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Assessment of Shipping's Efficiency Using Satellite AIS data

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EXECUTIVE SUMMARY

OBJECTIVE

The objective of this study is to generate new knowledge and insight on the subject of shipping's technical and operational energy efficiency, both to assist shipping industry stakeholders in understanding the statistics and drivers of energy efficiency in the markets in which they are operating, and to contribute to the ongoing discussions in the policy sphere around energy efficiency and GHG emission reduction. This study, which is the first to use Satellite Automatic Identification System data to analyse the energy efficiency of the global fleet, is also intended to act as an evaluation of this new data source and a discussion of its benefits and any shortcomings when used for the estimation of energy efficiency. Studying the fleet in 2011, this study's particular focus is on the extent to which the recent phenomenon of 'slow steaming' has influenced operational behaviour in different fleets (ship types and sizes), and the probable consequences to energy efficiency. As well as describing the technical and operational efficiency of different fleets of ships, analysis is also undertaken to assess whether energy efficiency appears to be represented in prices (time charter, newbuild, second-hand) in different markets and in the selection of ships for scrapping.

METHOD

There is no widely accepted method for quantifying the technical or operational efficiency of existing ships. Section 1 therefore outlines in detail the method, data and assumptions that have been applied here, primarily for the purposes of transparency. Both methods can be related back to the Energy Efficiency Design Index and Energy Efficiency Operational Indicator equations, a decision made to keep consistency with existing literature and to take advantage of the increasing familiarity in the sector with these quantifications. However, the details of the method in both cases have been tailored to the specifics of the input data used. In the case of operational efficiency estimation, Satellite Automatic Identification System (AIS) data is combined with established naval architecture and marine engineering analysis techniques in order to derive estimates of a ship's annual fuel consumption and CO_2 emissions. Operational efficiency is calculated using two different methods. One utilized Satellite AIS observed draughts to estimate the ship's loading condition and payload utilization. The second method (normalized operational efficiency) applied the IMO 2nd GHG Study estimate of capacity utilization to the ship's payload. For all energy efficiency calculations, an estimate of the quantification of uncertainty and a discussion of its significance to the findings is included in Section 2. A third analytical element of the study links the effects of ships' energy efficiency to wider market dynamics. To estimate the influence of ship energy efficiency on market prices, both regression analysis and mean comparison techniques, commonly used in economic analysis, were applied.

DATA

The data used as inputs to the method come from a variety of sources. Data characterizing ship's technical specifications are from Clarksons World Fleet Register. The dataset includes all ships active in 2011 (e.g. including ships built in previous years). The data characterizing ship's operational characteristics (speed, loading condition and voyage characteristics) are obtained from individual ship's AIS transponders, specifically Satellite AIS which means the AIS signal has been received by satellite, extending to global coverage previous AIS datasets which were obtained from shorebased receivers and only included ship movements in coastal waters. The Satellite AIS dataset is for the period 1st January 2011 to 31st December 2011 only. Where necessary (e.g. missing data), the technical and operational data is supplemented or compared with data and assumptions from the IMO 2nd GHG study, or in some instances other third party sources (e.g. describing the world fleet in 2007). Market data describing prices in different shipping markets are obtained from Clarksons Shipping Intelligence Network (2007-2012).

KEY FINDINGS

The study's quantifications and discussion of energy efficiency are presented in Section 2, analysis and discussion of energy efficiency and prices in Section 3, and key findings in Section 4. The study finds that the proposed method and its novel application of Satellite AIS data can produce valuable insights into the energy efficiency of the existing fleet, particularly in characterizing the variability and heterogeneity of the fleet's operational parameters (e.g. average annual operating speed) as well as updating estimates of operational energy efficiency for the first time since their presentation in the IMO 2nd GHG Study. The study also presents a number of further uses of Satellite AIS, demonstrating its potential for analysing energy efficiency on routes between individual countries and regions and the geography of shipping's energy efficiency.

The analysis estimates average operating speeds to be 10-15% lower for many of the bulk fleets (tankers, dry bulk), and approximately 25% lower for container ships, relative to the average annual operating speeds presented in the IMO 2nd GHG Study. The consequence of these observed differences in speed is significant reductions in fuel consumption (see Section 2 for details, but as much as 30 to 40% reduction 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 (using IMO 2nd GHG capacity utilization data) is approximately 10% for many of the bulk fleets, rising to 30% for some of the container fleets.

The study builds up the statistics of each fleet (ships of common size and type) using the technical and operational data characterizing each individual ship. To present the results, a number of scatter plots have been used (individual ships as individual data points), as well as histograms (Section 2 and Section 4). These show that there is high heterogeneity in the efficiency of each fleet. One example that illustrates this is the very large crude carrier fleet, which has estimated technical efficiencies ranging between 2-3 $gCO_2/t.nm$, but estimated average annual normalized operational efficiency (i.e. each ship's efficiency calculated to allow for variation in speed and fuel consumption specific to the operational parameters but with capacity utilization assumptions taken from the IMO 2nd GHG Study) of approximately 2-9$gCO_2/t.nm$. This wide spread between the most efficient and least efficient ship in many of the fleets is predominantly attributable to differences in average operating speed (even within fleets which have common design speeds), and shows a potential for further gains in average energy efficiency of many fleets from further take up of slow steaming.

Analysis of prices and energy efficiency data in Section 3 shows that most markets display evidence that supports the expectations that more efficient ships command higher prices. Higher prices were observed in the time charter market, to a limited extent in the newbuild market and the second hand market. There is also evidence that energy efficiency is influencing the scrapping of ships. However in the majority of cases the higher prices do not fully represent the fuel cost saving implicit in the efficiency differential. Differences occur between the ship types studied with container ship fleets generally showing evidence of higher price premiums in recognition of technical efficiency. This is a finding with important implications to the ongoing discussion around market based measures. The observation of a price premium for energy efficiency implies that the shipping markets will convert price signals (e.g. a carbon price) into energy efficiency. However the observation that this premium does not appear to represent the full magnitude of the available fuel cost savings implies that much of the analysis that applies Marginal Abatement Cost Curves (MACCs) to estimate the magnitude of the CO_2 emission reduction at a given carbon price may be optimistic. The findings in this study support the idea that there may be market barriers (e.g. informational or split-incentive barriers) obstructing the adoption of energy efficiency in shipping, however there is further work required before this can be fully attributed or quantified.

FURTHER WORK

The finding referred to above, that there is significant heterogeneity in operational efficiency in a given fleet in a given year, points in turn to the need to understand the drivers of operational efficiency. This study investigates whether there is a connection to ship age, but finds no evidence to support this idea. Further work could investigate whether there are other variables (e.g. type of charter, nature of the fixture, operator or customer preferences, technical constraints on machinery operation, crew details) which help to explain why the range of operational efficiency within a fleet is so high, and therefore whether anything could be done (e.g. incentive, training, funding) to enable a greater number of ships to operate at higher efficiency.

In addition to the need for further cross-sectional analysis, longitudinal analysis can help to explain the influence that commercial pressures (e.g. fuel prices and freight rates/prices) have on fleet's operational efficiency. Relative to the IMO 2nd GHG Study (2007 data), a significant change in many of the parameters (speed, fuel consumption) and ultimately operational efficiency is observed in this study (2011 data). Whilst a difference in fuel price has occurred in that time frame, the larger difference between 2007 and 2011 is in the freight rates/prices, with the shipping industry seeing a widespread reduction in revenues. In addition to the change in commercial drivers, there has been increased discussion (e.g. in the media, conferences, policy arena) of measures that can improve operational efficiency (e.g. Virtual Arrival, slow steaming, voyage optimization, Ship Energy Efficiency Management Plans), some of which may have created change in behaviour. Recent history is therefore a rich, complex, but relatively untapped source deserving further work to extract information that could provide significant insights both for the commercial strategy of shipping's stakeholders and also the policy makers attempting to design regulation that will achieve GHG emission reductions in the most cost-effective manner.

This study demonstrates there is a large potential for Satellite AIS data to be useful for understanding ship operational behaviour and efficiency. However, shortcomings include uncertainty on some of the data (particularly user-entered data such as ship draught), and difficulty with coverage (both sporadic coverage in the open ocean and poor coverage in coastal areas with high density of shipping). These shortcomings are manageable and this report details the processing steps for the raw data and how filtering can be applied to ensure that spurious data is not included in the fleet aggregate statistics. However, there is scope for further work to validate this processing to improve data quality and its application, such as further quantification of uncertainties through validation against other similar datasets (e.g. Long Range Identification and Tracking) and combination with global shorebased data to improve coverage. Whilst further work can be carried out on the theoretical naval architecture and marine engineering models that deploy the data to calculate fuel consumption, the most important next step is a detailed and transparent validation of such models against actual fuel consumption data from ship operators.

INTRODUCTION

Shipping is commonly cited as the most efficient transport mode. When expressed as a generalization (across all ship types) this is rarely disputed. However recent discussions and attempts to quantify the more specific detailed energy efficiency characteristics of the existing in-use ship fleet have met with objections. For example, among the objections to previous analyses, world ship efficiency studies have had issues related to unrepresentative input data, limited real-world operational data to reflect actual real-world conditions, incomplete quantification of technical versus operational efficiency characteristics. Many of these objections are well founded, the quality of global data describing the existing fleet of ships has been generally poor and the wide-ranging parameters that influence the performance and therefore efficiency of ships in their day-to-day operation (as opposed to on an artificial 'calm' sea or acceptance trial) are irregular and hard to measure.

Increasing the motivation for more comprehensive analysis of energy efficiency is the ongoing debate about how shipping's air pollution and greenhouse gas emissions should be regulated. In January 2013, the EEDI (Energy Efficiency Design Index) came into force, requiring all newbuild ships to meet a minimum energy efficiency standard. In the same regulation annex, the SEEMP (Ship Energy Efficiency Management Plan) recommends the use of the EEOI (Energy Efficiency Operational Indicator) for existing ships.

This index and indicator and their associated data and methods are designed for policy purposes, however their existence has led some to speculate about how their use could be extended (in other regulations or for commercial purposes). In some of the Market Based Measure proposals at the International Maritime Organization (IMO) (e.g., Shipping Efficiency Credit Trading and Efficiency Incentive Scheme proposals) it is suggested the indices could be used to categorise the existing fleet and determine the basis for differential treatment. Concerned that EEDI might now be used for purposes for which it was not originally designed, some have felt the need to voice limitations to its applicability (e.g. see Intercargo, 2011).

Still greater motivation for a more detailed understanding and richer, more detailed information about ship efficiency characteristics come from the most recent policy discussions related to the potential inventorying and monitoring of ships' carbon dioxide (CO_2) emissions. The European Commission has announced that it will propose 2013 legislation for monitoring, reporting and verification (MRV) of maritime industry CO_2 emissions and is conducting stakeholder meetings on the matter (EC, 2012). Such an MRV system would provide essential preparation for a global measure to reduce fleet greenhouse gas emissions. In addition, discussions at the IMO indicate that such MRV initiatives could serve as initial phases toward eventual in-use ship fleet efficiency standards (e.g., US, 2012). The IMO is considering a new greenhouse gas inventory from ship activity that would update its 2nd IMO GHG Study (Buhaug et al, 2009) with a major new study that would be conducted in 2013-2014. Such a new inventory could be based on more up-to-date data and incorporate richer global satellite data on global ship movement, changed ship routes, and operational practices that have changed since the previous work that was based on the 2007 fleet.

A simplified energy efficiency formula designed for a specific purpose need not be the only metric of efficiency in the shipping industry. Notwithstanding the additional technical challenges that arise when considering the existing fleet, the high-stakes policy discussions should not interfere with initiatives to progress transparency and increase economic efficiency through greater awareness of the parameters affecting the energy efficiency (and therefore fuel consumption, fuel costs and carbon emissions) of shipping. As long as characterizing energy efficiency is classified as "too difficult", a number of failings can occur. For example, customers of shipping have an information deficit when identifying which ship to use and how it should be operated. In other cases, owners of ships have no reference data with which to benchmark and compare their fleet. As a result, the industry lacks a detailed understanding of the consequence of energy efficiency interventions on its emissions (e.g. slow steaming). And more broadly, bottom-up estimates of shipping emissions (e.g., those used by the IMO and other groups) can potentially lack credibility or sources of validation.

Industry groups have sought to address these failings. Since starting the work for this report in mid 2012, the International Association of Class Societies (IACS) a major contributor to the development of EEDI, has made an announcement that it is convening a working group that will revisit the development of a method for quantifying the energy efficiency of the existing fleet. At the announcement Tom Boardley, IACS chairman and Marine Director at Lloyd's Register, stated "We cannot keep ignoring this, but there is no perfect way, it will always be caveat emptor," thereby alluding to the challenge of maximizing the reliability of any calculation.

To introduce the report, it is worth clarifying some of the different energy efficiency terms that are relevant in describing various aspects of ship efficiency. Table 1 provides descriptions of various efficiency-related terms and comments related to this analysis' investigation of ship efficiency.

Table 1: Some different definitions of energy efficiency

Term	Description	Practical Considerations
As-designed technical efficiency	The efficiency of a ship in its as-designed condition (straight from the yard) in ideal conditions.	This is what is captured in the EEDI when it is applied to newbuild ships
Technical efficiency in real operating conditions	The efficiency of a ship (straight from the yard) in real conditions (wind and waves etc.).	Careful attention to the hydrodynamics of a vessel in waves can save significant (20% and in some cases more) fuel consumption in actual use, but such benefits are not captured in the present EEDI formulation
Technical efficiency at a point in time	The efficiency of a ship of a certain age, following wear, deterioration and fouling, benchmarked in ideal conditions	Heavy fouling can increase fuel consumption by up to 40-50% for a low speed ship (e.g. wet/dry bulk).
Measured technical efficiency	The efficiency of a ship of any age and condition, measured from fuel consumption but assuming 100% capacity utilization	Measurements of fuel consumption from trial specification (e.g. specified speed and draught) produce data on a ship's measured technical efficiency, which can in turn be validated e.g. by a classification society.
Transport supply efficiency	This embodies the relationship between the transport demand (e.g., tonnes of a commodity shipped), with actual capacity-distance (e.g., dwt x nm sailed)	Often, assumed 100% capacity utilization ignores the backhaul voyage emissions (regardless of vessel loading, ballast), which is virtually never the case.
Achieved operational efficiency	The energy consumed to satisfy a given transport demand	This could be considered the ultimate measurement of a ship's estimated real-world efficiency in that incorporates all of the components listed above.

Abbreviations: dwt = dry weight tonnage; nm=nautical miles

This introduction of ship efficiency-related definitions reveals that even before ascribing formulae to quantify these terms, clarity is required for the definition of the type of energy efficiency to be analysed. No single definition provides all the information that might be needed to progress the discussion of energy efficiency. In addition, there are restrictions in the availability of data that limit freedom of choice – many required details are commercially sensitive e.g. voyage fuel consumption and payload, and therefore difficult to obtain or infer from publicly available data.

It is proposed that many of the shortcomings of existing analyses of energy efficiency can be addressed by bringing together the following elements: (1) attention to the underlying physics that influence the performance of ships; (2) attention to the uncertainties associated with input data sources and the sensitivity of efficiency quantifications to the different input parameters; (3) incorporation of new and far richer data sources (i.e. Satellite Automatic Identification System, or S-AIS)[1] to describe the real-world operational variables of shipping. In addition, the analysis critically updates previous shipping industry analyses that have not acknowledged some of the major shifts that have occurred in the shipping industry related to ship routes, technology, age, speed, etc. that have occurred in the 2007-2011 timeframe.

[1] Data applied here is from Satellite AIS Data © exactEarth Ltd

This report details a programme of work, funded by International Council on Clean Transportation and underway since mid 2012, with the ambition to produce more rigorous and robust data and analysis on shipping energy efficiency characteristics. An overarching aim of the programme is to drive improvements in energy efficiency by breaking down information barriers and providing an evidence base for policy measures and voluntary schemes. Another objective is to demonstrate data and analytical capabilities that are afforded by the use of global satellite data on ship movements with data that is publically commercially available. The study also seeks to investigate the relationship between energy efficiency and freight rate.

The study has built on all three of the perceived shortcomings of existing work: greater attention to the underlying physics, greater attention to the uncertainty of the calculation parameters and the use of Satellite AIS data. The analysis method still produces results which taken for an individual ship are uncertain, but which when aggregated to a population's average characteristics provide an increased level of rigour over previous analyses. The analysis is used to improve the data describing different potions of the world fleet (e.g. ship type, size, age) and an understanding of the variability of energy efficiency and the drivers of this variability. All analysis is carried out using data, which is publicly available albeit in some cases at a cost.

This study builds on the significant contribution made to this topic in the IMO 2nd GHG Study. In that study, quantifications are made both of the global fleet's technical efficiency and overall efficiency, which is analogous to operational efficiency. Consequently, this study will also focus on the global fleet's technical and operational efficiency. Throughout this analysis, unless particular metrics are otherwise specified, efficiency is evaluated as a CO_2 emission rate per unit of transport capacity. This follows the conventions of IMO (including as used in the IMO 2nd GHG Study), such that higher efficiency equates to lower fuel consumption or CO_2 emissions, per the direct relationship about fuel carbon content. The analysis quantifies the following:

- Technical Efficiency – the efficiency of a ship in its 'as designed' condition, without weather or deterioration, and assuming that it is loaded with 100% capacity utilisation
- Operational Efficiency – the annual average efficiency of a ship in its real operating condition, including speeds, draughts, capacity utilization (estimated for the individual ship), and distance travelled, and with estimates applied to represent the effects on fuel consumption of deterioration and weather
- Normalised Operational Efficiency – similar to operational efficiency (i.e., adjusted for ship speed, draught, distance travelled, deterioration and weather), but with default values for the capacity utilization applied in the calculation of the transport supply

The reason for the calculation of the normalized efficiency is two-fold: the value is calculated using the capacity utilization data that was derived for the IMO 2nd GHG study, and so this figure gives a direct comparison between the overall efficiency values included in that report, with the values calculated here which are adjusted for ship speed – particularly important due to the recent trends to slow steam. In addition, the normalisation provides an alternative to a calculation of operational efficiency (carried out with estimations of an individual ship's loading condition), should the uncertainty associated with the loading condition estimation be too high to attribute meaning.

