conditions a small proportion of the time.

This paper presents an analysis of operating profiles for different ship types and identifies key trends over recent years. This analysis considers the type of charter and the time spent: in ballast or laden; in port, maneuvering or sailing; draft ranges, speed ranges, encountered weather conditions. The analysis has been carried out based on reports commonly known as 'noon' and 'port' reports which are predominantly completed by seafarers using a variety of observation methods. Thus the data itself is inherently susceptible to errors, including human errors. The effect of these errors are discussed with a view to using the data for ship performance monitoring and with the aim of improving operational energy efficiency.

The role of crew for energy efficient ship operation

Energy efficiency has gained an increased focus within the shipping industry due to the direct relationship between fuel consumption and carbon emissions emitted. This focus has been driven by international pressure to reduce the impacts of climate change as well as to save costs due to high bunker prices. Short and long-term operational and technological methods to improve shipping energy efficiency have been identified and new maritime energy efficiency regulations were introduced on 1st January 2013. The Ship Energy Efficiency Management Plan is one of the two mandatory regulations introduced and it should be implemented onboard all new and existing vessels with aim to improve ship operations. There are many stakeholders involved in achieving operational improvements and each of these stakeholders has a different level of opportunity and responsibility. This paper examines observations that have been made based on the results from a questionnaire where 317 responses from seafarers were collected. The differences in opinion between operational teams onboard (deck, engineer, other) are examined in terms of carbon awareness, knowledge, motivation and perceived improvement areas. Differences between groups operating under different management environmental strategies are also discussed. The observations discussed demonstrate the requirement for improved resource management onboard, onshore, and between ship and shore, to maximise operational energy efficiency.

Operational practices to improve ship energy efficiency: with focus on seafarer maritime education and training and hull and propeller maintenance strategies.

Energy efficiency to reduce the amount of anthropogenic carbon emissions emitted into the atmosphere has gathered increased awareness at on International platform as state-of-the-state scientific methodologies reveal more about Climate Change, its' impacts, and the expected impacts into the future. Carbon emissions from shipping are estimated to have contributed to 3.3% of the total global anthropogenic carbon emissions in 2007 and their reduction is required by international parties under the United Nations Framework Convention on Climate Change and subsequent accords and protocols. Specifically the Kyoto Protocol identifies the International Maritime Organisation responsible for implementing measures to encourage reductions of carbon emissions in the shipping industry and this has lead to the maritime energy efficiency regulations being introduced into MARPOL Annex VI: including the Energy Efficiency Design Index and the Ship Energy Efficiency Management Plan. Both these regulations require effort and participation of many onshore and on board departments and personnel. Therefore the scope of this PhD is to identify and address human factors that can be improved to achieve practical operational improvements on board vessels to realise carbon emission reductions from shipping. Subsequently the key areas identified to address this focus are the education and training of cadets, seafarers and onshore personnel with relation to the daily operation of the ship, and effective performance monitoring and feedback to influence and improve operational procedures; where ship hull and propeller maintenance is identified as a critical energy operation and thus an example of how performance monitoring can be used to improve maintenance strategies.

Training and educational resources

The following Model Courses documents describe the framework for three energy management courses designed through this project. The documents should be used by course trainers to develop their own awareness and knowledge and inform their teaching plan for an intended trainee group. The framework includes chapter and section headings as well as the learning objectives that should be accomplished by the trainees for each: the learning objectives relate directly to the topic content and to the assessment criteria. An estimate of the hours required to teach each chapter are presented along with an example timetable for a week/three-day condensed course: this is only a guide and the number of hours will vary according to the teaching expertise of the trainer, the requirements of the particular group, and the resources available. As each chapter is self-contained and independent of the others in terms of theory, exercises, examples and assessment criteria, the course can be integrated into the weekly schedule of cadets completing their maritime education over a semester, or run as a condensed training course for experienced seafarers.

Each of the three courses incorporates generic chapters including;

- Introduction To The Course
- Climate Change
- The International Response To Climate Change And Shipping's Contribution
- Maritime Energy Efficiency Regulations
- Energy Awareness
- Additional Methods For Energy Management
- New Technologies

These chapters are assumed to be necessary for all trainees in all courses to complete to ensure that they have the correct level of awareness and knowledge about the background to the topic and the subject, which should lead them to be motivated to make improvements. However, if either the Energy Management for Deck Officers or Energy Management for Engineers course is run in series with the Energy Resource Management course, then these generic chapters do not need to be repeated.

Energy Management for Deck Officers – Model Course:

This course is aimed at a trainee group of Masters and Deck officers. In addition to the generic chapters it also includes specific chapters on Voyage Planning and Cargo Handling.

Energy Management for Engineers – Model Course

This course is aimed at a trainee group of Chief Engineers and Engineering Officers. In addition to the generic chapters it also includes specific chapters on:

- Energy Resource Management – Model Course: The Energy Resource Management Course is aimed at a trainee group of Masters, Deck officers, Chief Engineers, Engineering Officers, Vessel Superintendents, Voyage managers, (the relevant on shore personnel). This course differs from the other two as it places more emphasis on the development of non-technical skills as well as the development and knowledge of technical skills
- Energy Resource Management – Training Material: The Training Material document corresponds to the Model Course document (i.e. with the same chapter and section headings, learning objectives). The training material is what makes this course unique in that expert knowledge from academic work and practical experience from industry have been collected, combined and presented.

In addition to the model course the training material describes the technical and non-technical knowledge that is required by the trainer to teach the course, ensuring that they focus on best practice rather than their own experience. The training material is presented in an easy-to-read and digestible format as it is intended that it could be distributed to trainers internationally (spreading the knowledge further).

Chapters within the Energy Resource Management course promote awareness and knowledge of a ship's technical performance: however, non-technical skills essential for energy efficient operations (such as communication, teamwork, leadership, etc.) are also addressed. Additionally, operational practices (including those identified in the SEEMP) are considered in detail, discussing the responsibilities, expertise, barriers and enablers for implementation of all personnel involved with each practice, with the aim of achieving fully integrated and energy efficient operations.

Energy Resource Management – Course Notes:

The Course Notes are a summarised version of the Training Material and should be distributed to trainees to take notes during the course and keep for future reference.

Energy Resource Management – Teaching Aids

The Teaching Aids are presentations corresponding to the Training Material and Course Notes that can be adapted and used by the trainer to deliver the course. They also contain useful documents (such as excel spread sheets) that can be used as part of the specified examples. As with all related material, these are available from the authors.

The Training Material is the most comprehensive document within the set of documents and its' intended use is by the trainer of the course. The Training Material should provide the trainer with the knowledge and background information that they need to teach such a course and meet each of the learning objectives specified in the assessment criteria if they do not already have the knowledge. The language and style of the material has been presented in a way the best practices within the material can be distributed at an international scale. The detailed material has been collated from various sources including the industry, academic publications and modelling and experimental results. Where academic work has been utilised there has been a strong focus on integrating the state-of-the-art knowledge into practical solutions for ship operation. The content of the course has been reviewed by the industry to validate the knowledge content and practicality.

Questionnaire reports (confidential to participating companies)

Towards the end of 2011, a questionnaire was distributed to seafarers, to investigate current levels of awareness, knowledge and motivation towards carbon emissions in general and towards shipping carbon emissions in particular. The following reports were produced and distributed to four of the shipping companies that took part in the questionnaire.