The report is divided into four sections with content as follows:

Section 1 – describes the equations used for technical, operational and normalized operational efficiency calculations, the formulation of inputs to these calculations, the data used, assumptions and the approach used in the event of missing data.

Section 2 – presents the results from the calculations formulating energy efficiency, both the components of the efficiency calculations independently (speed, main engine fuel consumption, capacity utilization and transport work) as well as the results for the fleet's technical, operational and normalized efficiency in a variety of aggregations (ship type, size, age and route). The section also includes a discussion on the uncertainty associated with the calculated values.

Section 3 – utilizes the energy efficiency data to better understand the extent to which the fuel-saving benefits of energy efficiency are reflected in market prices. This can help in the study of whether a split-incentive or other market barriers and failures might be limiting access to what some analysts perceive to be cost-effective energy efficiency interventions.

Section 4 – draws together, not just Sections 1-3, but also observations made for each of the component fleets studied, in order to distil the report's findings into some key messages.

1. METHODS AND DATA FOR ESTIMATING ENERGY EFFICIENCY

1.1. METHOD FOR TECHNICAL EFFICIENCY CALCULATION

The calculation of technical efficiency, *TE* in gCO_2/t.nm and gCO_2/capacity.nm (where capacity is a unit varying depending on ship type), is carried out for the ship in its ideal, as designed condition i.e. the performance of the ship in still water conditions as if measured in its shipyard/client acceptance trials. The calculation's numerator includes the estimation for the daily carbon emissions of the ship in its loaded condition; the denominator is the daily amount of transport work done (t.nm) by a ship, on the assumption of 100% utilisation of the capacity.

$$TE = \frac{P_{me} EL_{me\_des} sfc_{me\_des} C_f + P_{ae\_des} sfc_{ae\_des} C_f}{MV_{des}} \qquad (1)$$

The function of the calculation here is to establish reference technical energy efficiency with a consistent method and assumption set and to establish 'baseline' values for the input variables. Deviations to those baseline variables will then be considered to calculate the 'real' operational energy efficiency using the relationships defined in the section "Method for Operational Efficiency Calculation". In the above formula (1), the variables are defined as follows –

P is installed power (kW)

EL is the engine load (% MCR or % of installed power),

sfc is specific fuel consumption (g/kWh)

C_f is the carbon fuel factor (gCO_2/gFuel)

me refers to the main engine

ae refer to the auxiliary engine

des refers to the design condition

M is the ship's cargo capacity (e.g., tonnes or container capacity unit)

V is the ship's speed (knots)

1.2. DATA SOURCES AND MISSING DATA APPROACH

The primary source of data for populating the terms in the technical efficiency calculation is Clarksons World Fleet Register (Clarksons, 2012). However, the dataset is not complete for all ships and all fields. In the case where there is missing data, values are estimated either from interpolation or from referencing another publicly available data source.

A summary of the data required for the calculation of the fleet's technical efficiency includes the variables listed in Table 2. Explanation of the sources and assumptions regarding missing data are given below.

Table 2: Summary of variables for technical efficiency calculations

Variable	Description	Main Source of data	Approach for missing data	Comments on data availability
P_{me}	Installed main engine power, power output at 100% MCR	Clarksons World Fleet Register	2nd order regression for each type and size category (dwt)	Well populated, high degree of confidence
EL_{me_des}	Main engine % of MCR in the design condition	2nd IMO GHG Study	See Annex 1	Not included in the World Fleet Register
sfc_{me_des}	*sfc* of main engine in the design condition	Clarksons World Fleet Register	Min values of ranges from engine test bed measurements (Table 4)	Moderately well populated; averaged according to ship age and engine type/size
-	Year built	Clarksons World Fleet Register		Assume engine age = year built
-	Fuel type of main engine	Clarksons World Fleet Register	See Table 6	2-stroke: High confidence 4-stroke: Less clear differentiation when power=1000-5000kW
-	Engine type	Clarksons World Fleet Register		Well populated
P_{ae}	Installed aux engine power	Clarksons World Fleet Register		Sparsely populated if missing, average according to ship size and type is applied
EL_{ae_des}	Aux engine % of MCR in the design condition	2nd IMO GHG Study	See Annex 1	
sfc_{ae_des}	*sfc* of the auxiliary engine in the design condition	2nd IMO GHG Study	See Table 7	Clarksons WFR is very sparsely populated
F_{B_pd}	Boiler fuel consumption per day	2nd IMO GHG Study	See Table 3	
C_f	Carbon factors for different fuels	IMO EEDI guidelines (IMO, 2012)		
V_{des}	Design Speed	Clarksons World Fleet Register		Clarksons WFR is well populated
M	Capacity	Clarksons World Fleet Register		High confidence, accurate linear regression for missing data

1.2.1. MAIN ENGINE POWER

The Clarksons World Fleet Register reports the maximum continuous rating (MCR) of the installed engine as matched for the ship specific propeller curve. There is a high degree of confidence in this factor and the list is well populated. Where there is missing data, a 2nd order polynomial regression provides an accurate prediction of MCR as a function of deadweight.

In port, the auxiliary engine is required to produce sufficient steam (at sea the exhaust heat is sufficient via a utilisator) for residual fuel oil heating (burnt in the main engine), in order to keep it liquefied. This is assumed to be included in the assumption of the auxiliary engine load.

1.2.2. BOILER FUEL CONSUMPTION

For some cargo types, a boiler is used to generate steam both for warming cargo and for running steam turbines, which are used for discharging cargo. The commodity where this is predominantly the case is crude oil and product tankers. The fuel consumption in these boilers is significant and so needs to be added in the calculation of the ship's operational efficiency. Since there is no data in the Clarksons World Fleet Register, the source used is the 2nd IMO GHG study. To standardize the application of the boiler consumption assumption, data is taken for the annual boiler consumption in the 2nd IMO GHG study, and divided by the assumed number of loaded days to derive an estimate of boiler consumption per loaded day. This can in turn is applied in the calculations of operational efficiency when a ship has a number of loaded days that deviate from the assumption in the 2nd IMO GHG study.

Table 3: Assumptions for the boiler daily fuel consumption

Ship type	Size	Boiler consumption per loaded day / tonnes
Tanker	> 200,000 dwt	10
	120-200,000 dwt	7
	80-120,000 dwt	25
	60-80,000 dwt	26
	10-60,000 dwt	13
	< 10,000 dwt	6
Product Tanker	> 60,000 dwt	38
	20-60,000 dwt	32
	10-20,000 dwt	20
	5-10,000 dwt	11
	< 5,000 dwt	4

1.2.3. MAIN ENGINE % MCR IN THE DESIGN CONDITION AND DESIGN SPEED

A ship's speed and % MCR (variable name EL_{me_des} in Equation (1)) are intrinsically linked through its power/speed characteristics. These are often observed to be polynomials of an order between 3 and 4. Because of that relationship they are of high sensitivity in the calculation of energy efficiency. For new ships, the EEDI calculation method defines the calculation point for technical energy efficiency at a standard % MCR (75%) at which the attained speed V_{ref} is achieved. However, 75% MCR does not necessarily coincide with the point at which the ship has been designed to be operated at. For much of the existing fleet, design may be optimised for a higher or lower % MCR, either to save costs in the engine (>75% MCR) or to provide flexibility or improved economy (</= 75%MCR).

Clarksons World Fleet Register does not list the %MCR that corresponds to the speed quoted in the database. However, it is standard practice to choose a design %MCR of 60-80% to allow for fouling and sea margin (performance reserve to ensure safety in adverse weather). The 2nd IMO GHG study defined presumptions of the design MCR for a range of ship types and sizes, listed in Annex 1. In the absence of any alternative, it is proposed that these are applied in this work as the % MCR that correspond to the Clarksons World Fleet Register speed data field. The uncertainty associated with this assumption and its consequence on the calculation of energy efficiency will be addressed in Section 2.

1.2.4. MAIN ENGINE SPECIFIC FUEL CONSUMPTION

For new build ships and major conversions it is required that the specific fuel consumption (*sfc)* be reported in the Engine International Air Pollution Prevention (EIAPP) certificate or the NO_X Technical Code Technical file, however shipbuilds predating 2000 have no such requirements therefore the database is fairly sparsely populated in this field. The engine manufacturer provides *sfc* data as measured in an engine test-bed (in accordance with ISO standard 3046-1).

Table 4: Engine test bed measured ranges for a variety of engine type, size and age

Engine year of build	2-stroke low-speed	4-stroke medium-/high-speed (> 5000 kW)	4-stroke medium-/high-speed (1000–5000 kW)	4-stroke medium-/high-speed (< 1000 kW)
1970–1983	180–200	190–210	200–230	210–250
1984–2000	170–180	180–195	180–200	200–240
2001 to 2007	165–175	175–185	180–200	190–230

Figure 1 shows plots of both the minimum range value in Table 4 and values taken from the Clarksons World Fleet Register main engine *sfc* and shows that for each engine speed/year built range there is reasonably good agreement. It is therefore proposed that this justifies use of the Clarksons World Fleet Register values in the technical efficiency calculation; this is also in agreement with work done by Faber et al. (2010).

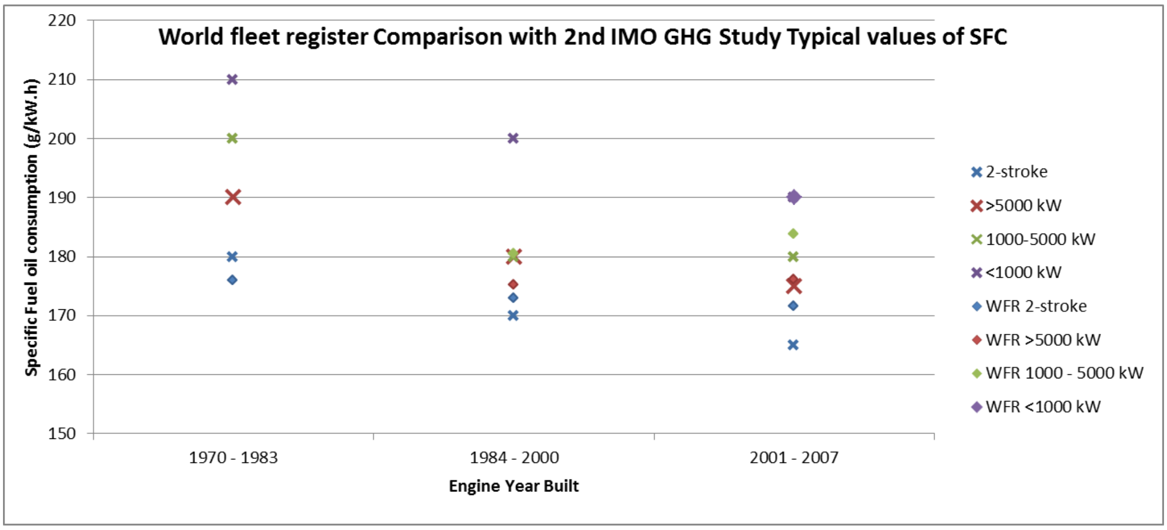

Figure 1: Sample set of 5000 tankers (1770 data points, 35%), 1200 LPG carriers (451 data points, 38%) and 2500 container ships (1465 data points, 59%), Source: Clarksons, 2012

1.2.5. FUEL TYPE OF MAIN ENGINE AND MAIN ENGINE TYPE

The fuel type dictates the carbon factor to be applied in the calculation of *TE*. The values used are those listed in Table 5 and are the same factors as those used in the most recent IMO guidelines on the EEDI calculation, by Rightship for the calculation of EVDI (Existing Vessel Design Index) and in the 2nd IMO GHG study. For LNG carriers burning boil off gas, the LNG carbon factor is applied.

Table 5: Carbon factors for different fuels

Type of Fuel	Clarksons Category label	Carbon content (carbon fraction of fuel)	C_f (gCO_2/gFuel)
Diesel/Gas Oil	MDO/MGO	0.8744	3.206
Heavy Fuel Oil	HFO/IFO/FO	0.8493	3.114
Liquefied Natural Gas	LNG-DF	0.75	2.75

The value of C_f needs to be matched to a given ship's fuel type; this partly coincides with the need to identify engine type so that the *sfc* can be looked up. Both 2-stroke and 4-stroke engines can be used with both MDO and HFO, so there is not a one to one matching of fuel type and engine type. Increasingly, ships may be operated with different fuels in order to comply with regional limits on air pollutants (e.g. in

Emissions Control Areas (ECAs), adding further to the difficulty of precise identification of fuel and therefore carbon factor. However, there is some data in the Clarksons World Fleet Register that can be used to derive assumptions that can then match fuel and engine type to a ship given a number of other parameters (e.g. installed power).

The scatter graphs of Figure 3show that there is a clear distinction in fuel type for 2-stroke engines depending on their size, therefor missing data can be assigned according to the matrix in Table 6: Fuel type allocation according to engine size and power type (excluding engines installed on LNG carriers), which determines fuel type from power type and engine size. 4-Stroke engines are predominantly operating on MDO for engine size < 1000 kW and HFO for engine size > 3500 kW. Categorisation for 4-stroke engines in the range 1000 to 3500 kW is more ambiguous (see lower graph of Figure 2:), ships of this engine type comprise 21% of the 8721 ship sample and of these 48% had an undefined fuel type.

From the relationships and trends shown in Figure 1, generic assumptions for use in the calculation of *TE* are generated and are listed in Table 6. The 1% MDO burnt in LNG dual fuel engines is not accounted for, as it is a small quantity.

Table 6: Fuel type allocation according to engine size and power type (excluding engines installed on LNG carriers)

Power Type:	**Main Engine Size & Fuel Type**	
	<1 400kW	**>1 400kW**
2-Stroke	MDO	HFO

	<1 000kW	**1 000kW – 3 500kW**	**>3 500kW**
4-Stroke	MDO	Ave. HFO MDO ($C_f = 3.16$)	HFO

	<5 000Kw	**>5 000Kw**
Diesel Electric	MDO	HFO

	All engine sizes/types
Steam turbines	HFO/IFO

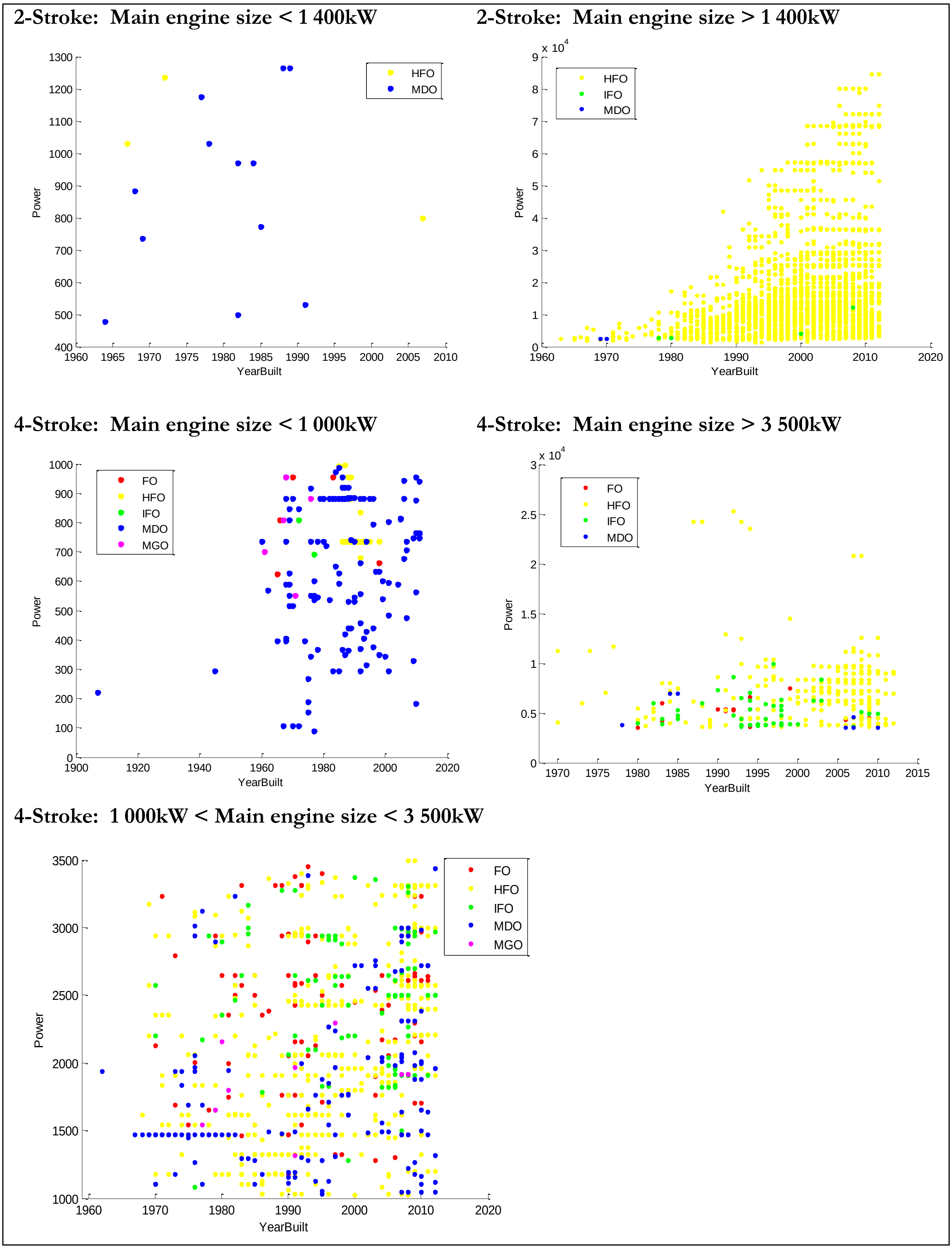

Figure 2: Power Distribution of Containerships/LPG carriers / Oil tankers (sample size: 8725 ships, 2394 undefined), source Clarksons, 2012

1.2.6. AUXILIARY ENGINE ASSUMPTIONS

Clarksons World Fleet Register includes sparse data for the installed auxiliary engine power. However, when compared against values found in the 2nd IMO GHG study, there is a good agreement. For consistency with the sourcing of the main engine data, the Clarksons World Fleet Register is also selected for the auxiliary engine data. To address the problem of missing data, any populated data is used to derive estimates of the auxiliary power based on a number of regression coefficients.