- Questionnaire Analysis Report: this was the most detailed of the three reports and presented the results for each question based on the responses from one specific company only. A discussion of the results was provided along with an introduction and conclusion.
- Questionnaire Comparison Report: this report compared the results of specific companies with the overall results from the questionnaire (317 participants in total) and a control group (50 responses from a training institute). Again a discussion of the results was provided along with an introduction and conclusion.
- Overview, Questionnaire Comments: this was compiled from the other two reports. Although the questionnaire analysis results were referenced, this report included a summary of the general opinions and comments generated from all the results as well as overall opinions and comments specific to the company.

The confidential nature of these reports means it is not possible for them to be published. However, the overall questionnaire conclusions can be found in the list of papers forming outputs from this work package.

Key Findings and Their Relevance to Commercial and Policy Issues

Education and training, seafarers' awareness, knowledge and motivation towards energy efficiency

The initial step of the research methodology for WP6 included contacting many companies and maritime education and training institutes internationally to ask if they were aware of any maritime education and training courses specific to energy efficiency. While very few companies reported that they held specific training sessions for their seafarers on energy efficiency, no formalised course was identified. (It was also noted that the WMU was commissioned by the IMO to develop an Energy Efficiency Model Course, for which the train-the-trainers course was piloted in May this year.)

As no current formalised education and training was identified, a questionnaire was designed, distributed and analysed to identify the levels of seafarers' awareness, knowledge, motivation and ideas about carbon emissions, their reduction, and achieving energy efficiency on board. The questionnaire was implemented at the end of 2011 and completed in 2012. Three hundred and seventeen seafarer responses were collected, with a relatively even representation of participants from the deck and engine room departments, and a smaller proportion of ratings, cadets and students. The participants predominantly worked for a small number of the larger shipping companies, although responses from maritime training institutes (where the seafarers have worked in a range of companies, both small and large) and cadet schools were also included.

The following paragraphs summarise the main findings from the questionnaire that were used to support the development of the work carried out in WP6: specifically the development of the crew resource management and seafarer specific education and training courses.

- Only 20% of participants had learnt about carbon emissions and their effects via an education or training course and the most common sources for knowledge acquisition were not technical or focused. Therefore education and training is required.
- The most sources of knowledge about carbon emissions and their effects were newspapers, TV documentaries, TV news and magazines, as shown in Figure 54. It is known that these sources are not comprehensive and/or specific to carbon emissions, particularly to carbon emissions from shipping. Furthermore, only 20% of participants reported learning about carbon emissions through an education and training course: further questioning revealed that the knowledge gained appeared to be related to SOx and NOx developments rather than specific to CO_2. This is a positive result for increasing awareness and knowledge about SOx and NOx.
- There was a lack of awareness and focus on energy efficient operation, and a lack of consistent knowledge about best practice. A reduced number of responses and the content of written answers also demonstrated that a lack of consistent knowledge about the best energy efficiency practices at a technical level and/or as well as a lack of focus on identifying and implementing them: 'This priority is not so high in my mind'; '[I have] no time to think about that'.
- There was a clear correlation between how much participants knew about carbon emissions and the energy efficient efforts they made; thus there

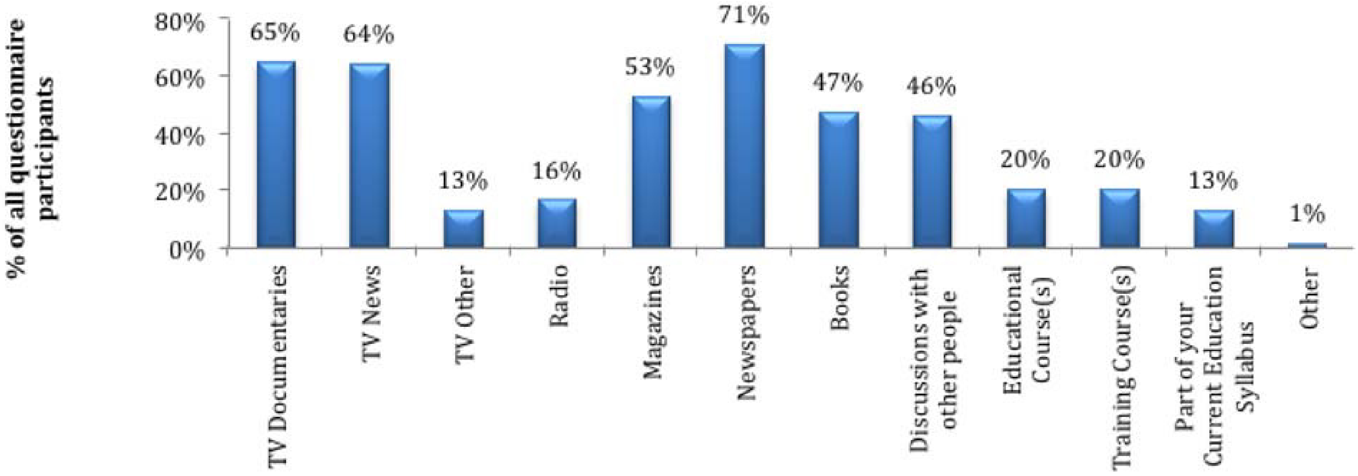


Figure 54: Methods for knowledge acquisition regarding the effects that carbon emissions have on our world (N= 311): participants were allowed to select more than one option for knowledge acquisition

is a real benefit in increasing knowledge. Figure 55 demonstrates that those participants with more knowledge had increasingly tried to make energy efficiency improvements on board: thus there is a benefit in providing knowledge about the effects of carbon emissions.

- There was a lack of knowledge about how individuals can contribute towards energy efficiency improvements (however small) and/or responsibility-shifting among individuals and departments. Subsequent questions demonstrated a lack of awareness about just how much seafarers, and specifically certain departments on board, can contribute to energy efficiency savings. This often results in responsibility-shifting and reduced motivation: 'Not much mainly because I am part of the deck department, but I do my best to contribute for the carbon emission cause.' This can be compared to written responses later in the questionnaire, which identified that the bridge department had some of the largest energy efficiency operational saving opportunities, related to improved voyage planning and implementation as well as ship handling. This highlights the need for the management to present clear and transparent management plans, procedures and responsibilities as well as disseminating efforts made. This will enable each department and individual to understand exactly what they are expected to achieve and how their efforts fit into the wider objective.

- Improvements in onshore support for energy efficient ship operation are required in addition to improved operations by seafarers at sea. A recurring area for improvement identified in the questionnaire was the need for good and useful onshore support. Comments around this included the timely supply of spare parts, good fuel quality,

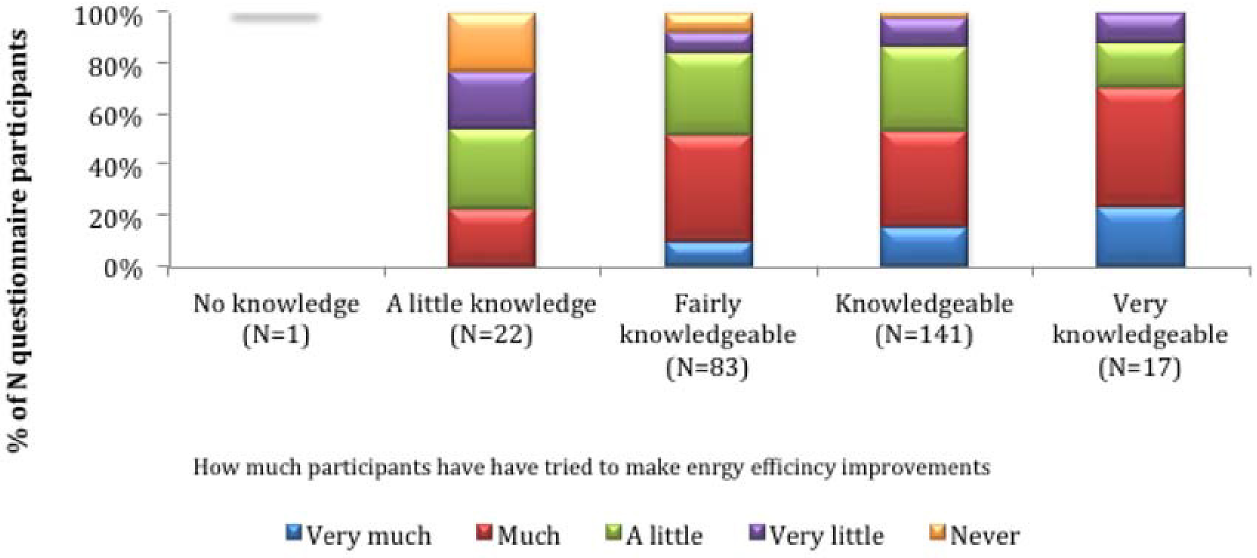


Figure 55: The extent to which participants had tried to make energy efficiency improvements on board, according to the level of knowledge they had about the effect of carbon emissions

hull and propeller maintenance, changes in voyage requirements (e.g. including good negotiations with external stakeholders such as the charterer), and investment in new technologies. Decisions and procedures made onshore were identified as the areas where some of the largest carbon emission reductions could be achieved. The step gains achieved via improved onshore decisions and procedures may be small, but they can add up to produce significant savings. Therefore, integrated operations (i.e. communication and co-operation between personnel both on board and onshore) were identified as a key area for improvement, and should be considered by the industry.

- Performance monitoring and performance feedback of the right information to the right people is important for generating awareness and motivation. The last significant point to emphasise from the questionnaire is that participants identified the importance of useful performance feedback for creating awareness and the motivation to implement improvements. Therefore, performance monitoring techniques should not just be developed for the benefit of the fleet and industry, but also to provide a method for identifying existing performance, areas for improvement, and the creation of awareness and motivation by distribution of the findings (feedback) to the relevant personnel in an accessible format.

Development of Education and Training

On the basis of the key findings of the questionnaire, three model courses have been developed to satisfy the objectives of specific education and training for cadets and seafarers and Crew Resource Management for cadets, seafarers and onshore personnel involved in ship operations. Many of the details have been described above as part of the discussion of the outputs of WP6.

In addition to the documents already described, the following documents are in development – it was not possible to complete these within the timescale of this project:

- Instructors Manual (the same document for all three courses)
- Training Material – (for the Energy Management for Deck Officers and Engineers courses)
- Assessment Material (different documents for all three courses)

Ship operations and energy efficiency

Real operational data collection

A significant task within WP6 was the collection of real operational data. The primary dataset collected is referred to as ‘noon’ and ‘port’ reports. These reports are typically completed by the crew onboard the ship, using a variety of observation methods. They take their name from the time of day reporting is completed, which is typically noon when the ship is at sea; reports are also completed on arrival into port, when in port, and when departing port. Whilst noon/port reports for different companies contain similar information fields, there are some differences between field names, formats, and the inclusion of some fields. Sorting and correlation of the data from different companies was therefore carried out so that a comparison of results could be made: it was not possible to correlate all data without changing the meaning and accuracy of some of the fields. The fields included within noon/port reports are shown in Figure 56.

In total the noon/port reports were collected for 15 tankers, eight bulk carriers and five container ships. The datasets for each ship varied in length, typically from 1 to 8 years with an average of around 4 years. For each year there were typically around 300 reports, making an average of around 33600 records in total. The data was sorted into a large database where (if applicable) the report fields were combined under the generic headings shown in Figure 56.

Once sorted within the database data analysis was carried out, first to identify operating profiles, then weather effects, then the effects of hull maintenance. This was followed by the use of the data in voyage optimisation analysis. The key findings of the analysis are presented below.

A key point identified during the analysis was the accuracy of some of the data fields and entries and hence their usability in indicating ship performance. Reasons for the inaccuracies were identified to include human error, ambiguous observational methods and current procedures. The most significant data inaccuracies and absences important for performance monitoring included:

- **Fuel consumption:** several reasons as to why accuracies occur in noon/port report fuel consumption data have been identified, including uncertainties about the amount of fuel bunkered, inaccurate methods for measuring remaining fuel onboard/fuel consumed, and human error in recording values. Variance in fuel consumption data is therefore high and provides a scatter of results for performance monitoring (for example see Figure 57)
- **Weather:** the observation of weather effects is a field susceptible to a large amount of error for several reasons. Recorded values in noon/port reports are predominantly based on an individual’s observation on the bridge; the observation recorded may or may not be an accurate representation of the average weather encountered over the reporting period; typically Beaufort and direction fields are recorded, where a single

Report date/time	Observed speed	Vessel Heading	Total HFO Consumption	
Duration	Observed distance	Wind Force	Total LSFO Consumption	
Sailing hours		Wind Direction	Total MDO Consumption	
Report type	ETA	Sea Force	Total MGO Consumption	
(sailing, arrival, port, departure)	Location	Sea Direction		
Passage type (ballast, loaded)	Port of departure	Swell Force	Main Engine HFO Consumption	Auxiliary HFO Consumption
Mean draft	Port of arrival	Swell Direction	Main Engine LSFO Consumption	Auxiliary LSFO Consumption
Forward draft	Latitude (degrees)	Current Direction	Main Engine MDO Consumption	Auxillary MDO Consumption
Aft draft	Latitude (minutes)	Current Speed	Main Engine MGO Consumption	Auxiliary MGO Consumption
Trim	Latitude (compass)		Main Engine Power	
	Longitude (degrees)		Main Engine RPM	
Comments	Longitude (minutes)		Slip	
	Longitude (compass)			