In the same way as for the main engine characteristics, the design condition engine load (EL_{ae_des}) expressed as a % MCR is taken from the 2nd IMO GHG study report according to ship type and size. The values used are listed in Annex 1. In common with the 2nd IMO GHG study, the assumption that the auxiliary power is produced by three engines, which are variously running, in maintenance and standby at any one time. Therefore the %MCR is normalized for the annual running days (from 2nd IMO GHG study) and applied to one third of the installed power.

The *sfc* for the auxiliary engine is a function of the size of the auxiliary engine, an assumption taken from the 2nd IMO GHG study, the values used are listed in Table 7.

Table 7: Specific fuel consumption values as a function of auxiliary engine size

Engine Size	> 800 kW	< 800 kW
sfc_{ae_des}	200	230

1.3. METHOD FOR OPERATIONAL EFFICIENCY CALCULATIONS

Operational Efficiency, *OE*, is the ratio between the actual CO_2 emissions and the actual transport supply. It incorporates all the practicalities of ship operation that result in deviations from the 'design' condition, which is assumed in the calculation of the technical energy efficiency. In this project, limited to publicly available data, each of these (CO_2 and transport supply) are estimated from a mix of sources and assumptions.

The calculation of *OE* can be sensitive to the time-period over which it is assessed. For a ship that spends a significant time in the ballast condition, if the time period covers one loaded voyage, it will misrepresent the actual operational efficiency. Consequently, a period of one year is used for all the calculations. This also allows for the fact that some of the assumptions that are used for the components of the calculations that might vary significantly from voyage to voyage (e.g. weather) will be spread over a time period where averaged values are applicable. Over the period of a year, in addition to variations in loading condition there may also be variations in speed and time spent manoeuvring, at anchor, loitering or in port. In each of those states, the main engine and auxiliary engine power requirements will vary, resulting in variations in the fuel consumption. Consequently, the estimation of annualised carbon emissions *C* and transport supply *S* for a given ship must be built up from estimates of these characteristics in a number of different states.

Estimates of annual transport supply can be made using reported data on ship draught, transmitted in the AIS signal. However, there is some uncertainty associated with this data because its quality has yet to be rigorously tested. For this reason, a second calculation of transport supply will be performed

$$OE = \frac{C}{S} \qquad (2)$$

$$NOE = \frac{C}{S'} \qquad (3)$$

Where C is shown algebraically for annual CO_2 emissions, in (4) and annual transport supply S in (5) and normalized annual transport supply S' in (6), where i indicates a unique operating 'state'.

$$C = \sum_i (P_{me\_i}.sfc_{me\_i}.C_f + P_{ae\_i}.sfc_{ae\_i}.C_f).D_i.24 \quad (4)$$

$$S = \sum_i dwt.L_i.D_i.V_i.24 \quad (5)$$

$$S = \eta_u \sum_i dwt.D_i.V_i.24 \quad (6)$$

where η_u is the IMO 2nd GHG Study estimated capacity utilization (listed in Annex 1). In the event that an alternative description of capacity to deadweight is used, then this is substituted in the equations.

The calculation of the main engine and auxiliary engine parameters in a given state are found by looking at deviations to the variables for the ship in its 'design' condition (the values used in the calculation of technical efficiency). These are expressed in (7) and (8).

$$P_{me\_i}.sfc_{me\_i} = \frac{P_{me\_des}}{\eta_v.\eta_L.\eta_c.\eta_w}.sfc_{me\_des}.\eta_{fme} \quad (7)$$

$$P_{ae\_i}.sfc_{ae\_i} = \frac{P_{ae\_des}}{\eta_L}.sfc_{ae\_des}.\eta_{fae} \quad (8)$$

To account for the operational state's specifics, a number of efficiency parameters that represent the deviations from that reference state due to the specifics of the operating state of the ship (its speed, loading condition, deterioration, weather etc.). The efficiency parameters used are the following:

η_v – operating speed impacts – a function of (V_i/V_{des}), hull resistance, propulsion coefficient
η_L – loading condition impacts – a function of (L_i/L_{des}), V_i, hull resistance
η_c – condition impacts – a function of fouling (hull frictional resistance)
η_w – weather impacts – a function of added resistance in waves
η_{fme} – main engine specific fuel consumption impacts – a function of (P_{me_i}/P_{me_des}) and engine %MCR, RPM and *sfc* relationship, also age (engine wear)
η_{fae} – aux engine specific fuel consumption impacts – a function of (P_{ae_i}/P_{ae_des}) and engine %MCR and RPM relationship, also age (engine wear)

1.4. DATA SOURCES AND MISSING DATA APPROACH

Input data is predominantly based on Satellite AIS (S-AIS) data supplemented with parameters from the 2nd IMO GHG study. Table 8 outlines the sources for each input variable and is followed in the section below by a more detailed description of the approach used. In addition to input variables, the efficiency parameters, which are state dependent, are summarised in Table 8.

Table 8: Summary of variables for operational efficiency calculations

Variable	Description	Sources	Approach for missing data	Comment on data availability
i	given operating state (loaded (speed 1,2,3…n), ballast (speed 1,2,3..n), in port, at anchor)	S-AIS data and 2nd IMO GHG Study	See Section 1.4.1	High for vessel types and sizes that have good S-AIS coverage.
L	is the loading condition in the given operating state, number from 0 to 1 where 0 is empty and 1 is 100% loaded	S-AIS and 2nd IMO GHG Study	The draught of the vessel (as identified in S-AIS) is used to identify a vessel's loading condition, however, this value must be checked for reliability.	Low, due to uncertainty surrounding data input.
D	is the days per year spent in the given operating state	S-AIS and 2nd IMO GHG Study	Output data from naïve bayes on S-AIS. This is compared against IMO figures for consistency.	High for vessels with good coverage in S-AIS. Moderate to low for the remainder
V	is the speed in the given operating state	S-AIS and 2nd IMO GHG Study	Identified from S-AIS data.	High for vessel types and sizes with good coverage. Moderate for the remainder
P_{me_des}, P_{ae_des}	Installed powers of the main engine and aux engine	Same as *TE*		
sfc_{me_des}, sfc_{ae_des}	Reference specific fuel consumption of main and auxiliary engine	Same as *TE*		
C_f	Carbon factor of the fuel of the main and aux engine	Same as *TE*		

Table 9: Summary of impact parameters

Parameter	Key determinants	Method	Additional data required
η_v	V_i/V_{des}	Holtrop and Mennen and propeller calculations (e.g. Rawson and Tupper)	Geometry (L,B,T,dwt etc)
η_L	L_i	Holtrop and Mennen	Same as η_v
η_c		Literature on performance deterioration	Build year
η_w	Operating area (coast, ocean)	Literature on added resistance in wind and waves	Geometry, weather statistics if undertaking first-principles calculations
η_{fme}	P_{me_i}/P_{me_des}	Engine manufacturer data / literature	Main engine model and specification
η_{fae}	P_{ac_i}/P_{ae_des}	Engine manufacturer data / literature	Aux engine model and specification

1.4.1. IDENTIFICATION OF VESSEL STATE USING AIS DATA

- The Operational Efficiency calculations were applied for each vessel state, type and size range:
  - Series of loaded states corresponding to a range of speeds
  - Series of ballast states corresponding to a range of speeds
  - Loitering state
  - In port state
- For each of these states, the following information were determined:
  - Mean loading condition Li (a continuous variable between 0 and 100% where 100% is payload mass = deadweight, applied for all ship types as draught is the only available indicator of loading condition)
  - Mean days at sea, Di
  - Mean operating speed Vi

Ultimately, these are calculated as mean values for each vessel type and size identified in the fleet disaggregations (Annex 2). The dominant source of data for this analysis is Automatic Identification System (AIS.).

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.

The 2nd IMO GHG Study used AIS data captured using shore based transponders. The report was able to determine when each vessel was in port (although it was assumed some port traffic was not captured) using the reported navigational status of the vessel. Due to scarcity of coverage remote from landmasses in shorebased-AIS data, the message gaps were filled in using great circle distance calculations to generate the shipping network. The report captured port traffic with good granularity but was unable to capture voyage profiles for long haul voyages. Therefore, effectively capitalising on the position reports, to determine operational behaviour, provided by shorebased-AIS has meant limiting its use to localized studies for specific sea areas (e.g. Jalkanen et al, 2011).

Other position report datasets also exist and have been extensively used in determination of global maritime emissions inventories. The Automated Mutual Assistance Vessel Rescue (AMVER) system was used by Corbett & Koehler (2003) and Endresen et al (2007) in their global emissions estimates but it lacks unique ship identifies that can be matched back to shipping registries (Wang et al, 2008). Another dataset is the International Comprehensive Ocean Atmosphere Dataset (ICOADS, formerly COADS), which was used for the first ship emissions inventory calculations with a geographic disaggregation (Corbett & Fischbeck, 1997, Corbett et al, 1999). ICOADS data contains ship identifiers but according to Wang et al (2008) only captures about 4.4% of the world fleet. Both AMVER and ICOADS are also subject to bias to certain ship types (Corbett & Koehler, 2003). The Arctic Maritime Shipping Assessment

(AMSA) dataset was used by Corbett et al (2010) for a study of emissions in the arctic region but, although it does contain vessel unique identifiers, was not considered for this study as most freight traffic occurs away from this region (indeed fishing vessels, not considered in this report, make up over half of the vessels reported).

For these reasons the S-AIS dataset was considered most appropriate as the data source for position report data. S-AIS has only recently become available at the level of granularity that is appropriate for an analysis of this kind. It provides good granularity of vessel journeys for long haul transit (i.e. away from land masses) but is sparse in coastal areas. As documented by the data providers, Exact Earth, data collisions in densely reported areas prevent the satellite from receiving clear messages (www.exactearth.com). Without a complete dataset, it is hard to illustrate the extent to which there is missing data in the S-AIS dataset. To illustrate the point, Figure 3 demonstrates coverage of small (0-7000 GT) and large (>65,000 GT) container ships. The traffic coverage in the European coastal area appears to be less than expected for a region where there is significant transhipment for the smallest vessel size. The absence of reliable data for a number of geographical areas is only significant if the ships spend a significant proportion of their time in such areas. For the majority of the global fleet engaged in international trade this will not be the case due to such ship's time spent on the high seas where the S-AIS coverage is best, however for smaller coastal ships operating a service dedicated to an area that happens to feature a high density of marine traffic the results may be less reliable. As a consequence this study will focus its discussion on the energy efficiency of the larger ship sizes for each ship type category.

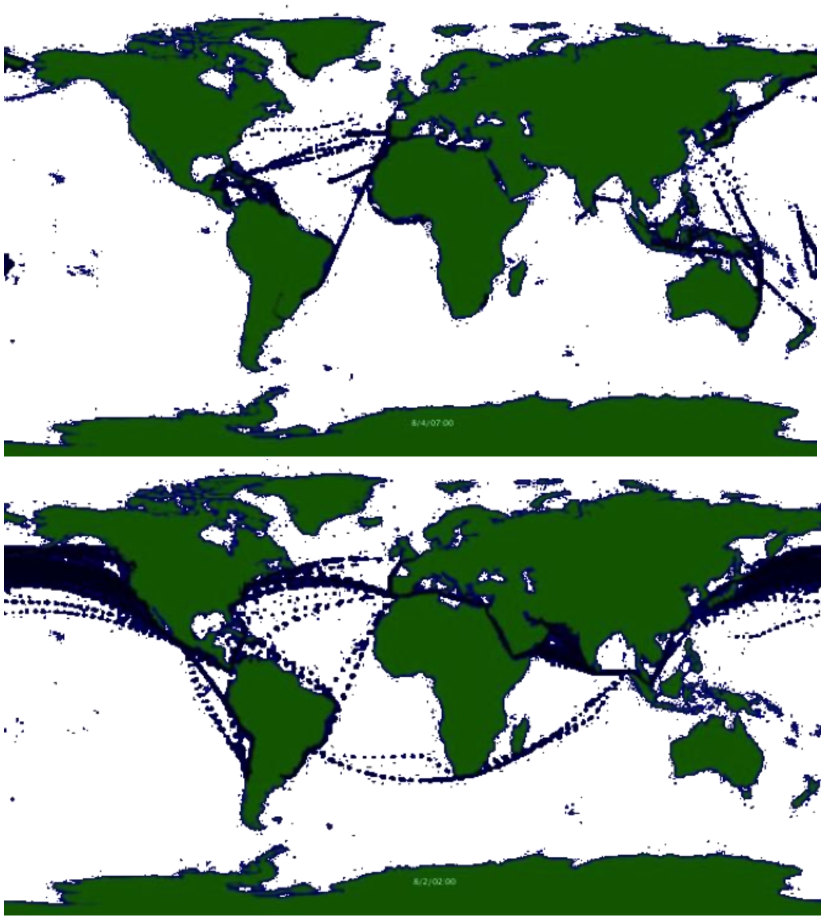

Figure 3: Coverage of container ships of 0-7,000 GT in August and September 2011 (top) and container ships greater than 65,000 GT in August 2011 (bottom). Black dots indicate messages received from vessel at the reported locations

Contrary to the approach of the 2nd IMO GHG study, which adopted only two speed states, this report identified a number of speed states for each vessel type. The following section outlines how each of these operating states will be identified. This method will produce output that is used as the basis for calculating loading condition, days at sea and operating speed.

As well as reporting on speed, location and course, vessels also report their destination and estimated time of arrival. However, these observations can contain reporting errors, as they require manual input. Therefore, these observations will be used as a corroboration dataset to augment the supervised learning approach discussed above.

1.4.2. DERIVATION OF OPERATIONAL DATA

The overall approach in determining this data is outlined in Figure 4. S-AIS was used to generate operational profiles (defined in terms of periods of time at various speeds and draughts over the year) for each vessel. From this operational profile data, time spent in various loading conditions was determined.

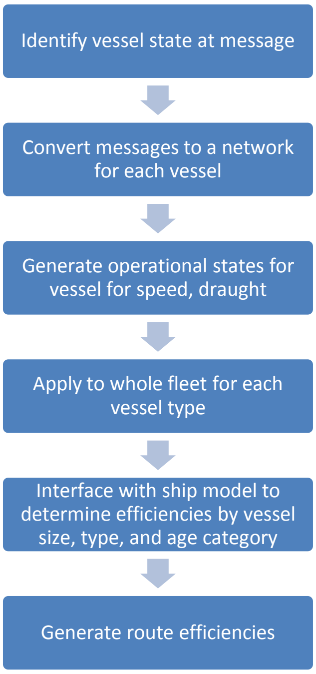

Figure 4: Overview of approach for generating operational data

To understand the uncertainty associated with use of S-AIS data, it is important to realize that S-AIS data is reported in different message formats that are reported at different time intervals Message 1 being more frequent as it contains location data). Message 1 indicates vessel location together with instantaneous readings such as speed over ground and course, provided as automatic readings from the vessel. Message 5 indicates the vessel destination, IMO number and other details of the ship's specific state on a particular voyage such as draught. Message 5 data is often entered manually by the crew, rather than automatically captured from instrumentation. It is thus susceptible to reporting issues such as spelling errors and also retained data from previous journeys due to a failure to update. Therefore, errors are more likely in the Message 5 messages.

Further to this, the geographic coverage of S-AIS is hindered when there are a large number of vessels due to message clashing. This results in reduced coverage around coastal regions, particularly Northern European waters. As a result, accurate attribution of S-AIS messages to port locations is difficult. Furthermore, vessel coverage changes during the year as ExactEarth launched new satellites. This results in greater coverage in December 2011 as compared to January 2011. The reliability of S-AIS as a data source for the analysis of shipping's energy efficiency is expected to evolve over time, as further satellites are launched and as algorithms used to process the received data (to reduce the loss of information in high shipping density areas) improve. However if it is not yet known whether investment will continue to increase the number of satellites to the point when close to 100% coverage will be achieved.

As outlined in Figure 4, each S-AIS message was identified to be in a particular state (defined as sailing, in port, loitering or first message out of port). This is a process commonly referred to in the associated literature as 'pattern recognition', literally the identification of patterns of behaviour, which in this instance focused on the identification of operational patterns of ships. The technique of pattern recognition applied here includes using a probabilistic model that determines the state (sailing, in port etc.) from information passed in the Messages 1 and 5. An additional filter for anomalous identifications of state was used to ensure continuity in messages. The particular probabilistic model adopted was a naïve Bayes model (using Bayes' theorem, this tests a number of variables independently to attempt to identify a state). This is not a dynamic model, thus assuming no dependency between each sequential message. One advantage of such an approach is its comparative simplicity and therefore computational speed, however, in reality it can be assumed to some extent to be representative of a Markov process i.e. a process in which a future state (sailing, in port etc.) can be determined from its present state alone just as well as if a full time history was known. Due to the variance in time between each message, the application of a dynamic model was deemed inappropriate and thus the necessity of an additional filter to ensure state continuity. Associated with the probabilistic model, there is inherent uncertainty not least due to limitations of the training data. Training data was based on actual fixtures for voyage charters where the time of entry into port is known, through "laycan from" and "laycan to" variables in the fixture dataset. A training and test dataset was manually generated by visually identifying the states of vessels at each message associated with the fixtures. This dataset was then used to train and corroborate the naïve Bayes model parameters.

A significant variable on which to classify S-AIS messages is port proximity (i.e. messages located close to or at a major port location have an increased probability of being in port or in a loitering state especially if the reported speed is low). Therefore, an indicative list of "port cluster locations" was generated based on three sources: UN Locode (2012), World Port Source (2012) and World Shipping Register (2012). Generating this "port cluster locations" dataset was done by first dividing the globe into 250kmx250km cells. Where one or more ports from one of the above port lists are located within a cell, that cell was included as a "port cluster location" and thus representative of all the ports in that cell with a single representative location at its centroid. This reduces a list of over 10,000 ports to 1,022 and thus reduces running time.

Further to the issues with geographic coverage of S-AIS data, temporal coverage of vessels also varies. This results in some vessels being captured less than 100 days and others captured for 365 days. Therefore, it was assumed that if a vessel has been captured for over 500 messages (the amount of time this covers varies), then the speed states and proportion of time spent in each can be applied for the assumed 355 days of active service (2nd IMO GHG Study).

Identification of messages in port, as alluded to in the geographic coverage limitations, was difficult. Therefore, for some network edges (i.e. port to port links) there was no designated port message (due typically to message clashing as described above). In the case where there was a designated loitering message and the next message was a "first out of port message", it was assumed that the "first out of port message" was the start of the journey, although this message could be several miles offshore.

Some messages also contain anomalously high speed over ground values. In calculating time at each speed, the maximum speed allowed was assumed to be the design speed of the vessel plus 20%. For the purposes of determining the loading condition of the vessel it was assumed that a vessel remains in the same draught condition on each journey leg. The draught condition is only applied if there is an associated Message 5 network edge (the Message 5 network is described in the following paragraphs), otherwise no draught is applied.

Following the identification of vessel state using the naïve Bayes approach, the vessel network plan was created. Each cluster of port related states (i.e. loitering, in port and first out of port) were grouped as a single node and the intervening messages grouped as a single edge. An example of the output for a Very Large Crude Carrier (VLCC) is shown in Figure 5.

Figure 5: Graphic showing vessel states and generated edges. The yellow "comet" (original code provided by Dr Austwick, UCL CASA) indicates the current location of the vessel (previous locations are shown in its stream with transparency increasing over time). The red Bezier curves (steeper curve indicates origin) indicate the voyages generated (linking origin to destination, not showing the route taken), with each node indicating a port stop. This example is for a VLCC vessel in March 2011.

To fully leverage the S-AIS data, a complimentary route network was generated based on the Message 5 data using the estimated time of arrival and the destination. This allows comparison between the reported Message 5 network (which contains omissions due to the issues discussed above) and the model-derived network. This is shown indicatively in Figure 6.

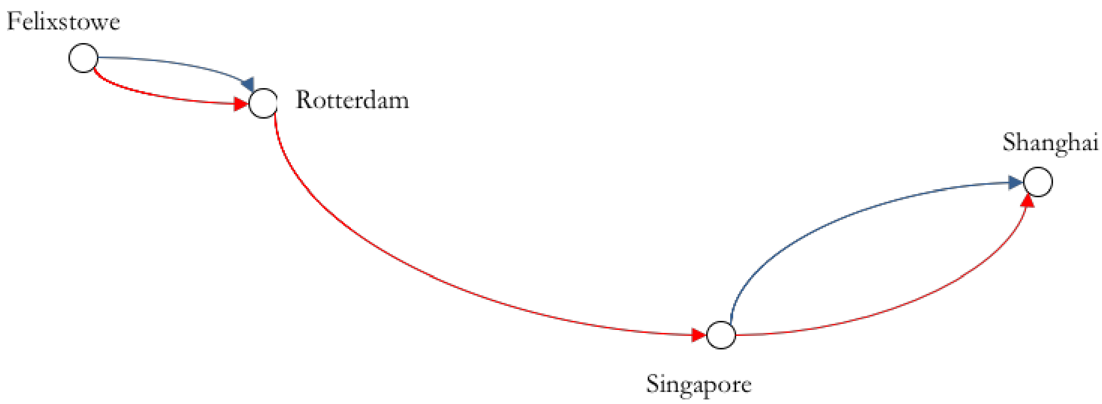

Figure 6: Indicative representation of the addition of the network generated using both the modelled approach (red network) and the message 5 (blue). When there is a match between the modelled port time and the Message 5 ETA, the Message 5 edge is overlaid (in the graphic there was a match for Shanghai and Rotterdam but not Singapore and Felixstowe). The origin port for the message 5 edge is set as the origin port for the same edge in the modelled network. The

reason it is not set as the previous port indicated in the message part (i.e. an edge from Rotterdam to Shanghai) is that there are gaps in the message 5.

Leveraging the modelled network using the message 5 allows some quantification of the uncertainty of the sailing parameters to be developed. Further to this, data gaps were also captured in the form of max time missing at each node and each edge. The combination of these three edge and node statistics allows the error and uncertainty gap to be narrowed. The following table shows a comparison of vessel operational data for various vessels using these uncertainty statistics. In this regard, Figure 7 shows a scatter plot of proxies for the uncertainty.

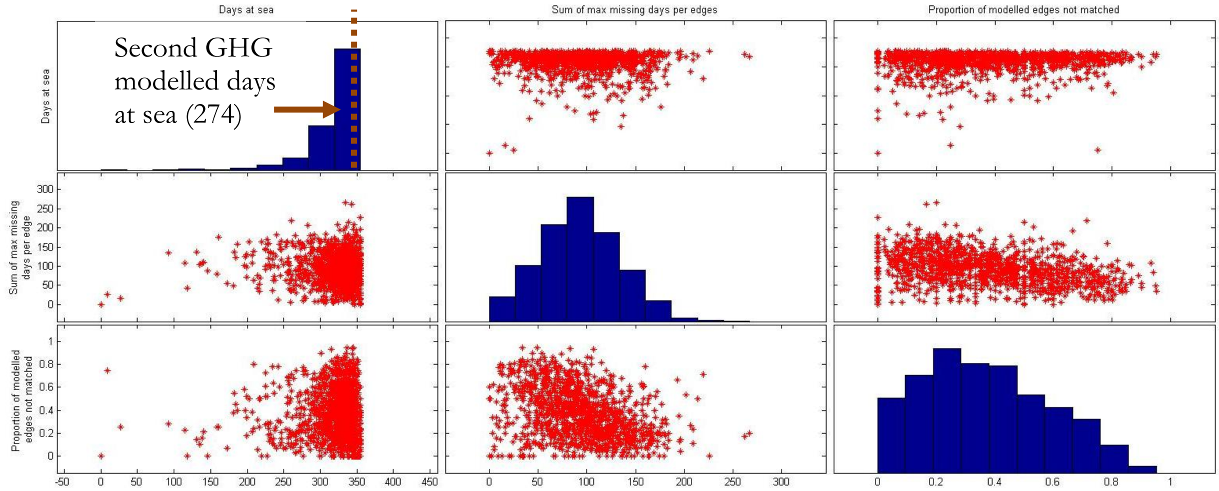

Figure 7: Scatter plot matrix of proportion of days at sea, the sum of the maximum amount of time missing at each edge or node in the modelled network and the proportion of modelled edges not matched to edges generated from the S-AIS message 5 for the VLCC fleet represented in the model. For example the proportion of modelled edges not matched in the network in Figure 6 would be 0.5.

1.4.3. EXTRAPOLATION OF OPERATIONAL PARAMETERS

Using the approach outlined in Section 1.3.3, operational parameters used in efficiency calculations were then generated for each vessel as a three dimensional matrix of IMO number of vessel, vessel speed, vessel draught and period (e.g. days) in the state (a state is as long as the time for which it is continuous, e.g. it could be 1 hour or less if the ship is manoeuvring or several weeks if the ship is travelling across an ocean at constant speed).

Depending on the satellite coverage and whether the AIS transponder was turned on, there is significant variability of the total period of operation captured. For total periods between 100 days to 365 days, it is assumed operational conditions captured were a representative sample for the vessel and thus the period captured for each state was factored in proportion to the ratio of the total assumed active days (355, as applied in the IMO 2nd GHG Study) to the total period captured by the AIS data. For each vessel, the draught and speed was divided into 10 ranges. All port, loitering/manoeuvring time was set to a speed of 0 knots. For each message, it was assumed that the vessel travels at that speed until the next message. This period of time was then added to the operational matrix corresponding to the range for that speed. The average speed for each range is then a weighted average of the time spent at each speed in that range.

The same approach was applied for calculating the draught. In the cases where there was not a corresponding edge for the Message 5 and the modelled network, there would obviously be no corresponding draught for that edge. In this case the draught was attributed the design draught or the ballast draught as proportions of time spent in each state.

1.4.4. GENERATING THE REGION TO REGION FLOWS

Using the model network, each node was resolved back to its parent country. Countries are then resolved into the region groupings outlined previously, thus creating an intra and inter-regional direct movement for each vessel. This directly connected network was then resolved to a vessel-connected network. A vessel-connected network is one that links regions together where the destination region follows the source region but not necessarily directly. For example, in a directly connected network a vessel that begins at Shanghai, calls at Singapore and then at Rotterdam, would have two edges, one connecting Shanghai to Singapore and one connecting Singapore to Rotterdam. While in the vessel-connected network, there are three edges, Shanghai to Singapore and Singapore to Rotterdam as with the directly connected network. But furthermore, it also contains an edge connecting Shanghai to Rotterdam.

Following determination of this vessel connected network, the efficiency data output from the efficiency models was applied to each vessel and a flow-weighted efficiency was then generated. Note that the efficiency data used is the average data for that size and age and for that particular vessel.

1.4.5. LOADING CONDITION

The loading condition can be determined using the draught parameter with the S-AIS message. As the port-to-port network is created, the draught parameter will apply uniformly across each voyage (this criteria will be used to verify data integrity).

Where data coverage is insufficient, capacity utilisation figures as reported in the 2nd IMO GHG study are used instead.

The draught of a ship indicates it's loading condition, and is also the indicator used to differentiate between a ship's "loaded" and "ballast" state. When loaded, the ship might not be filled to its maximum capacity and draught is also used to distinguish the extent of part loading. Capacity utilization is calculated as the % of the total deadweight, which is being used to carry payload at any one time.

For the interpretation of loading state and extent, the following assumptions are applied:

- Maximum draught = design draught (from Clarksons World Fleet Register)
- Minimum draught = design draught – the change in draught attributable to the ship's deadweight.

When the draught data reported from AIS is above or below the maximum or minimum draught above, this implies that the data could be spurious and the values are reset to the associated maximum or minimum.

When a ship is in the ballast condition, for safety and stability reasons, its unlikely to be at the minimum draught (the draught corresponding to lightship displacement), but is likely to carry some quantity of ballast water. The exact quantity of water will vary depending on a number of factors including the salinity and temperature of the seawater, the weather conditions and risk of adverse weather and any special operating constraints. There was no study found that could be used as a detailed data source for the ballast condition assumptions, but experience indicates that for the majority of the ships studied in this analysis, 33% of the maximum deadweight is a typical quantity of ballast water used. For this reason, the ballast condition (associated with 0 quantity of cargo carried) is assumed to be attributed to any draught corresponding to less than 33% capacity utilization, and ships in ballast condition are given a 33% of payload mass. The loaded condition is attributed to any draught corresponding to above 33% capacity utilization. However, it is emphasized that these are broad and unverified assumptions, there are scenarios (for example if undertaking multiple pick ups and drop offs of cargo) for a ship to be sailing at a displacement corresponding to less than 33% of maximum deadweight. It is thought that the time spent in such a condition is likely to be small (i.e. a short leg between two loading or unloading ports) and therefore that the contribution to overall uncertainty is tolerable.

The information on draught is manually entered and liable to error. In most instances, this manifests itself as the draught field permanently being left at some value, normally the design draught or some minimum value. The consequence is that it is not possible to use AIS to estimate the distinction between loaded and ballast voyages for these ship types, and therefore the transport supply and the operational efficiency.

1.4.6. DAYS AT SEA

In many cases, the AIS data does not include records for a ship for every day of the year. For this reason, it is necessary to extrapolate the data for which there is AIS observation in order to estimate total time spent at sea and in the ballast and loaded condition. Whilst the coverage of the ship when in the open ocean is generally good, the scarcity of AIS data observations when the ship is in port makes it difficult to reliably estimate when the ship is at sea and when it is in port or loitering and therefore provide a sound basis for this extrapolation. When extrapolation is applied, it magnifies any error further. For these reasons, it has been decided to apply the assumption that all ships will operate with a total days at sea as represented by the data reported in the IMO 2nd GHG study. The total days is divided between the ballast and loaded states (and the component states therein representing time spent at different speeds and loading condition) according to any observed AIS data.

This assumption will affect the reliability of figures calculated for the total transport supply of each ship, but the majority of the data (operational and normalized operational efficiency, and average to design speed ratio) will not be significantly affected.

1.4.7. OPERATING SPEED

The use of S-AIS allows calculation of actual services speeds of vessel throughout their annual operation. Previous studies using AIS data for operational speed calculation have either being limited by their geographic scope (i.e. sea areas rather than ocean; for example Baltic sea area) and/or by selecting a single operational speed (Whall et al., 2010 & Jalkanen et al, 2009 & Pitana et al., 2010). As discussed above, this report will seek to identify a range of service speeds for each vessel type and size.

For each vessel type and size, a cluster analysis will be conducted to identify the vessel main operational speeds. For the relevant ship types (i.e. wet and dry bulk), the speeds will be further split by ballast and loaded journeys.

2nd IMO GHG study calculates speed as average speed between observations in shorebased-AIS based on time between observations and great circle distance between points. Shorebased-AIS has large geographic coverage gaps as it only covers near shore observations. Using S-AIS allows these gaps to be filled, leading to greater detail on ocean-going vessels obtained from this dataset.

1.4.8. RELIABILITY INDICATORS

S-AIS does not produce datasets that have 100% coverage of the voyages of ships (satellite coverage and data missing through collisions) and some of the information that is sent in the Message 5 is not fully reliable. The extent of coverage and the data's quality varies from ship to ship (depending primarily on where the ship is active and how the AIS system has been operated), and in cases where the data quality is low it could be desirable to discard the estimates of efficiency from aggregations in order to maximize the reliability of the fleet aggregate statistics. A number of indicators are used to document the reliability of the AIS data analysis derived for each ship. These include:

- The % of total days at sea on which the loaded ballast assessment is based shows the amount of extrapolation that is required to complete the total days at sea (in loaded and ballast conditions). 40% indicates that 60% of the days' properties have been extrapolated.
- Estimated or measured indicates whether the AIS field is obtained from AIS Message 5 (0) or estimated from the fleet's average parameters (1).
- In the event that there is no record at all of a ship from the Clarksons database in the AIS database, the estimated or indicated measure is set to (2), in this scenario, the IMO 2nd GHG assumptions on capacity utilization and design speed are applied to define the operational characteristics
- The sum of maximum amount of days missing on each edge and end node is a rough indicator of how many days there is missing data. A high value is associated with lower reliability.

- The proportion of edges where there is an associated message 5 destination for the end node shows when the data in the Message 5 on destination can be used and when the probabilistic calculation used to estimate of the ship's destination has to be relied upon. A low value indicates a lower reliability
- The total number of edges (journeys, voyages) indicates the number of voyages detected on AIS, however as this only covers the period during which there is AIS coverage, this should not be assumed to be representative of total voyages per year.

Of these indicators, only the "estimated or measured" field is currently used to filter the data prior to aggregation, however this shows that there are many ways in which the data's quality could be tested and if so desired controlled (e.g. through filtering of which data to include in aggregated statistics). If the indicator is (2) i.e. the ship has not been observed on AIS at any point during the year, then it is omitted from the aggregated statistics.

1.4.9. SPEED IMPACT PARAMETER

The operating speed efficiency parameter is assumed to take the form:

$$\eta_v = k\left(\frac{V_i}{V_{des}}\right)^b \quad (9)$$

The Holtrop and Mennen approach is adopted to evaluate the values of *k* and *b* for each ship type, size and age category. This method uses regression formulae to determine wave-making resistance combined with the ITTC (International Towing Tank Conference) formula to determine frictional resistance. The appendage and immersed transom resistances are not calculated due to insufficient data available describing ship's hull forms. Hull efficiency and relative rotative efficiencies are calculated using Holtrop and Mennen relationships. The input constants and assumptions are summarised in Table 10.

Table 10: Input variables and assumptions for the calculation of the coefficients k and b

Input Variable	Source	Missing data
Beam	Clarksons WFR	=f(Dwt), R^2=0.9894 2%
Length between perpendiculars, Lbp	Clarksons WFR	0.85xLoa
Length overall, Loa	Clarksons WFR	
Deadweight	Clarksons WFR	
Draft	Clarksons WFR	=f(Dwt), R^2=0.9831 (5%)
Block coefficient	Schneekluth and Bertram (1998)	
Number of shafts / skeg	Clarksons WFR	

The block coefficient is assumed from the Jensen (1994) C_b/F_n (Where F_n is the Froude Number of the hull in its design condition) relationship, which is described by the formula:

$$C_b = -4.22 + 27.8\sqrt{F_n} - 39.1F_n + 46.6F_n^3 \quad (10)$$

Figure 8 shows the speed to shaft power relationship for an exemplar chemical/product tanker, best fit analysis using the least squares method yields k=0.195 and b=3.54 for this particular ship.

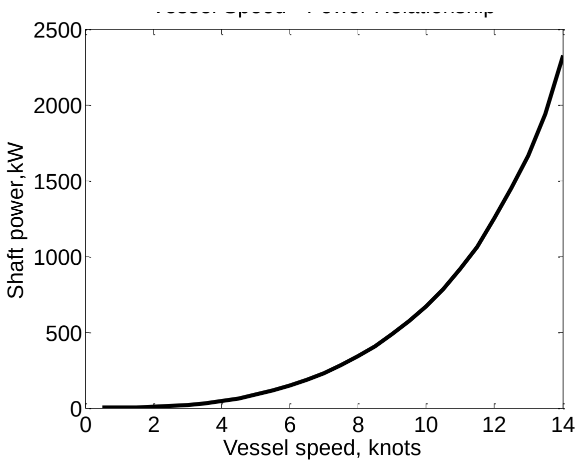

Figure 8: Exemplar vessel speed power relationship

In addition to variations in wave-making and frictional resistance with speed, the propulsion coefficient is also speed dependent. In the calculation of the relationship shown in Figure 8, a constant value is used for the propulsion coefficient, obtained using the assumptions listed in Table 11, sourced from Rawson and Tupper (2001).

Table 11: Propulsion coefficient assumptions

Variable	Coefficient assumption
Propeller diameter	0.74xT (container ships), 0.65xT (other ships)
Shaft efficiency	0.98
Open water propeller efficiency	0.6
Mid-ship area ratio coefficient	0.985
Length at the waterline	Lbp/0.97
Bulbous bow surface area	0.035xBxT
Number of propeller blades	5

T = draught; Lbp = length between perpendiculars; B = beam

The main speed dependency in the propulsion coefficient is due to variations in the propeller open water efficiency. The impact of this variation was explored in order to test the sensitivity of the propulsion coefficient to the V_i/V_{des} ratio. A large 2-stroke, direct drive LNG Carrier with a fixed pitch propeller was considered and the open water efficiency calculated using the regression analysis of the open water characteristics of the Wageningen B-Series propellers as investigated by Oosterveld and Oossanen (1975).