Figure 56: Example fields within noon/port reports

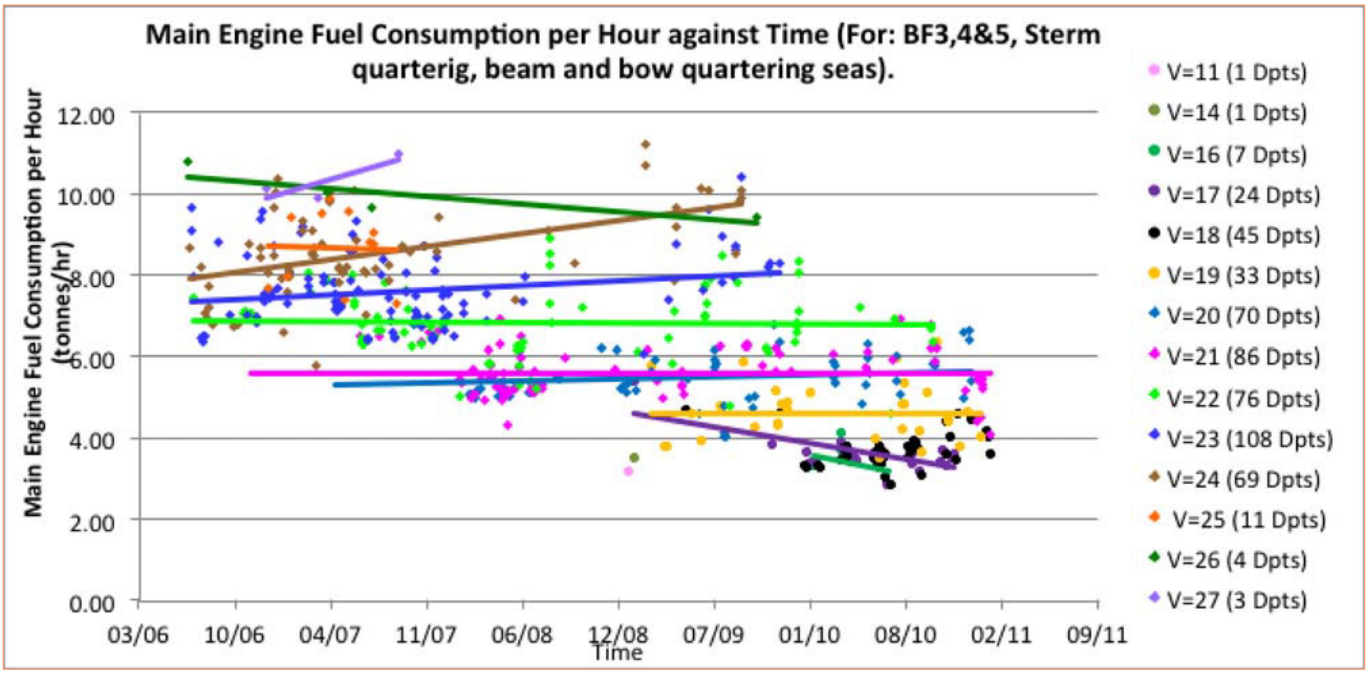


Figure 57: Example of variation in data points for different performance indicators

Beaufort number encompasses a range of wave heights and wind speeds. Wave, wind, swell and current strength and direction all have an effect on vessel performance but are typically not recorded in the noon/port reports.

- **Draft and deadweight:** it is known that the underwater displacement of a ship changes the resistance, hence power, and fuel consumption, of the ship. The shape of the underwater hull is also important and is influenced by trim. However, whilst these fields are recorded in separate documents they are not always included in the noon/port reports and are therefore rarely correlated to identify ship performance.
- **Power:** the majority of ships are not equipped with a torque meter, and therefore direct power measurements are not recorded in the noon/port reports. This is an omission of valuable information about a ship's performance.

It was also apparent that the noon/port data alone was not sufficient to complete the entire analysis and so other types of information and data were also collected, including:

- Vessel particulars;
- Vessel information (i.e. dry docking and cleaning dates, hull - and propeller - coatings used, retrofit technologies installed, date of SEEMP installation);
- Speed trial documents; and
- Lines plans (obtained for only few vessels).

Specific monthly reports and additional external reports were also collected. In particular, the known dates and external reports provided importance for validating the results found using the noon and port reports, whilst the speed trial documents provided information for benchmarking, and the lines plans for the potential to performance more advanced performance modelling.

Data analysis and operational profiles

The noon/port report data was used to provide a valuable insight into the operational profiles of different vessel types. The operational profiles refer to the conditions that the ship is operated in, such as: time sailing, in port or manoeuvring; time spent ballast or loaded; operating speeds; range of drafts operated at; and so on. Each of these factors relates to the overall performance of the vessel and thus how efficiently it is operated and utilised for the given conditions (e.g. weather) and requirements (e.g. charter). Furthermore, typically in a ship is designed for a limited set of design criteria to optimise (i.e. design speed and draft, calm water) and therefore operation away from these design conditions indicatively results in a loss in performance. Therefore, an understanding the operating profile of a ship is not only valuable for consideration in future designs, but can also be used to improve prediction, expectations and identification of strategies for improved ship performance.

The first operational profile considered was the percentage of time spent in port, ballast and laden during one year. Figure 58 demonstrates examples of the case groups of Aframax tankers, Suezmax tankers, bulk carriers and post-panamax container ships. The key conclusions from this analysis include:

- The percentage of time spent in each passage type mode varies slightly from year to year but there is no significant trend indicating an increase or decrease over time.
- The differences in port and in ballast times and percentage loaded times indicates that there are opportunities to improve port procedures for quicker turnaround as well as voyage scheduling to maximise percentage of time loaded.
- The percentage of time spent in port is around 42% for Aframax case tankers. The ballast time is around 27% whilst the loaded utilisation of the vessel is only around 30% of the year.
- Suezmax case tankers appear to spend less time in port (around 32%) and more time in ballast (around 33%) and loaded (around 34%) compared to Aframax tankers.
- The percentage of time spent in port varies between case bulk carriers (between 53% and 25.2%, averaging around 35%). Whilst it appears that in the last three years the percentage of time spent loaded has increased for the case bulk carriers, there is no increasing or decreasing trend shown in the ballast and port times.
- The containers, as expected, show different operating profiles where very little time (or no time) is spent in ballast. However in 2012 the largest proportion of time spent in ballast was observed. Furthermore, the port time varies from 55% to 25% (averaging around 34%), again emphasising the opportunity to optimise port operations.

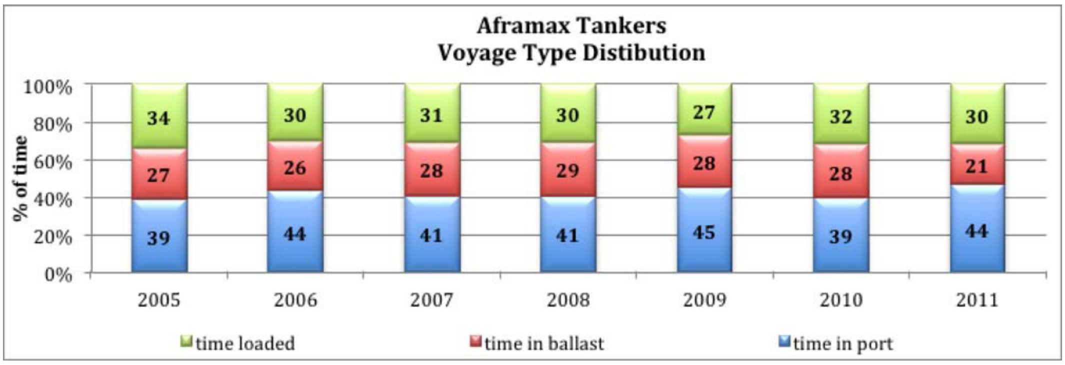


Figure 58: Example of the distribution of voyage type over the years for Aframax case tankers

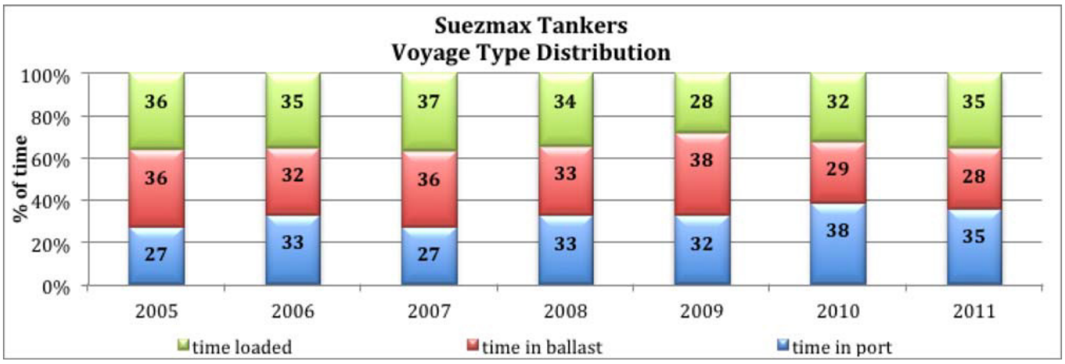


Figure 59: Example of the distribution of voyage type over the years for case Suezmax tankers

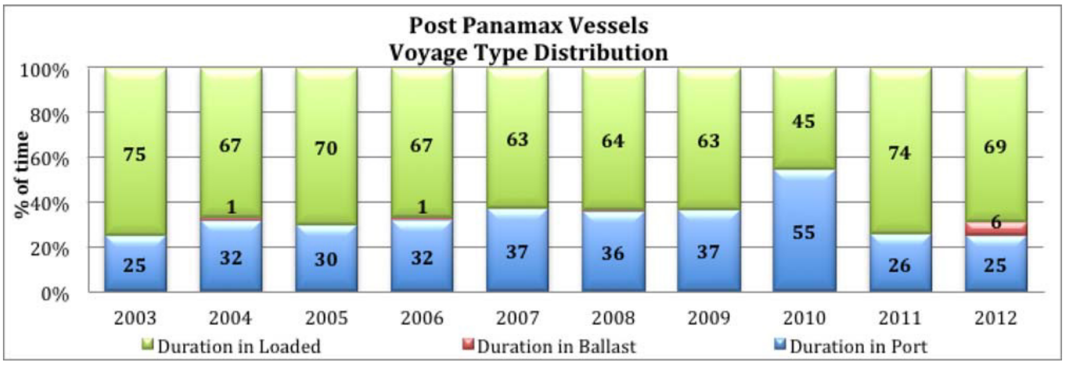


Figure 60: Example of the distribution of voyage type over the years for case post-panamax containers

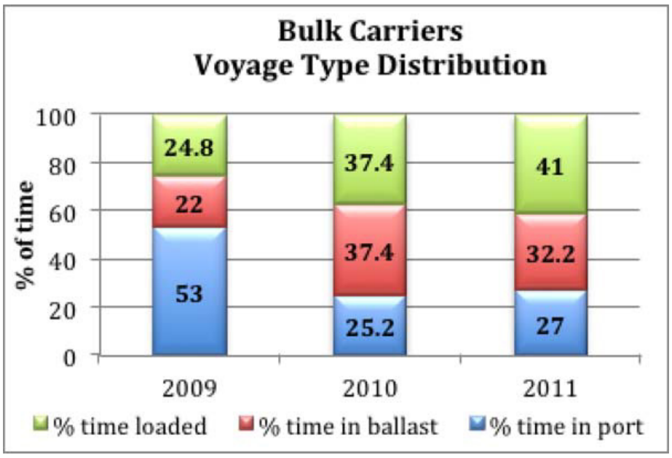


Figure 61: Example of the distribution of voyage types over the years for case bulk carriers

Where available, the noon/port report data was used to examine the distribution of vessels' drafts. For tankers it was noted that, while the ballast drafts were relatively constant, there was a greater distribution of mean drafts for the loaded voyages, indicating they were not always operating at 100% load. For a very small number of ships the data needed to calculate the trim was available. This analysis found that for the case ships a trim was only used in the ballast condition where propeller immersion may become a greater factor. Knowing that the displacement (related to mean draft) of a vessel greatly influences its resistance through the water, and recognising that trim optimisation is an operational practice where energy efficiency savings can be made (see the work carried out in WP2), it should be highlighted that for many companies and in many instances these key fields (drafts and displacement) are not recorded within the noon/port reports. Their inclusion (or at least correlation with the noon/port reports at analysis) is important for performance monitoring using noon/port report data as well as the other sources available.

The speed distribution for the case ships was analysed and Figure 62 demonstrates an example for the group of post-panamax case ships. Figure 63 shows an example for the Aframax tanker case ships. The key findings from this analysis include:

- For all vessel types the speed profiles have changed over the years. In more recent years: there has been less time spent at one specific speed; the most common speed observed has decreased; the distribution of speed has become greater, tending towards lower speeds.
- The above statement is true for all ship types, although the change in distribution has been less pronounced for the case container ships (noting that this will also change dependent on the charter type).

As a final comment, the analysis of individual voyages provides useful information that can be incorporated into the performance modelling: for example, the length of port stay in different geographical locations will affect the rate that fouling forms on the hull, hence decreasing the ship's performance.

The effects of weather

The available operational data for different types of ship are analysed to establish performance trends and, where possible, to determine the effect of various parameters on the fuel consumption. Environmental effects can include the wave, wind and, in some cases, sea currents. If the effects of weather are determined accurately, this would help weather routing and voyage optimisation to maximise the benefits in terms energy efficiency as well as the safety. A process of data filtering was used to determine the effects that weather has on the performance of a ship. This involved isolating key parameters (such as speed loss) for different Beaufort (BF) numbers and sea directions. This resulted in a number of key findings:

- The analysis of the database indicated that the sea and wind direction in most cases is recorded the same. Sea states recorded are based on naked eye observations by the crew while wind speeds are reported as BF. The sea state for wave heights between 0 and 9, corresponds BF=0 being calm water and BF=9 is being confused seas (sea state 7 corresponds to 9.15 m wave height.
- For low speed vessels such as bulkers and tankers, the increase in fuel consumption for head waves is between 2% (for sea state 2) and 6% (for sea state 5) against the following waves depending on the ship speed and the sea state. The slower the ship, the higher the difference between bow and stern waves in terms of increase in fuel consumption
- Again for the same group of vessels, fuel consumption increases when the sea state increases. This increase may vary between 6% and 12% as the sea states vary from 2 to 5, and naturally this increase will be even higher if the state increases to 6 and 7. Lower the speed higher the difference will be.
- Weather routing may therefore have an important role to play in saving fuel.

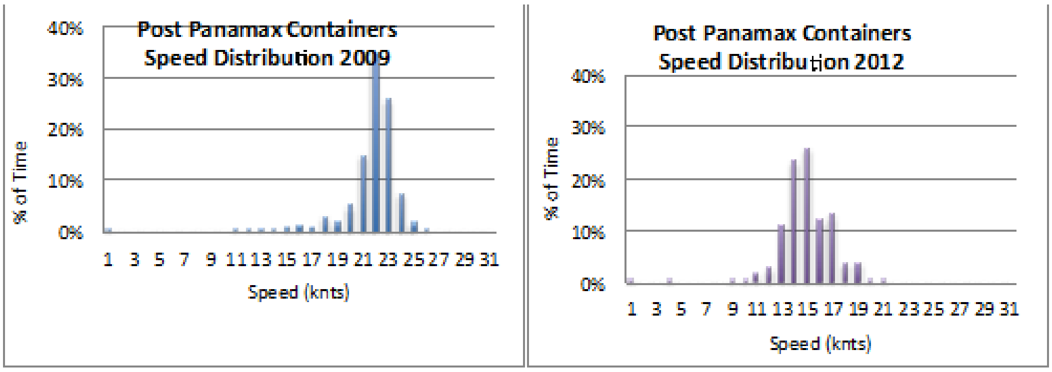


Figure 62: Example, Speed distribution for different years for case post-panamax container ships