At each vessel speed the advance coefficient for optimum propeller open water efficiency is used in the overall propulsion coefficient calculation; the hull and the relative rotative efficiencies stem from the resistance and thrust requirements for this hull geometry according to the Holtrop and Mennen formulations. The relationship between V_i/V_{des} and the propulsion coefficient is shown graphically in Figure 9. The variation in the propulsion coefficient is 8.8% over a 60% speed range (8 knots to a design speed of 19.5 knots) and so this fluctuation is assumed negligible and omitted from the calculation of the terms *k* and *b*.

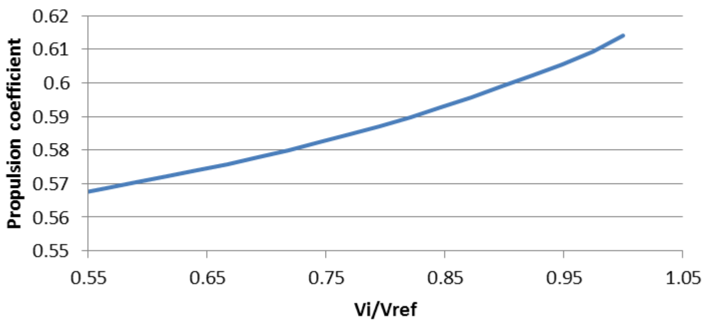

Figure 9: Speed dependency in the propulsion coefficient

1.4.10. LOADING CONDITION IMPACT PARAMETER

The loading affects the propulsion power requirement from the main engine because of the resultant change in displacement, which is calculated directly from the block coefficient and draught relationship. The displacement change affects the wave and frictional resistance as shown in Figure 10 for an exemplar oil tanker.

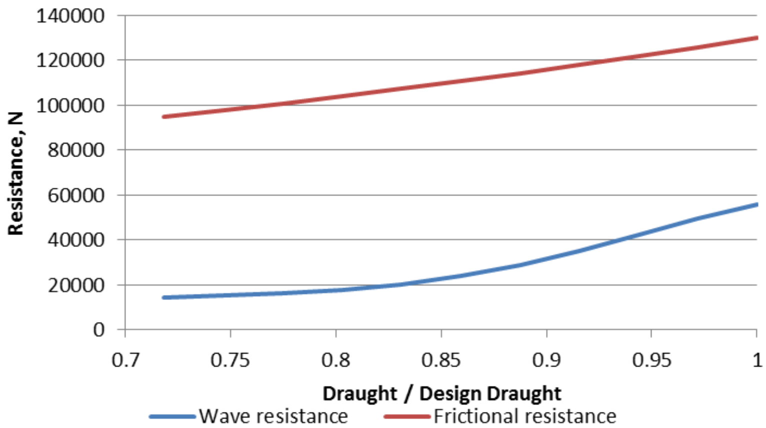

Figure 10: The variation in resistance components as a function of draught

The Holtrop and Mennen method can also be applied in order to quantify the coefficients k_L, b_L and c in the equation that describes the loading efficiency:

$$\eta_L = k_L \left(\frac{L_i}{L_{des}} \right)^{b_L} + c \qquad (11)$$

The particular hull characteristics and installed engine power of the oil tanker in this example results in values of k_L =0.4346, b_L =5.762 and c =0.2878 from best-fit analysis. The impact of this on ship power requirements is shown in Figure 11. A look-up table contains k_L, b_L and c values for each ship type and size.

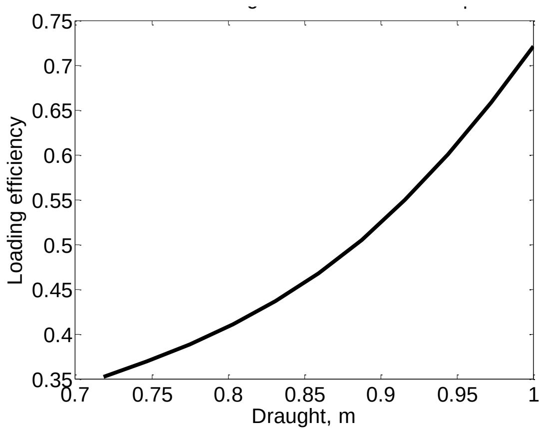

Figure 11: Draught – Power relationship example, draught = draught/design draught

1.4.11. CONDITION IMPACT PARAMETER

The hull condition can have a considerable impact on the power requirements of a ship due to fouling which works to increase the hull's frictional resistance. At low Froude number (low speeds or long ship lengths), the frictional resistance is the largest component of drag and so increases in hull roughness have a larger effect relative to other components of resistance. The absolute coefficient of frictional resistance remains relatively stable over the range of Froude numbers as shown in Rawson and Tupper (2001).

In the Holtrop and Mennen approach the effect on resistance of the standard hull roughness (mean apparent amplitude, k_S=150μm) can be included in the formula for the correlation allowance coefficient,

C_A that comes from the results of sea trials. As well as the hull roughness, the correlation allowance coefficient incorporates the effects of resistances that are not represented by the wave or frictional resistance, i.e. the effect of three-dimensionality on the viscous resistance and the scale effect on both the propeller characteristics and on the ship wake. Increases in hull fouling above the standard may be included by an additional hull fouling term, which is added to the correlation allowance coefficient (ΔC_A) according to the relationship adopted by the Holtrop and Mennen approach:

$$\Delta C_A = \frac{0.105 k_s^{1/3} - 0.005579}{L^{1/3}} \qquad (12)$$

Where k_s is the mean apparent amplitude of the surface roughness over a 50mm wavelength and L is the ship length (maximum = 400m), both are measured in metres.

Due to the number of factors involved in hull fouling build up there is a degree of ambiguity surrounding the values that should be used for the amplitude of initial hull roughness and the subsequent increase per year. Fouling depends on ship type, speed, trading pattern and distances travelled, fouling patterns, dry-dock interval, the ports visited and their cleaning/fouling class, sea temperatures, polishing (wear off) rate of anti-fouling paint, thickness of anti-fouling paint and type of anti-fouling paint.

In this study an initial amplitude of hull surface roughness of 150μm is assumed, this is the same value used by the Holtrop and Mennen model. A model by Doulgeris, Korakianitis et al. (2012) assumes a clean hull roughness amplitude of 120μm, a model by Carlton assumes a value of 130μm. With regards to the increase in hull roughness amplitude over time, Table 12 shows a general indication of the probable increases according to Carlton (2007). In the Lucy Ashton trials the type of paint varied the frictional resistance by up to 5% (Tupper (2004)).

Table 12: Typical annual hull roughness increments (Carlton, 2007)

Coating type	Annual increase in roughness (μm/year)
Self-polishing	10-30
Traditional	40-60

Further to Table 12, hull coatings in regular use today fall into at least three categories:

- Ablative epoxy resin (assumed to be the traditional coating referenced by Carlton)
- Self-polishing co-polymers
- Non-stick biocide free

Without access to detailed data on the uptake of these different coatings, the assumption is applied that the majority of hulls in this study have the 'traditional' coating and this has a corresponding annual roughness amplitude increase of 50μm/year (the median value from Table 12). *ks* in Equation 11 is increased incrementally according to this value in order to produce the values shown in Table 13.

Table 13: increments in total resistance over time

Time (years)	Hull roughness (μm)	% Increase in total resistance
0	150	
1	200	3.59
2	250	6.63
3	300	9.28
4	350	11.65
5	400	13.80

These values lead to the hull fouling – power relationships shown in Figure 12, which incorporates the total percentage resistance increases shown in Table 13.

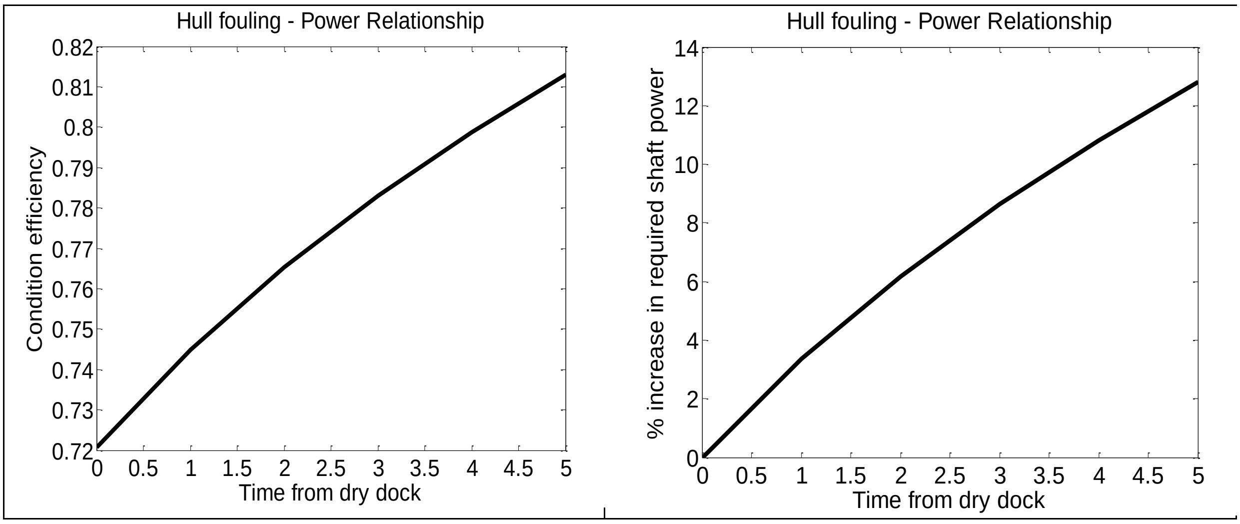

Figure 12: Changes in condition efficiency and shaft power with time out of dry dock

These correspond with assumptions made in similar studies; Doulgeris, Korakianitis et al. (2012) assumed an increase in annual average hull roughness amplitude of 30μm from an initial amplitude of 120μm which led to an annual hull resistance increase of 2%.

On the assumption that maintenance takes place every 5 years (IMO 2nd GHG Study) to restore initial hull roughness, an average increase in total resistance of 9% (constant in time) is applied for all ships. However, there is considerable uncertainty in this assumption. Many ships may dock and repaint with higher frequency than 5 years, may use a higher performance coating or may undertake cleaning/scrubbing in the interim between dry docking, all of which would reduce the average increase in total resistance. Unfortunately, at this point in time, lack of data in the public domain that can clarify both the absolute effect of fouling and deterioration on performance for the fleet, or enable differentiation between ship types, limits this work to a simplistic assumption applied consistently for all ship types and sizes.

1.4.12. MAIN ENGINE SPECIFIC FUEL CONSUMPTION IMPACT PARAMETER

To determine accurately the emissions when the engine is operated at off design speeds and % of MCR, changes in *sfc* must be considered. The *sfc* primarily depends on the engine load (% MCR). As reported by Faber et al. (2010), the variation in *sfc* of the main engine when it is operated between maximum power and 50% of the maximum is less than 3% for 4-stroke and 2-stroke engines. At 25% of the maximum the fuel consumption increases to 10-15% above the optimum and below 25% the fuel consumption may increase to anywhere between 40% and 100% above the optimum (there is minimal data available from the manufacturers for this lower operating envelope). Figure 11 shows a typical *sfc* curve for a 2-stroke marine engine installed on an LNG carrier, the optimum *sfc* (i.e. the minimum) is at 70% MCR. As described by the data in Annex 1, the main engine load at the design point is dependent on the vessel type.

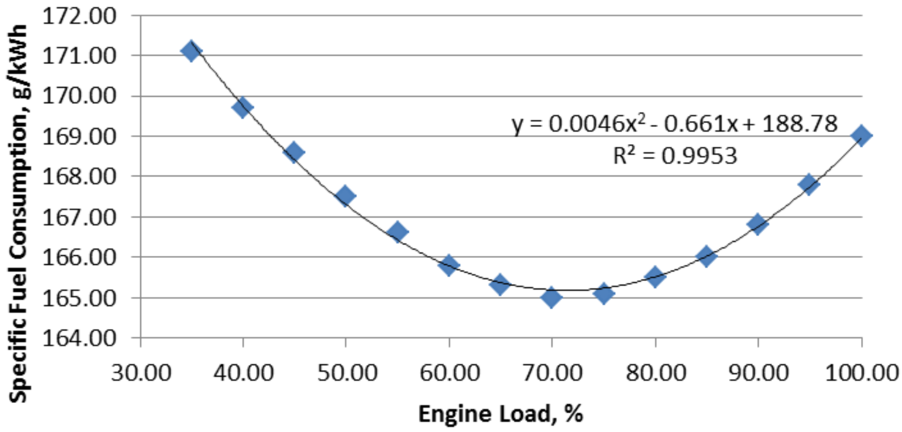

Figure 13: *sfc* – Engine load curve (MAN 6S70ME-C8.2)

It will be assumed here that for an individual ship, the minimum *sfc* is equal to the value used in the *TE* calculation sfc_{me_des} The relationship between the engine load and the *sfc* can then be approximated by a parabola as demonstrated in Figure 13. To avoid potentially very high *sfc* at low engine loads that would distort the results then upper limits are applied according to Table 14. This is similar to the procedure by Faber et al (2010)

Table 14: Upper limits of *sfc* used in the estimate

Engine Type	**2-Stroke**	**4-stroke**	
Engine Size		Power <= 1MW	Power > 1MW
***sfc* upper limit g/kW.h**	210	375	305

In addition to variations with engine load, there are discrepancies between *sfc* test-bed data and actual operating performance (discussed in the 2nd IMO GHG study). Various reasons are given; there are differences between fuel energy content of the test-bed fuels and the actual bunker fuel used (up to 5%), the engine is not always operating exactly at the single optimum point (there is an allowable tolerance of 5% on the given optimum point) and finally the engine wear, fouling and general condition can have an effect. The study described by MEPC 60/4/33 (Ozaki et al. (2010)) quantifies this variation as being between 2% and 4%. An additional percentage increase in specific fuel consumption is therefore added, and an average value of 3% is used.

1.4.13. WEATHER IMPACT PARAMETER

The weather impact parameter aims to quantify the added resistance in waves and the wind resistance and to therefore determine the extra load on the propeller and the additional power requirements from the engine in realistic operating conditions. In ship design it is common practice to include a 'sea margin' (typically of between 10%-30%) based on experience of the power requirements for maintaining the speed of similar ships operating on similar routes. The actual figure depends on ship type, hull geometry, sea keeping characteristics and environmental conditions. However, this represents the upper-bound of the power required to overcome wind and waves as the ship will only be sailing in conditions where the full margin is required for some of its operating time. To estimate the impact of weather on the CO_2 emissions of shipping, added resistance needs to be estimated for the range of environmental conditions that are encountered over the period of operation (one year).

Methods for estimating added resistance fall into four categories; approximate, theoretical (i.e. strip theories from the vessels motion in calm water plus superposition theory and a known wave energy spectrum), model experimental and computer aided numerical approaches. However, the accuracy of the method used needs to be traded off against the availability of data describing the wind and wave environment that the ship has experienced over the period of operation. Whilst it is theoretically possible to match the routing data in S-AIS with historical meteorological data to produce an estimate of weather impacts experienced on a ship-by-ship, voyage-by-voyage basis, the level of detail for input to the calculation and the computational resources required to apply this to the world fleet over the course of a year is not feasible within this project.

Consequently, the approach taken here is to apply findings from other more detailed studies. Work by Prpic-Orsic and Faltinsen (2012) undertook a detailed modelling of the effect of weather on fuel consumption for an S-175 container ship in the North Atlantic using state of the art models for ship added resistance. Their calculations revealed that this ship type had, on average over the voyages, a 15% increment in fuel consumption over the calm water fuel consumption. Whilst simplistic, this same assumption is applied as the average increase in resistance for all ocean-going ship types (as classified according to the IMO 2nd GHG Study) in this study. A lower value of 10% is applied as the added resistance of coastal shipping as it is expected that they would experience, on average, less extreme environmental conditions (see Annex 1).

1.5. DATA AND METHOD APPLICATION IN THIS STUDY

1.5.1. PAYLOAD CAPACITY

In the majority of calculations, the capacity of the ship is based on the deadweight data in Clarksons World Fleet Register. There is a risk that the deadweight is not reported consistently for all ships as there is no indication in the database that these are reported at a specific load line (e.g. summer, which is the reference used in the calculation of EEDI). The presumption is that the database values are the deadweight in the 'design' condition. This is the definition of capacity applied for all the plots in Section 4.

However, this was not the convention used in the IMO 2nd GHG study. In the case of container ships and car carriers, an estimate of the mass per TEU container and per lane metre was used in conjunction with the total TEU or lane metre capacity (see Table 15). To allow comparability of the energy efficiency calculations with the data reported in the 2nd IMO GHG Study, these conversions are also applied to calculate the efficiency data presented in the tables in Section 2.

Additional to the mass units, because some ship types' supply of transport work is not best characterized by units of mass, two units are used in the calculation of each efficiency (technical, operational and normalized operational efficiency) for the results presented in Annex 4.
Table 15's column "Additional capacity measures and unit" lists the different capacity measures that have been used to characterise the different ship types.

Table 15: Ship types and their corresponding capacity measure

Vessel group	Ship type	Method used to characterize mass when used in the *TE* calculation	Method used to characterize mass when used in the *OE* and *NOE* calculation	Additional capacity measure and unit
Wet	Crude Tanker	dwt	% of dwt	dwt tonnes
	Product Tanker	dwt	% of dwt	dwt tonnes
	Chemical Tanker	dwt	% of dwt	dwt tonnes
Dry	Dry Bulker	dwt	% of dwt	dwt tonnes
	General Cargo	dwt	% of dwt	dwt tonnes
Gas	LNG tanker	dwt	% of dwt	Cubic metres
	LPG tanker	dwt	% of dwt	Cubic metres
Unitised	Container Ship	TEU capacity x 7 tonnes per container	% TEU capacity x 7 tonnes per container	TEU (Twenty foot Equivalent Units)
	Pure Car Carrier	CEU capacity x 1.5 tonnes per CEU	% CEU capacity x 1.5 tonnes per CEU	CEU (Car Equivalent Units)

1.5.2. COVERAGE OF THE GLOBAL FLEET

Some of the ships in the Clarksons World Fleet register had missing fields for key parameters such as draught, vessel design speed and deadweight. A database was downloaded from Clarksons World Fleet register for all the ship types of relevance to this study. This initial database included 46 646 ships, of these 2051 had an empty deadweight field, 9339 had missing speed information and 3840 had missing draught information. Without this data, it is not possible to estimate some of the key parameters of the ship required to calculate energy efficiency and so the entries were discarded. This reduced the ship database to 36 340 ships (some ships had empty fields for more than one of these parameters).

Dry bulk carriers and general cargo ships were the ship type most often found to have data missing; this is true for all three of the key fields. They are followed by tankers (including product chemical, crude and other). Table 16 shows the proportion of ships with missing deadweight information. This is 10% of the total number of dry carriers in the fleet. 16% and 33% are missing draught and speed details, respectively.

Figure 14, Figure 15 and Figure 16 illustrate some of the characteristics of the missing data. Due to the nature of the missing data, the aggregate calculations for the majority of ship types and sizes will not be affected by their omission, however, some care should be applied when interpreting the results for the smallest ship size categories as, shown in Figure 17, it is the smallest size category which has the greatest proportion of ships with missing information (missing speed, draught and deadweight).

1.5.3. MISSING DWT

Table 16: List of missing information for different ship types

Vessel group	Ship types included	Missing dwt field	Total in database	Percent ships missing
Wet	Crude, Product, Chemical Tankers	278	12823	2.2
Dry	Dry Bulk carrier	97	10386	0.9
	General Cargo	1676	15965	10.5
Gas	LNG and LPG tanker	0	1612	0
Unitised	Pure Car Carrier	0	753	0
	Container Ship	0	5110	0

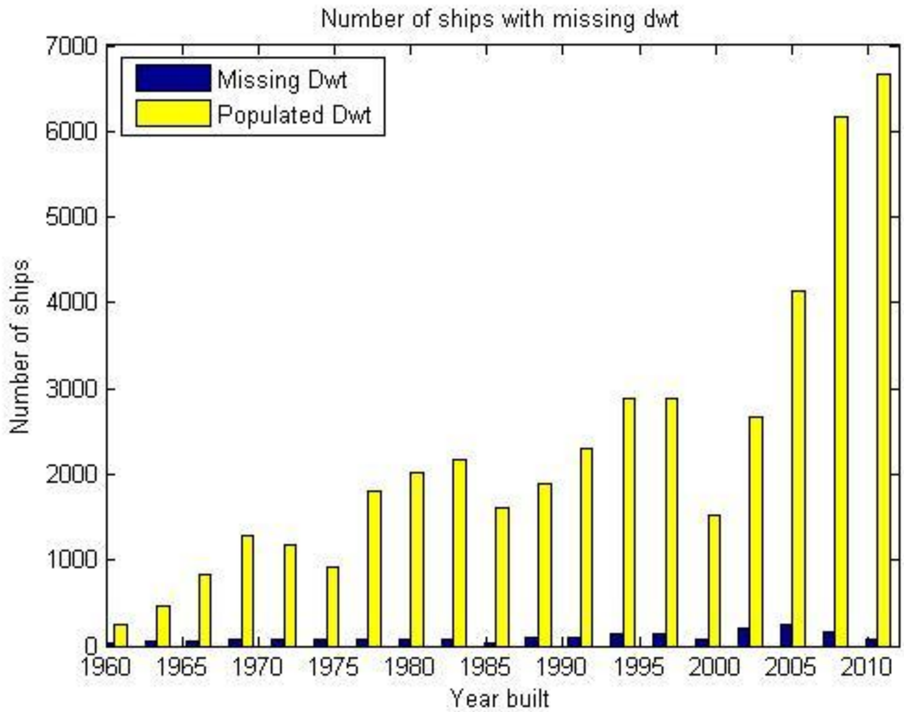

Figure 14: Distribution of ships with missing deadweight according to built year

1.5.4. MISSING SPEED

7724 Ships are not missing deadweight but are missing speed information. This is a large proportion of the total number of ships missing speed (including both those with and without deadweight information), which is 9339. Therefore 79% missing deadweight are also missing speed. The following analysis is for all the ships missing speed in the entire database.

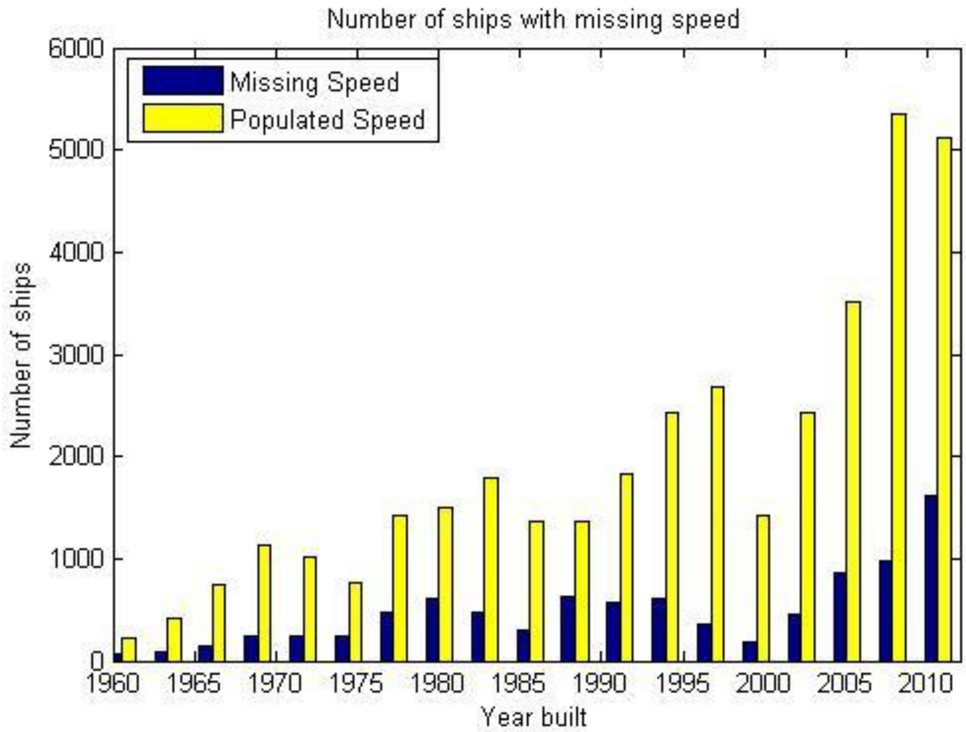

Figure 15: Distribution of ships missing speed data, by year built

Table 17: Missing speed information by ship type

Vessel group	Ship types included	Missing	Total in database	Percent ships missing
Wet	Crude, Product, Chemical Tankers	2663	12823	20.8%
Dry	Dry Bulk Carrier	1073	10386	10.3%
	General Cargo	5300	15965	33.2%
Gas	LNG and LPG tanker	256	1612	15. 9%
Unitised	Pure Car Carrier	33	753	4.4%
	Container Ship	14	5110	0.33%

1.5.5. MISSING DESIGN DRAUGHT

531 ships both missing deadweight and speed but missing draught is 531. The total number missing draught is 3840. The following analysis is for all the ships missing draught field in the entire database.

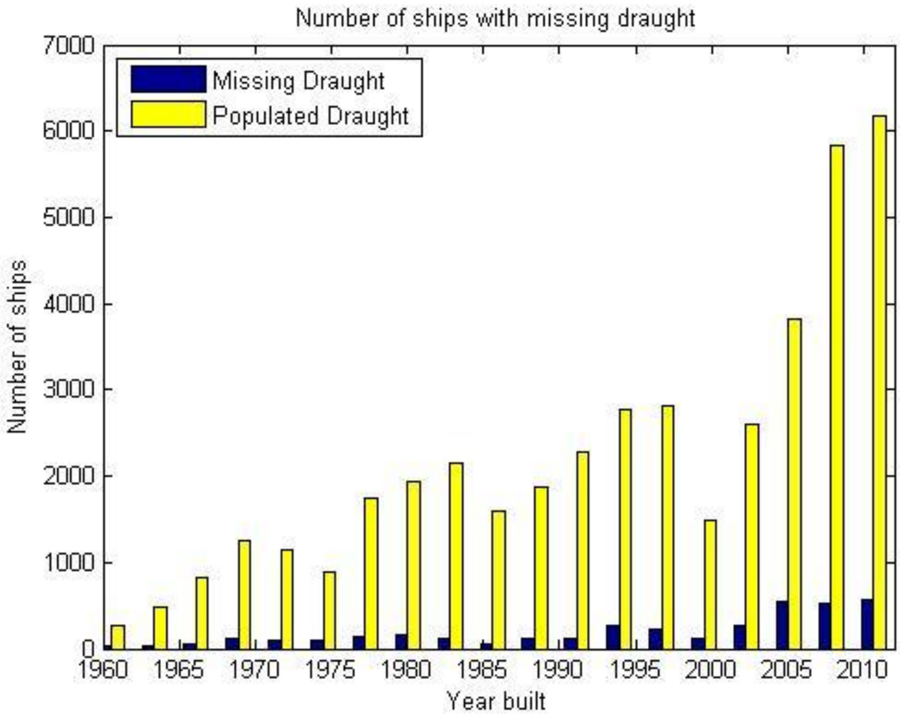

Figure 16: Distribution of ships missing draught data, by year built

Table 18: Missing draught information by ship type

Vessel group	Ship types included	Missing	Total in database	Percent ships missing
Wet	Crude, Product, Chemical Tankers	766	12823	6.0%
Dry	Dry Bulk Carrier	377	10386	3.6%
	General Cargo	2680	15965	16.8%
Gas	LNG and LPG tanker	14	1612	0.9%
Unitised	Pure Car Carrier	0	753	0.0%
	Container Ship	3	5110	0.1%

1.5.6. MISSING DATA, ALL VARIABLES, WITH RESPECT TO GROSS TONNAGE

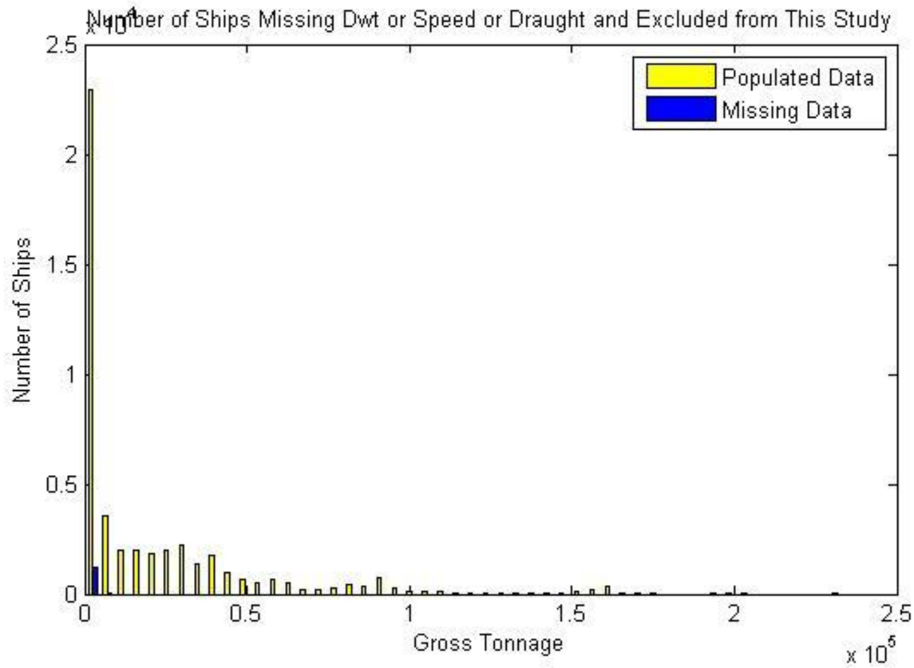

Figure 17: number of ships (x 10^4) missing dwt, speed or draught data, by Gross Tonnage

2. CALCULATIONS OF WORLD FLEET ENERGY EFFICIENCY

2.1. AGGREGATIONS INTO FLEET STATISTICS

Analysis was undertaken of the global fleet, which includes the calculation of an individual ship's Technical Efficiency (*TE*), Operational Efficiency (*OE*) and Normalised Operational Efficiency (*NOE*), (see preceding Section for definition, method and data). In addition to the calculation of these variables, a number of other parameters were calculated, plotted and tabulated in order to explain the underlying fundamentals of the fleet's calculated energy efficiency.

The purpose of this Section is to present the results and discuss the findings. The outputs are presented using a number of aggregations including: by ship type, by ship size, by ship age and by route (by ship type but all sizes and ages).

The categories of ship type and size that are used are listed in Annex 2. Ship age categories are defined for 5 year periods (0-5, 5-10, 15-20 etc). Routes are categorized as the routes between the following regions (full taxonomy listed in Annex 3):

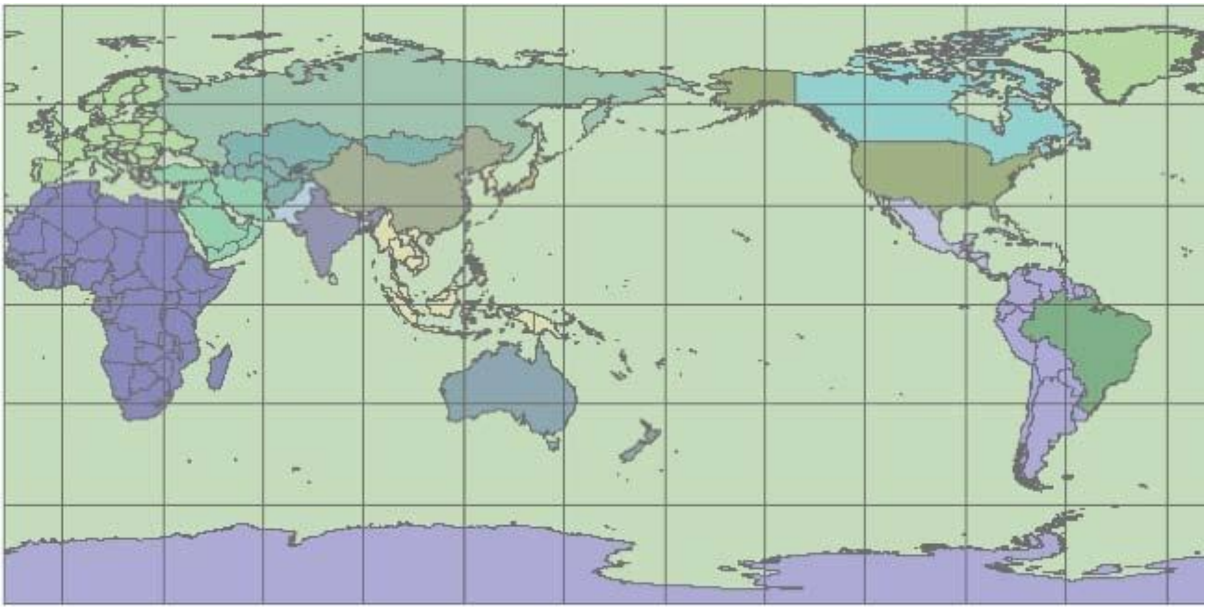

Figure 18: The global regions used in the model: Africa, Australasia, Brazil, Canada, Central America, China, Europe, India, Indian Subcontinent, Japan, Middle East, North East Asia, Russia, South America, South East Asia, USA.

2.2. FILTERING

In an attempt to filter out ships for which the AIS reported draught data is spurious (see discussion on draught data reliability in preceding Section), only ships which spend between 40% and 160% of the days at sea corresponding to the default capacity utilization (taken from IMO 2nd GHG) are included. For example, a VLCC which is reported in the IMO 2nd GHG study to have an estimated 48% capacity utilization is included in the filtered results if its loaded days at sea are estimated from AIS to be greater than 19% (40% of 48%) or less than 77% (160% of 48%) of its total days at sea. Similarly, a container ship which is reported in the IMO 2nd GHG study to have a 70% capacity utilization is included if its loaded days are greater than 28% (40% of 70%) and less than 100% of its days at sea (100% being the maximum possible). This is simplistic, particularly for container ships, for which the capacity utilization is less a reflection of the loaded/ballast voyage ratio and more a reflection of the average payload utilization when loaded. Greater sophistication could be applied in the filter using the AIS quality indicators discussed, if logic for their application could be developed (e.g. using operator data).

In some cases, this filter removes too many ships and the remainder may be too small to be statistically significant and therefore the basis of meaningful analysis. However, as the fleet sizes in the following section show, this is not the case for the majority of ship types and sizes.

2.3. COMPARISON WITH NUMBERS OF SHIPS REPORTED IN IMO 2ND GHG

The following tables detail the number of ships observed on AIS and that pass through the filter that discards data with spurious draught data (described above). There is a difficulty in defining the exact aggregation to ship types (e.g. crude oil tankers, product tankers) as used in the IMO analysis, because the component ship types in that analysis were never listed. This places a limit on the comparability, particularly for ship types, which are harder to classify (e.g. general cargo or the distinction between product and chemical tankers). A further constraint on comparability is the 4 year period between the IMO analysis (2007) and this study (2011). During that time, the shipping industry has changed significantly with substantial scrapping of older ships and delivery of newbuilds. Due to the state of the market in 2011, it may also be the case that many ships are laid up and therefore unobservable on AIS (all ships in the register are included in the IMO analysis as no activity indicator such as AIS was used to filter the results). It should be noted that the source for the data in this study is Clarksons World Fleet Register and not the Fairplay dataset, which was used in 2007.

In order to aid the discussion of the tabular results, a number of figures plotting the characteristics of the fleet (scatter plots where each data point represents a ship) and aggregations of the fleet (bar charts corresponding to size and age categories). The age categorization is described in the legend, but in all cases the size category corresponds to the size ranges used for the tabular data (where 1 is the smallest ship size category). A comprehensive set of the plots for each of the ship types examined in this report can be found in Annex 4.

With respect to fleet numbers, crude oil tankers shows generally good agreement with the IMO size classification and represents some growth in fleet size. However, the numbers observed in the smaller size categories imply that there may be ships classified in this study inconsistently with IMO. The coverage in the filtered dataset (those ships observed on AIS for which the draught data appears credible) is poor for all ship sizes except Suezmax and VLCC.