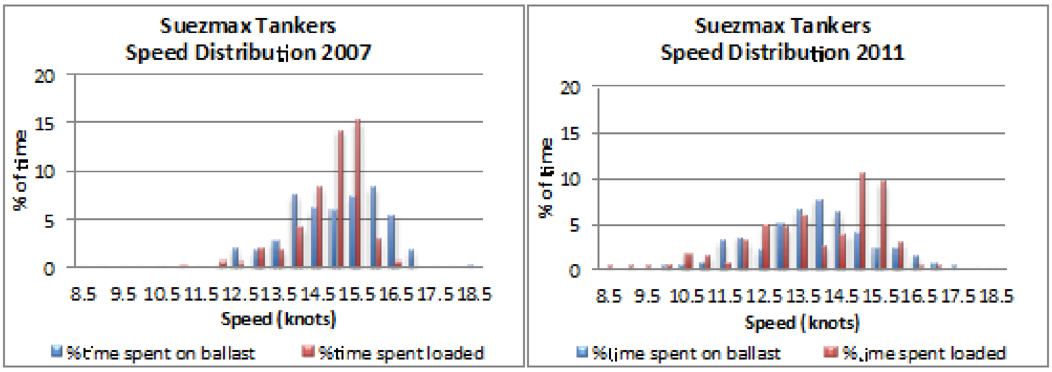


Figure 63: Example, Speed distribution for different years for case Suezmax tankers

The effects of hull and propeller maintenance

Fouling attaches itself to the hull, creating increased surface roughness. This increases the ship's frictional resistance and hence its total resistance, resulting in increased power requirements to maintain the same speed. This means increased fuel consumption and carbon emissions. The amount of fouling that attaches to the hull and the rate at which it attaches varies significantly, dependent on many operational factors (to be discussed).

The analysis carried out in WP6 again utilised the noon/port report data, with the addition of ship particulars and sea trial information to model performance and create a reference for ship performance against sea trial conditions. The identification of the influence of weather effects was also incorporated into this modelling.

Filtering the data for weather condition isolated performance loss over time due to fouling and hull degradation, draft, and so on (according to the variable selected for presentation). Trim and additional weather information such as current were also isolated where the data was available to do so. Several performance indicators (i.e. variables) were examined to determine which provided the best indication of performance loss, as well as to represent consistencies between results.

An example of one of the key performance indicators used, as the data was available for most vessels, was the change in speed over time for a constant RPM.

A review was made of existing procedures used for ship hull and propeller maintenance and found that at present most hull and propeller maintenance decisions are based on:

- dry docking intervals;
- noted observations of significant performance loss (e.g. by seafarers, ship managers, etc.);
- underwater inspections carried out by divers.

The decision on when to carry out hull and propeller maintenance also very much depends on the particulars of the operation of the vessel, such as:

- type of charter (which stakeholder pays for the maintenance and which gains from the fuel savings); and
- the schedule of the vessel (the scheduled port stops, the hull and propeller cleaning facilities at each port stop, etc.).

In addition there is currently a lack of awareness (although this is slowly improving) about the significance of hull and propeller degradation and fouling, particularly as antifouling coatings (such as TBT, now banned) in the past were so effective. The literature review, discussions and analysis of case data concluded that the typical practice for hull and propeller maintenance is to carry it out during dry dock (i.e. at the time of the five-year special survey) and only clean intermediately if a significant performance loss has been identified.

A number of further findings were identified:

- The amount and rate of fouling on hull varies significantly with the ship's operating profile and the type of hull coating used. The amount and rate of fouling is affected by water conditions (temperature, salinity, fouling population, etc.), the populations of fouling organisms in an area, the speed of the ship, and the type of hull (and propeller coating) used. The rate of change also depends on the amount and type of fouling that already exists on the hull. Case data shows that fouling increases at an average rate of 0.75% added resistance (above baseline total resistance) and could increase to 2% or be as little as 0.5%. Additionally, it is estimated that vessels are operating in the world fleet with an average of 30% added resistance over a ten-year period; but this could be as little as 15% or as high as 50%.
- The gain from hull cleaning and dry dock repairs varies greatly according to the condition of the hull before maintenance and the quality of the maintenance carried out. In case scenarios no savings and even negative savings were observed, due to increases when the hull coating has been damaged during cleaning. However, it is estimated

that an average of 20% added resistance saving will be observed when carrying out hull cleaning, and this could typically rise to 30% or reveal no savings at all 0%. Case study data also demonstrates that cleaning alone (without dry docking) could result in an average of 10% added resistance saving, increasing to 20% and potentially being 0% or negative if damage has been created.

- Performance monitoring and modelling needs to be incorporated and utilised as a tool for improving hull and propeller maintenance strategies. To identify practical optimal maintenance scheduling the costs must also be considered. These include cost of maintenance and facilities, cost of paint, cost of hire, and so on.

Voyage Optimisation

Voyage optimisation is the optimisation of ship operation, which refers to improved voyage planning, weather routing, speed optimisation and 'just-in-time arrival', while creating the most energy efficient operational profile of ship (most energy efficient trim, minimum port time and utilisation of the right operational aids). The aims of voyage optimisation are to increase energy efficiency, to arrive on time and to reduce carbon dioxide emissions. There are many aspects to voyage optimisation that require consideration and the practical and logistical components are just as significant as performance-related modelling. Figure 64 demonstrates many of these components.

The voyage optimisation framework therefore has two levels: (1) voyage prediction and planning based on the operational profile, time of the year and the past weather statistics for the voyage dates; and (2) real-time voyage optimisation and decision support system.

For the development of accurate voyage optimisation it is important that the ship's operational profile is recorded accurately in the data bank. Due to the uncertainties in the operational data during voyage data, appropriate modelling should be utilised in the performance predictions. Voyage planning is affected by many factors and therefore charter contracts need to ensure that the operational decisions and communication/relations between ship management, commercial departments and external agents and bodies' roles are clearly defined.

A self-learning voyage optimisation framework was developed and is shown in Figure 65. It demonstrates that the knowledge bank supports the whole system as the system database. This knowledge bank draws information from eight parts of a particular ship together with the previous experience from learning process and rules from both international organizations and companies. These eight parts, shown in Figure 65, sketch out the full optimisation structure of a ship optimisation. It is noteworthy that updating the knowledge bank is a dynamic process, i.e. it will be continually renewed. The optimization method will collect the information from five simulating and calculating system with the assistance from four monitoring system.