For product tankers and chemical tankers there appears some disagreement with the IMO ship type classifications. In the Panamax size range (60-80,000 dwt), a surplus of product tankers ships in this study is consistent with the deficit in the crude oil tankers size range (relative to IMO analysis). Similarly, it appears that a surplus in the 5-10,000 dwt range of product tankers is consistent with a deficit in the similar size range for chemical tankers (relative to IMO analysis). In general, both product tankers and chemical tankers have good representation in the filtered dataset.

Similarly, dry bulk carriers and general cargo numbers imply some differences to the IMO categorisations. The dry bulk carriers fleet has grown substantially in the last four years and this comes across clearly. Some interchange between the classifications is apparent, and relative to the IMO analysis there are many fewer ships observed in the smallest size range. Coverage of both fleets in the filtered datasets appears to be good.

Table 19: Numbers of wet and dry bulk ships

	dwt (tonnes)		number		
	>=	<	IMO (2007)	observed on AIS (2011)	in filter (2011)
crude oil tankers	0	10000	114	368	11
	10000	60000	245	128	2
	60000	80000	180	95	3
	80000	120000	651	623	33
	120000	200000	353	377	89
	200000	+	494	531	276
product tankers	0	5000	3959	2680	2391
	5000	10000	466	884	697
	10000	20000	193	652	370
	20000	60000	456	1559	606
	60000	+	198	518	167
chemical tankers	0	5000	1659	165	26
	5000	10000	642	307	260
	10000	20000	584	437	225
	20000	+	1010	276	93
dry bulk carriers	0	10000	1120	395	365
	10000	35000	2090	2340	1009
	35000	60000	1864	2919	1411
	60000	100000	1513	2051	1083
	100000	200000	686	1123	586
	200000	+	119	257	91
general cargo	0	5000	12492	6965	6520
	5000	10000	2617	1559	898
	10000	+	1899	371	243

Table 20: Numbers of gas bulk ships

	Cubic Metre Capacity, CBM (m3)		number		
	>=	<	IMO (2007)	observed on AIS (2011)	in filter (2011)
LPG	0	50000	943	920	688
	50000	+	138	116	12
LNG	0	200000	239	298	86
	200000	+	4	16	4

The observed numbers of LPG and LNG ships shows good agreement with the fleets observed by IMO (in terms of ship type classification). The growth in the LNG fleet over the last 4 years is apparent. Reasonable coverage in the filtered results is obtained.

Table 21: Numbers of container ships and car carriers

	TEU and CEU		number		
	>=	<	IMO (2007)	observed on AIS (2011)	in filter (2011)
2.3.1.container ships	0	1000	1110	1164	937
	1000	2000	1115	1257	839
	2000	3000	667	673	345
	3000	5000	711	949	332
	5000	8000	417	584	222
	8000	+	118	465	148
2.3.2.pure car carriers	0	4000	337	201	166
	4000	+	398	518	371

Similarly to the gas bulk ships, container ships have none of the difficulties of ship classification found in the wet and dry bulk ship types and show good qualitative agreement with the IMO analysis. The growth of the fleet numbers over 4 years (particularly larger container ships), is clear. The coverage of ships in the filter is generally good.

2.4. VESSEL SPEEDS AND SLOW STEAMING

Recently, one of the most commonly discussed trends in the shipping industry has been slow steaming. Taking advantage of the approximately cubic relationship between fuel consumption and speed, ships operated more slowly can generate cost savings that outweigh any reduction in revenue. Applying the cubic 'rule of thumb', a 10% reduction in speed equates to about a 27% reduction in fuel consumption, although there is a diminishing return in practice as the ship's engine propeller and hull are taken further away from their design condition specification.

Whilst the generics are simple, the specifics are not. Even in depressed markets there are reasons to travel at high speed, such as competing with another ship to arrive at a loading area in time for a fixture or following the 'utmost dispatch' clause in a charter party. This can lead to significant heterogeneity in the actual operating speeds of a ship over the course of a year, or even within a specific ship type, size and age range.

Satellite AIS data provides an excellent opportunity to understand the heterogeneity and also the average characteristics of subsets of the fleets. It should be noted that AIS reports here are for speed over ground and not speed through the water, which could be either higher or lower than the speed over ground depending on whether the ship is travelling against or with the assistance of a current. For trans-oceanic voyages, the effect of currents should be negligible and create a minimal net impact, however for smaller ships operating in coastal, tidal waters and planning their voyages to maximize the benefits of tides, the AIS data could be misrepresentative.

The tables and figures below detail the findings. It should be noted that in 4 years there has been a slight change in the fleet's average design speed and any definitive comparison of 2007 to 2011 data should take this into account. However, the design speed change is negligible relative to the operational speed change and it is the comparison against the 2007 assumed operating speed that is of greatest significance to this report.

Table 22: Speeds in the wet and dry bulk fleet

	dwt (tonnes)		average service speed (kts)			
	>=	<	IMO (2007)	calculated (unfiltered) (2011)	calculated (filtered) (2011)	% difference (unfiltered)
crude oil tankers	0	10000	12.1	10.4	10.4	-14%
	10000	60000	14.5	10.9	10.6	-25%
	60000	80000	14.6	12.9	13.0	-12%
	80000	120000	14.7	12.5	12.6	-15%
	120000	200000	15	12.7	12.8	-15%
	200000	+	15.4	13.4	13.3	-13%
product tankers	0	5000	11	10.5	10.6	-4%
	5000	10000	12.8	10.7	10.9	-16%
	10000	20000	14.1	12.0	12.0	-15%
	20000	60000	14.8	12.8	12.9	-13%
	60000	+	15.3	12.9	12.9	-16%
chemical tankers	0	5000	14.5	10.3	10.4	-29%
	5000	10000	14.5	11.8	11.8	-19%
	10000	20000	14.5	12.8	12.8	-12%
	20000	+	14.7	13.6	13.5	-8%
dry bulk carriers	0	10000	11	10.4	10.4	-5%
	10000	35000	14.3	12.4	12.4	-13%
	35000	60000	14.4	12.7	12.8	-12%
	60000	100000	14.4	12.8	12.8	-11%
	100000	200000	14.4	12.7	12.8	-12%
	200000	+	14.4	12.8	12.7	-11%
general cargo	0	5000	11.7	10.1	10.2	-13%
	5000	10000	13.4	10.5	10.4	-22%
	10000	+	15.4	12.0	12.1	-22%

Consistent with the reports in the media, the average speed (a weighted average of loaded and ballast days) for each of the fleets can be seen in Table 22 to be significantly lower than those used in the IMO 2nd GHG Study. Trends are consistent across all large wet and dry bulk (Panamax and above) for speed reductions of between 11 and 16%. Some smaller sizes chemical and crude tankers show even greater reductions relative to the IMO 2nd GHG, but these should be considered in the context of the challenge of classify ship types described in the section on ship numbers.

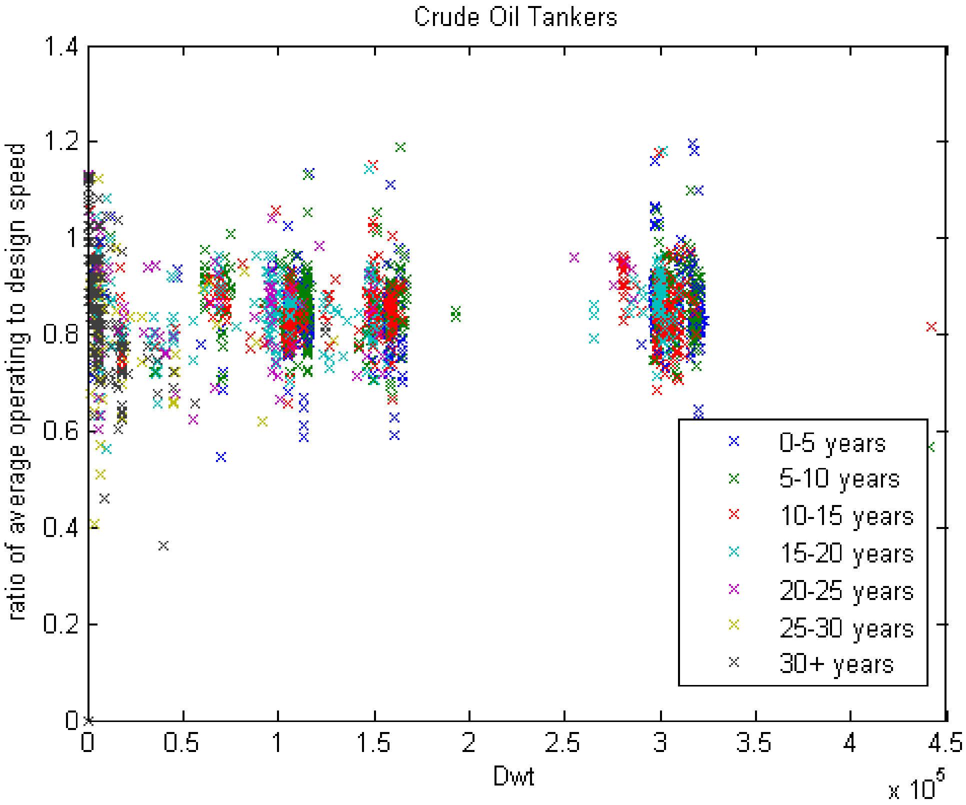

Figure 19: Ratio of average operating to design speed, crude oil tankers all ages

The heterogeneity of the average speeds in the crude oil tanker fleet can be seen in Figure 19 (each data point represents an individual ship) and Figure 20 (size categories corresponding to those in the tabular data (1 = 0-10,000 dwt, 6 = 200,000 + dwt). In the larger size category (e.g. VLCC, Suezmax, Aframax), the inter-quartile range is consistent in range (approximately 0.8-0.95) and there is no pattern apparent from the ship age. This is reversed for the smaller size categories (Handymax and smaller) in which the more modern ships are being operated (on average) at substantially higher speeds. This is an interesting observation because below a certain %MCR, older engines (e.g. before common rail and some advances in lube systems) can require significant modification to ensure that they do not experience excessive wear or loss in efficiency. The data implies that either substantial retrofit activity has already taken place in the smaller, older ship fleets, or that the original engines are flexible enough to be able to be operated at the corresponding %MCR (a ratio of 0.75 on design speed could correspond to approximately 30% MCR, depending on the design point of the engine)

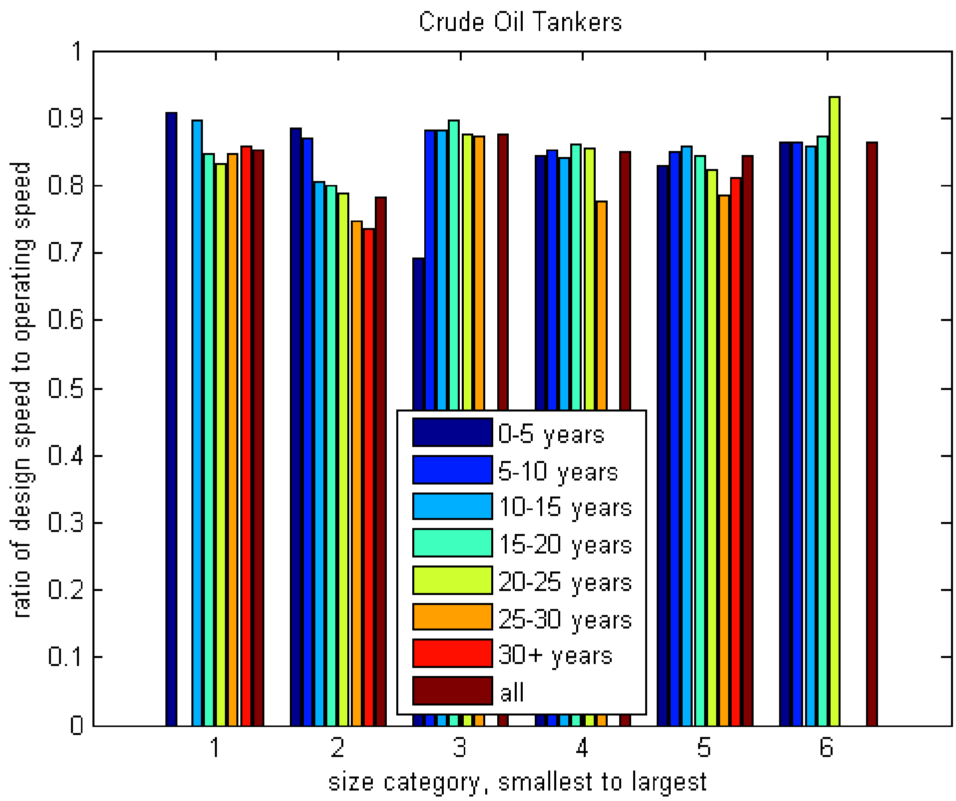

Figure 20: The fleet average ratio of design speed to operating speed for each of the size and age categories, crude oil tankers

Figure 21 shows the variation in average speed between the loaded and ballast voyage. A value of 1 implies that on average the speeds are the same. 1.1 implies that the loaded speed is 10% greater than the average speed. This plot shows that typically there is not a strong difference between the two. When undertaking economic modelling of the 'optimum' speed (based on freight rates, fuel prices and inventory and/or opportunity costs), it can be the case that calculated optimal ballast speeds a knot or two lower than the optimal loaded speeds, conversely some literature (e.g. Lindstad et al. 2011) which found that ballast speeds were often faster than loaded speeds. The data shown here appears to contradict both of these theories.

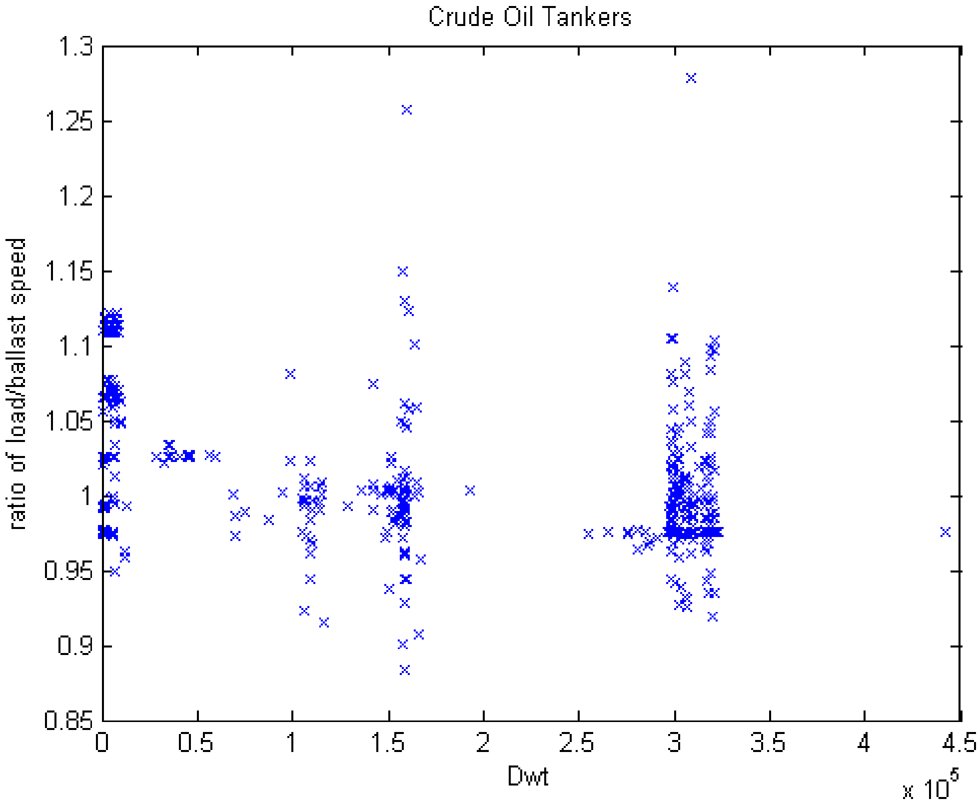

Figure 21: Loaded to ballast average speed ratios for the crude oil fleet

Relative to the wet and dry bulk, the gas bulk fleets (Table 23) show similar uptake of slow steaming, with only the smallest category of LPG tankers retaining an average speed close to their design speed.

Table 23: Speeds in the gas bulk fleet

	CBM (m3)		average service speed			
	>=	<	IMO (2007)	calculated (unfiltered) (2011)	calculated (filtered) (2011)	% difference (unfiltered)
LPG	0	50000	14	13.8	13.6	-1%
	50000	+	16.6	14.8	15.2	-11%
LNG	0	200000	19.6	15.8	15.5	-19%
	200000	+	19.6	16.7	16.6	-15%

Figure 22 shows the average speed of each ship in the LPG fleet and explains how the smallest size category has an average speed that is close to design speed, indeed, it is apparent that in many cases the operational speed is exceeding the design speed by 10-20%. This may be because of differences between the speed over ground and speed through the water (discussed above) affecting this size category. Alternatively, it may be because the economics of this ship size and type are incentivizing higher speeds of operation and that is reflected in practice.