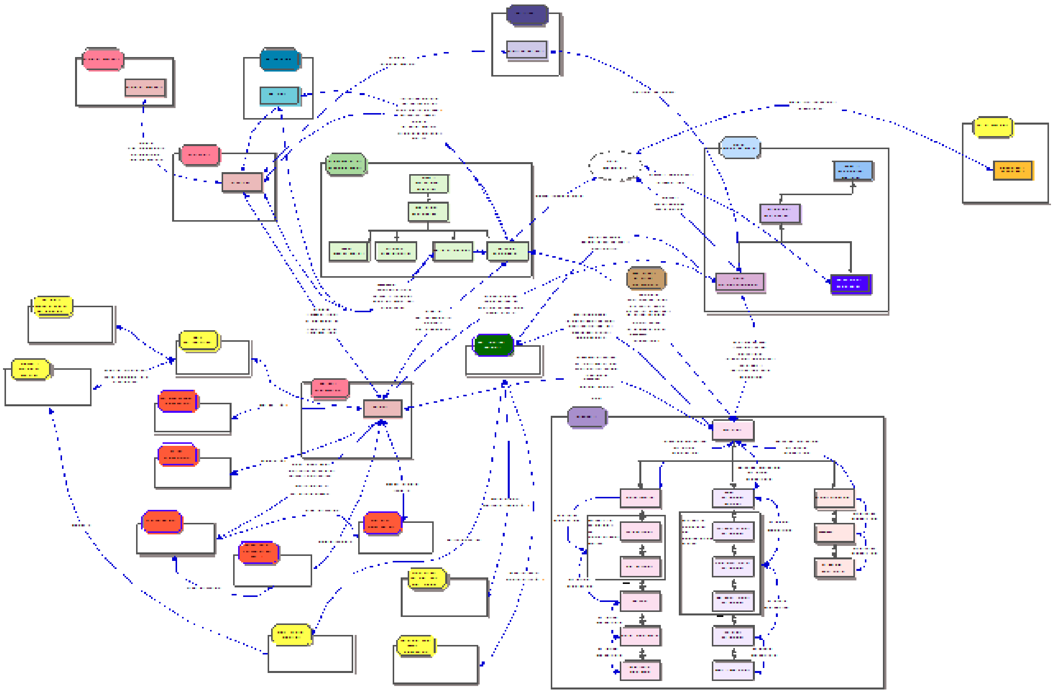


Figure 64: Stakeholder and personnel communication links for voyage operations

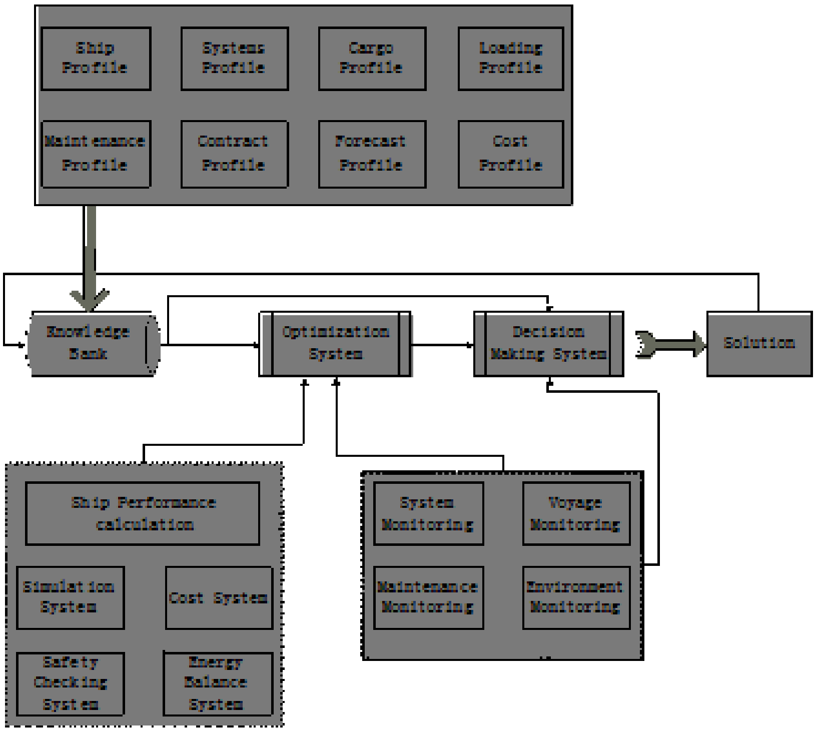


Figure 65: Voyage optimisation structure

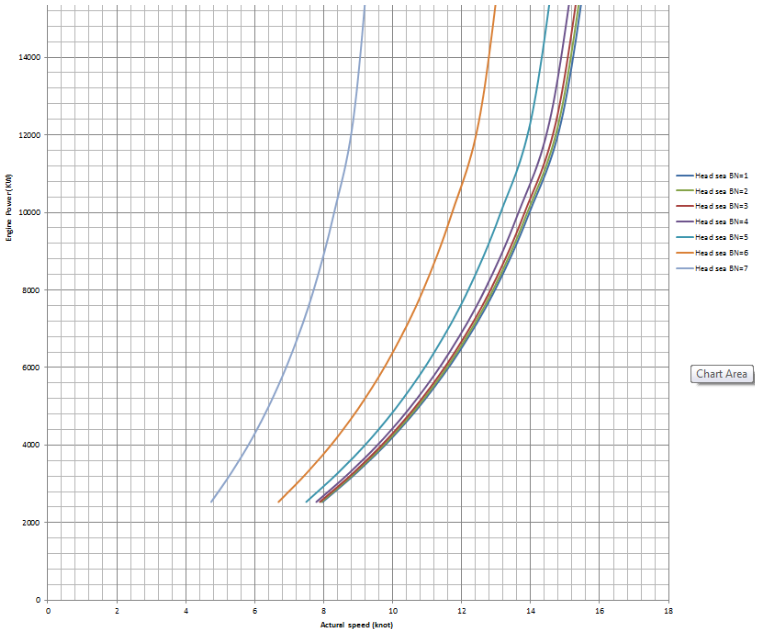


Figure 66: Effect of sea state on power requirements can be predicted using the model developed.

Two optimization methods, HCPSO and NSGAII, are employed to process the multi-objective optimization and both of these methods are improved with learning functions proposed by Cui and Turan (Cui 2010).

Modelling for accurate prediction of power requires the definition of different sea states and wave directions. This is important as the sea state increases the power required to achieve the same speed. There is a point where weather routing will allow using less power and fuel consumption, although mileage covered will be greater. The model developed will be able to predict the power required for different sea states and directions.

The accuracy and technique of predicting the power required depends on the data available for the ships. If the hullform is available the prediction will be more accurate, but availability of the lines plan for ship operators may not always be possible (almost impossible), as became obvious during the data collection campaign. Shipyards in general do not provide the lines plan to the ship owners/operators. Figure 67 shows the prediction capability of the model against the recorded data, which still requires further improvements.

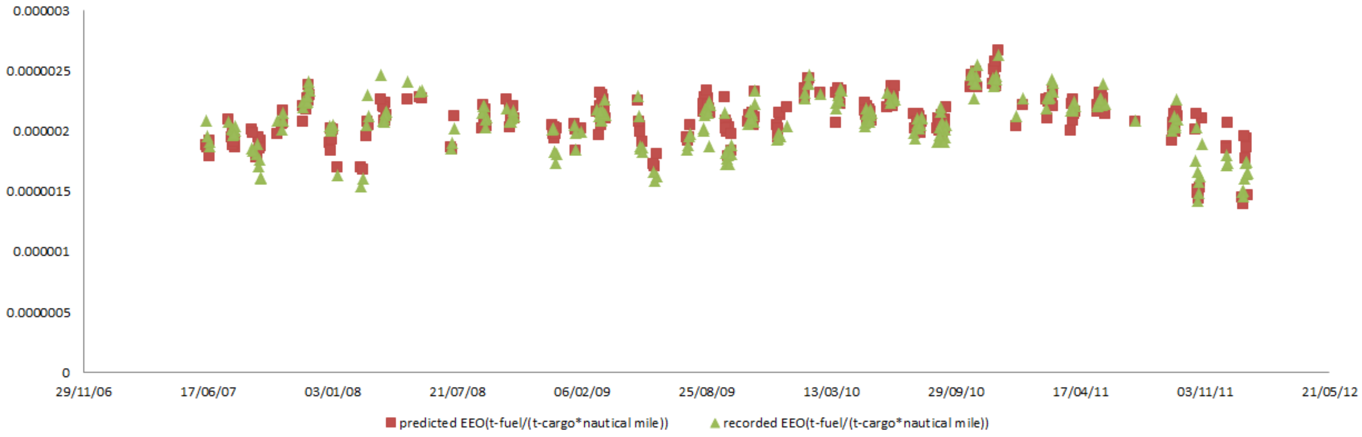


Figure 67: EEOI comparison between the predicted value and the recorded data

Further Work and Key Remaining Challenges

Rolling out education and training

Although a significant start has been made towards developing an education and training package, and the framework is complete for all three courses, further development is required before it can be released as a formalised course. This will include:

- Several rounds of testing;
- Certification of assessment; and
- Presentation to the IMO and interested partners.

Development of integrated decision support

The development of tools for voyage optimisation has been addressed within LCS. However, there is great scope for this work to be continued to further enhance the capabilities of the developed modelling and to continue integrating the prediction model into a fully automated Decisions Support System, utilising importance weighing of the user for specific parameters (multi-objective optimisation) and a self-learning function. The methodology for this development has already been developed within WP6.

Performance monitoring – data recording

A unique and significant set of data has been collected during the past three years, encompassing a range of sister ships and size ranges for tanker, bulk carrier, and container vessels. Furthermore, a mix of commercial reports and specific performance reports has been collected and there remains a vast amount of information that can be extracted and used (for example, main engine performance monitoring).

Dissemination

Banks, C., Turan, O., Incecik, A., Lazakis, I., Lu, R. (2012) Seafarers' current awareness, knowledge, motivation and ideas towards low carbon – energy efficient operations. LCS 2012

Banks, C., Lazakis, I., Turan, O., Incecik, A. (2011) An approach to education and training of seafarers in low carbon – energy efficiency operations. LCS 2011.

Cui, H., Banks, C., Turan, O. (2011) Self-learning based ship onboard decision support system. LCS 2011.

Banks, C., Turan, O., Incecik, A., Theotokatos, G., Izkan, S., Shewell, C., Tian, X. (2013) Understanding the operating profiles with an aim to improve energy efficient ship operations. LCS 2013

Banks, C., Turan, O., Incecik, A., (in prep) The role of crew for energy efficient ship operations.

Banks, C. (in prep) Operational practices to improve ship energy efficiency: with focus on seafarer maritime education and training and hull and propeller maintenance strategies. PhD Thesis.

CONCLUSIONS AND NEXT STEPS

CONCLUSIONS AND NEXT STEPS

Low Carbon Shipping – A Systems Approach was deliberately ambitious in its scope and breadth. The need to bring consistency, objectivity and numeracy to the assessment and optimisation of the various options necessitated a system-wide approach to understand shipping's potential to decarbonise. GloTraM is the model developed in this project that links all the issues together, providing transparency of data and overall costs. In addition to modelling, the project undertook a broad range of fundamental and multidisciplinary analyses in order to address many of the key drivers and the complex interactions that characterise the shipping industry, including:

- Capturing the logistic supply chain/ship design interactions
- Joining up the technical and operational parameters to properly understand and evaluate energy efficiency interventions
- Assessing the economic implications of radical departures from current technologies and operating practices
- Closing of the loop between the operational measurements of performance and the tools used to model and optimise ship specification
- Taking the wider system view of carbon emissions (rather than just the emissions from the ship itself), e.g. the work on alternative fuels
- Capturing the interaction between mitigation policy and climate finance
- Understanding the reasons for the gap between perception and reality, e.g. analysis of market barriers
- Making visible the importance of life cycle assessments

The project found that shipping is a significant and growing climate change challenge. There is a wide range of evolutionary improvements in ship design that could be applied over the next few decades (enabled both through existing regulation - EEDI and SEEMP, expectations of sustained high energy prices, and technological advancements) that offer modest improvements but will not deliver the levels of decarbonisation required to avoid dangerous climate change. Therefore more radical change is required and the sooner fair frameworks and mechanisms to enable this change are established, the less damaging this will be for the industry.

The detailed explanation for this shortfall is that for many technologies, the savings are often found to be less than claimed by some manufacturers. A shift to LNG offers significant improvements but also requires major changes in ship design and shipping infrastructure, and still can only deliver modest reductions in transport carbon intensity. Bioenergy is expected to be supply-constrained, insufficient power outputs are available from solar and the evaluation of the potential of wind-assistance shows that its potential and future role remain uncertain. Operational measures (other than ship speed reduction) also offer improvements through better informed hull/propeller maintenance and voyage optimisation. In combination with many of the technology and operational solutions, significant speed reduction has the potential to close the gap but markets alone won't do this since slowing down beyond a certain speed is uneconomic and has increasingly negative impact on the supply chains that shipping serves. Given the expected long term growth which sets the backdrop to the emissions trajectories of the industry, all of the above changes are unlikely to achieve progress proportionate to shipping's responsibilities (as taken from the Copenhagen Accord) under the current scenario for "business as usual". Therefore there is a need for the development of further voluntary measures or regulation (market-based or command and control measures).

Both from this project's outputs and an increase in the research activity on this subject internationally in recent years, the knowledge and understanding required to enable shipping to make its contribution to minimising the risks of dangerous climate change are now better understood and shared across the sector. However, a number of significant uncertainties are perceived as still being important:

- A lack of clarity on the drivers of ship performance in real conditions (fouling, speed, weather, crew): due to the complexity of the marine environment and the low standard of data monitoring and analysis that is currently used in many firms.
- A lack of confidence that theoretical and experimental modelling of ship performance (particularly with respect to performance characterisation of energy efficiency technology) is representative of 'real world' performance. This is related to the complexity of the physical processes determining ship performance, a lack of clarity on the drivers of ship performance, and also the lack of standardisation in the way theoretical and experimental modelling is undertaken and the inevitable simplifications that are necessary to generate analysis affordably.
- The potential of step-change technologies to be commercially viable and create significant change in the industry (e.g. wind assistance, hydrogen and fuel cells). Mainly due to uncertainty in the performance and costs of the technology, uncertainty in infrastructure development and the high costs associated with the rigorous analysis of performance combined with a shortage of investment in research and development.

- The interaction between global and regional mitigation scenarios and their impact on global demand for different energy commodities, and shipping's transport demand. This is currently dominated in terms of mass lifted by crude oil movements, as well as substantial shares of its transport supply devoted to coal, oil products and gas transport demands.
- Shipping's responsibility to decarbonise, given the social benefits it supplies e.g. in facilitating global markets, which enable energy and food security.
- In the event that the ambition of the Copenhagen Accord is missed, and dangerous climate change modifies the production and consumption patterns of food, fuel, raw materials and goods; how this could affect shipping transport demand and therefore the wider shipping system.
- Opacity in the shipping markets (particularly the lack of transparency in the way prices are set) leads to challenges in forecasting the incentivisation of the investors in technology (typically ship owners) and therefore the technology uptake and flow of capital to the sector's technology providers.

The first round of EPSRC funded projects have established a cadre of newly educated champions. A further EPSRC & Industry funded project is commencing shortly "Shipping in Changing Climates" that will build on the investments to date, pick up many of the areas identified as the source of continued uncertainty, and research how to transition shipping to a low carbon, more resilient future.

- **Theme 1:** Understanding the scope for greater efficiency on the transport supply side
- **Theme 2:** Understanding demand side drivers and trends – trade and transport demand
- **Theme 3:** Understanding supply/demand interactions – transition and evolution of the shipping system

ulling together the complimentary strengths of the UK Universities involved in this project and the support of key industry players together with the volunteering of data and knowledge from across the shipping stakeholder space have been critical to the success of this project, as they will be for the successor project ***"Shipping in Changing Climates".***

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