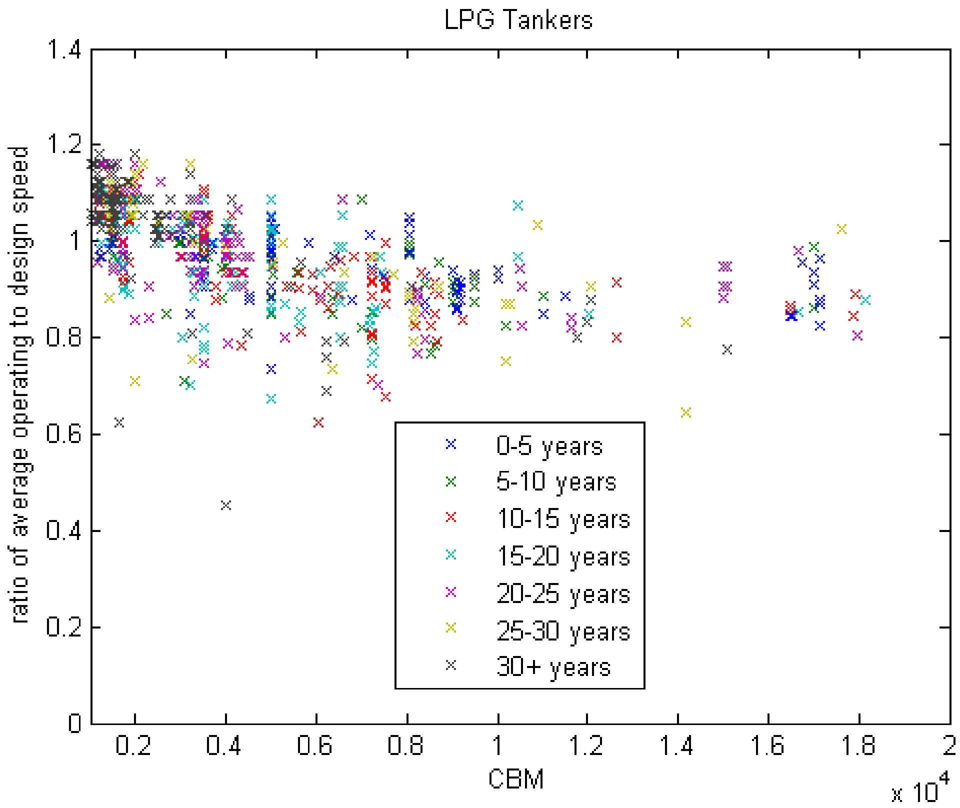

Figure 22: Ratio of average operating to design speed, LPG tankers all ages

The LNG fleet has a remarkable homogeneity in design speed. Almost every ship above 50,000 dwt is designed for between 19 and 20 knots. However, Figure 23 shows that in practice the average operating speeds vary significantly between individual ships and their loading condition. This may be because of differences in the propulsion technology (there remains a mix of steam turbine, diesel electric and conventionally propelled ships, which each have different levels of flexibility of operation and operational economics optima). Another explanation could be associated with the use of boil off gas for propulsion on many of the LNG fleet, which often sets a lower bound to the operating speed. The rate of boil off varies as a function of the type of insulation and LNG tank used, and in some instances there may be reliquifaction machinery which returns boil-off to the tank for storage, all differences will affect the amount of boil off available for propulsion between ships.

Figure 24 shows the extent to which the average operating speeds correspond to slow steaming in the LNG fleets of different ages and sizes. Typically, there is no correlation between the extent of slow steaming and age, with all ships in the 130-160,000 CBM capacity range showing an even spread across a ratio of operating to design speed of between 0.65 and 0.95. The larger Q-Flex and Q-Max ships appear more tightly grouped, although this could be because of homogeneity of owner and operator.

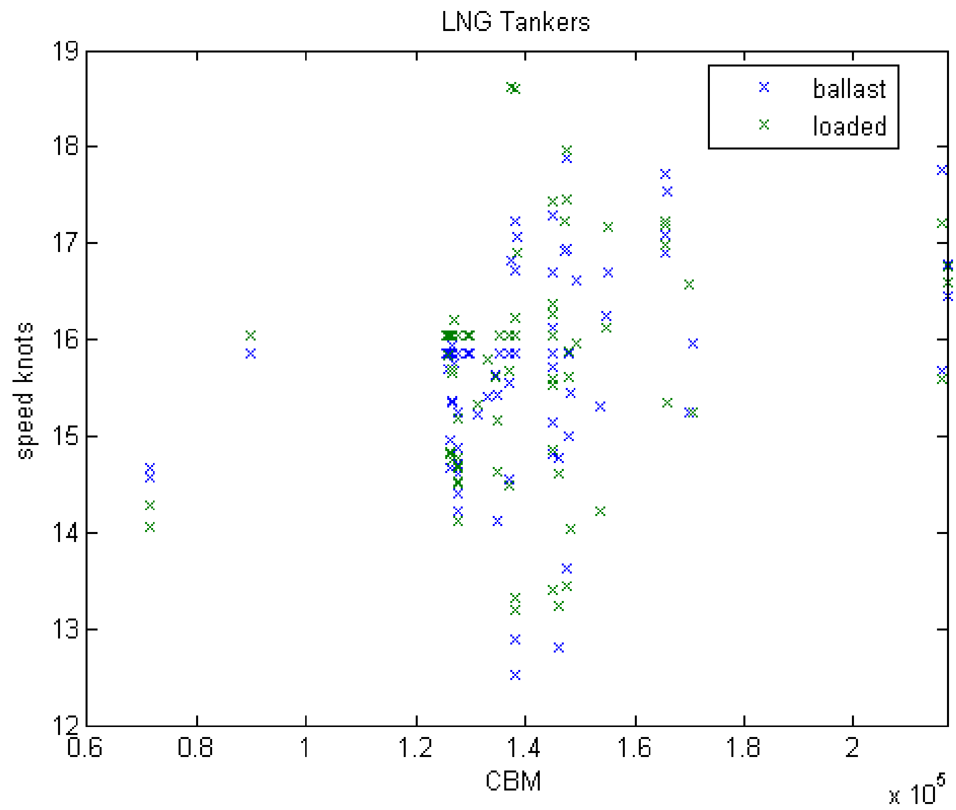

Figure 23: Average operating speed in the loaded and ballast condition, LNG tankers

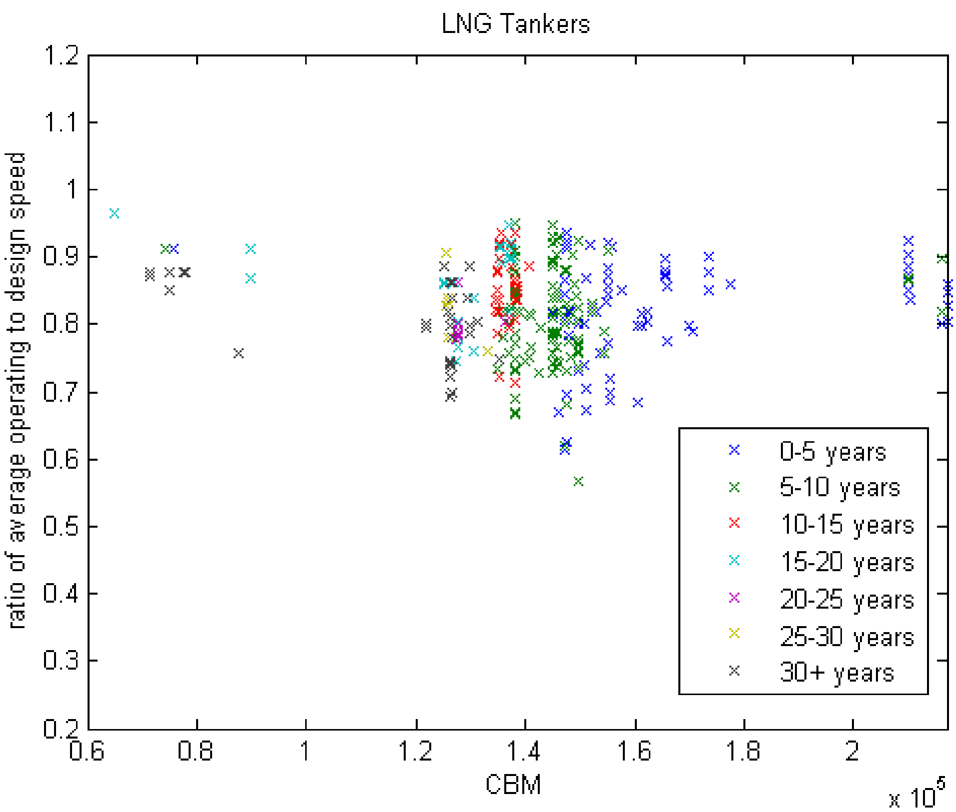

Figure 24: Ratio of average operating to design speed, LNG tankers

The container shipping sector is commonly cited as having the greatest potential to take advantage of slow steaming, not just because of the current state of the market (low revenues and high voyage costs) but also because of the existing fleet's high design speeds (2000 TEU and greater typically have design speeds of 20-25 knots as shown in the IMO data). Table 24 shows that the average speed reductions in each of the size ranges are significant and mainly greater than those observed in the wet, dry and gas bulk fleets. For ships larger than 2000 TEU, the extent of slow steaming is fairly consistent at approximately 25% of design speed. The pure car carrier fleet also appears to be slow steaming (relative to the IMO 2nd GHG data, but also shown in Figure 26), though less than the container fleet.

Table 24: Speeds in the container ship and car carrier fleets

	TEU equivalent		average service speed			
	>=	<	IMO (2007)	calculated (unfiltered) (2011)	calculated (filtered) (2011)	% difference (unfiltered)
container ships	0	1000	17	13.7	13.7	-20%
	1000	2000	19	15.5	15.5	-18%
	2000	3000	20.9	17.0	17.0	-19%
	3000	5000	23.3	18.0	17.8	-23%
	5000	8000	25.3	18.4	18.3	-27%
	8000	+	25.1	18.6	18.5	-26%
pure car carriers	0	4000	17.7	16.1	16.3	-9%
	4000	+	19.4	16.4	16.3	-16%

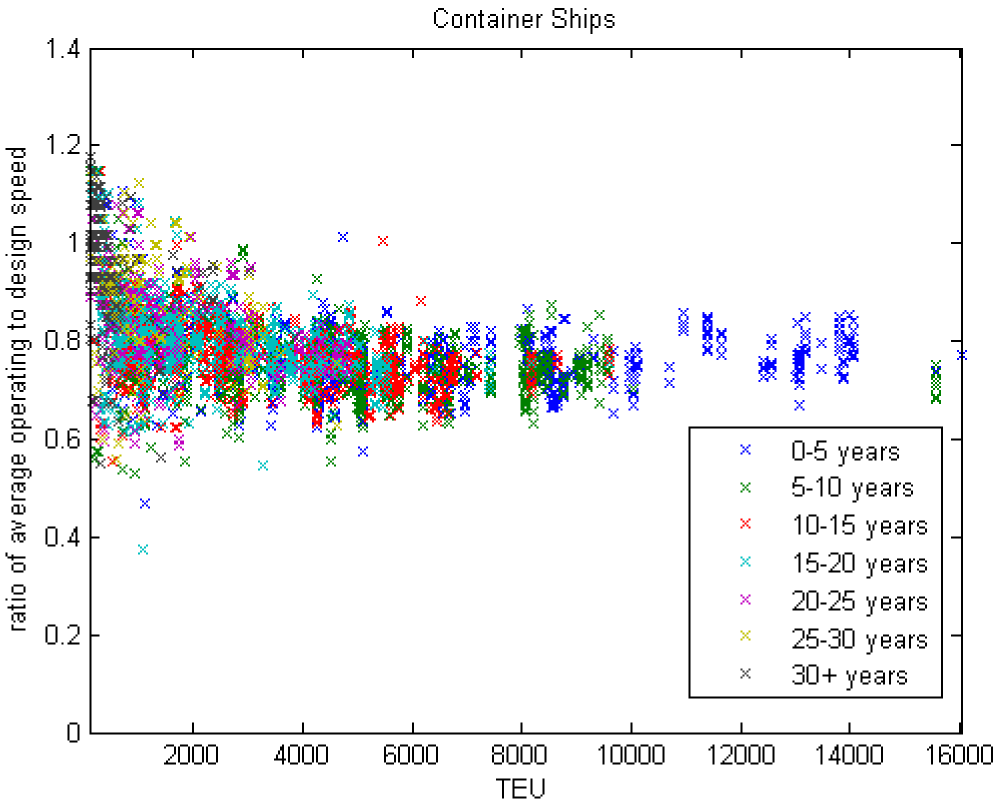

Figure 25: Ratio of average operating to design speed, container ships

In contrast to the bulk fleets, which typically showed no relationship between ship age and the extent of slow steaming, Figure 26 and Figure 25 shows a consistent trend of older ships maintaining speeds closer to design speed than the newer ships. This is least apparent in the size range 5000 TEU, although these fleets are comparatively younger with no ships greater than 20 years old. However, as each of the size categories has a relatively young average age, the weighted average speed across all age categories is strongly biased towards the average speed of the newest ships.

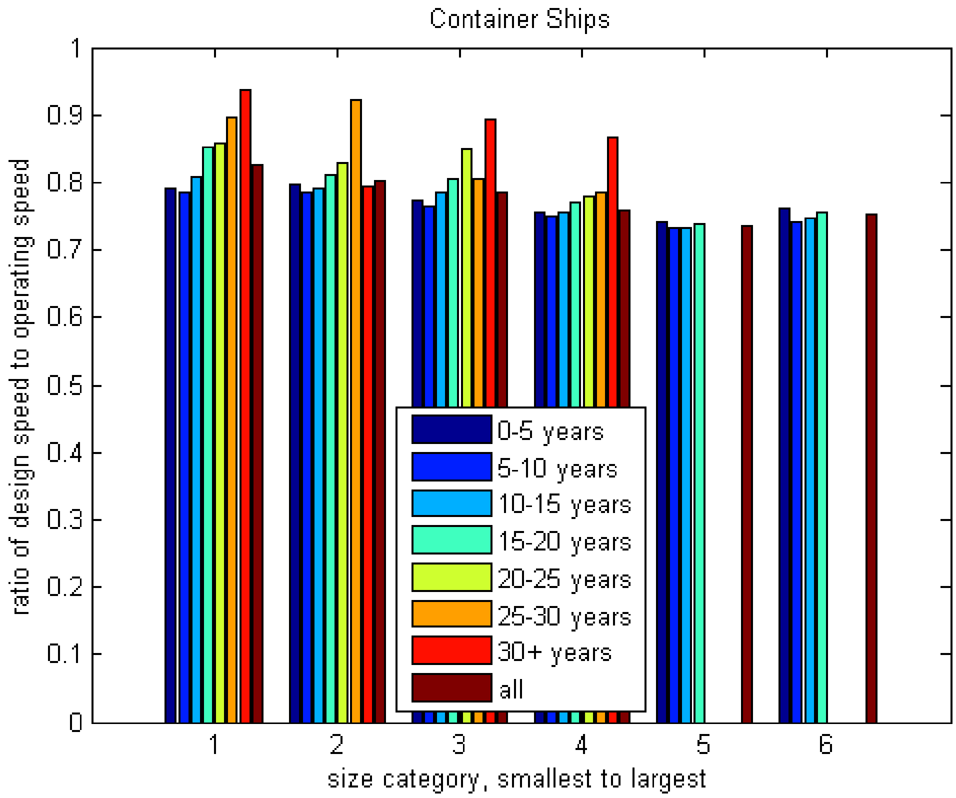

Figure 26: The fleet average ratio of design speed to operating speed for each of the size and age categories, container ships

2.5. FUEL CONSUMPTION

Ship speed is closely related to a propulsion engine's fuel consumption. A cubic relationship is often used, however this can oversimplify the interaction of the different resistance components (wavemaking and frictional resistance) and the behaviour of the propulsion system (off-design performance of the engine and propeller). As well as speed, resistance is also a function of loading condition, as discussed in Section 1, ceteris paribus, fully loaded ships consume more fuel than partially loaded or ships operating in the ballast condition. Along with these operational specifics, its important to take into account reasonable allowances for hull fouling and weather.

With a manageable degree of uncertainty (see discussion on uncertainty below), the method detailed in Section 1 is capable of estimating the contribution of all of these factors to the resistance, propulsion and machinery of a ship. This allows a comparison to be made against the data in the 2nd IMO GHG, and reveals the extent to which the observations of slow steaming may be influencing the fleet's fuel consumption. It should be noted that the IMO 2nd GHG made no explicit allowances for the effects of condition deterioration (hull fouling) or weather, unlike this study. In the case of an ocean going and coastal vessel these are estimated (Section 1) to amount to an addition of 25% and 20% to their respective basic resistance.

The following tables and figures are focused on the main (propulsion) engine fuel consumption. In addition to this, there is fuel consumption in the auxiliary machinery and the boiler. These are calculated based on input assumptions from the IMO 2nd GHG study and whilst changes in ship operation (time spent at sea loaded), have some impact on the values, this is of low significance relative to the differences observed in the main engine fuel consumption.

Table 25: Main engine annual fuel consumption in the wet and dry bulk fleets (average per ship)

	dwt (tonnes)		main engine fuel consumption ('000 tonnes pa)			
	>=	<	IMO (2007)	calculated (unfiltered) (2011)	calculated (filtered) (2011)	% difference (unfiltered)
crude oil tankers	0	10000	1.1	1.0	1.3	-7%
	10000	60000	6.2	2.7	1.7	-56%
	60000	80000	8.2	5.6	7.0	-32%
	80000	120000	12.2	7.3	7.2	-40%
	120000	200000	16.5	10.2	10.2	-38%
	200000	+	21.8	15.3	13.8	-30%
product tankers	0	5000	0.6	0.6	0.6	-3%
	5000	10000	1.8	1.1	1.1	-39%
	10000	20000	2.9	2.1	2.0	-27%
	20000	60000	4.5	3.1	2.8	-31%
	60000	+	7.7	4.8	4.3	-37%
chemical tankers	0	5000	0.7	0.7	0.6	-3%
	5000	10000	3	2.2	2.2	-28%
	10000	20000	4.7	3.8	3.7	-19%
	20000	+	8.5	6.7	6.2	-21%
dry bulk carriers	0	10000	0.9	0.7	0.7	-18%
	10000	35000	5.4	3.8	3.5	-29%
	35000	60000	7	5.1	4.9	-27%
	60000	100000	8.8	6.2	6.0	-29%
	100000	200000	13.1	9.3	9.1	-29%
	200000	+	15.2	12.8	12.9	-16%
general cargo	0	5000	0.6	0.5	0.5	-16%
	5000	10000	2.7	1.4	1.4	-47%
	10000	+	5.8	3.3	2.7	-44%

The larger (Panamax and above) wet bulk fleets show consistent reductions in fuel consumption of between 30 and 40%. Dry bulk carriers show the least reduction in their fuel consumption, particularly in the largest (200,000+) size category. For smaller ship sizes the reductions are less consistent, which may be associated with ship type classification inconsistencies, but are all for a reduction in the fuel consumption relative to the IMO estimate (even allowing for the effects of fouling and weather).

The discrepancy between loaded and ballast fuel consumption and the manifestation of slow steaming can be seen in the average daily fuel consumption plotted in Figure 27. The difference is attributable to two effects, the difference in average speed in the loaded and ballast condition, and the change in resistance due to the difference in draught. Figure 21 shows that for the majority of ships, the loaded and ballast speeds are very similar, therefore the discrepancy shown in the plots can predominantly be attributed to the change in resistance due to the difference in draught.

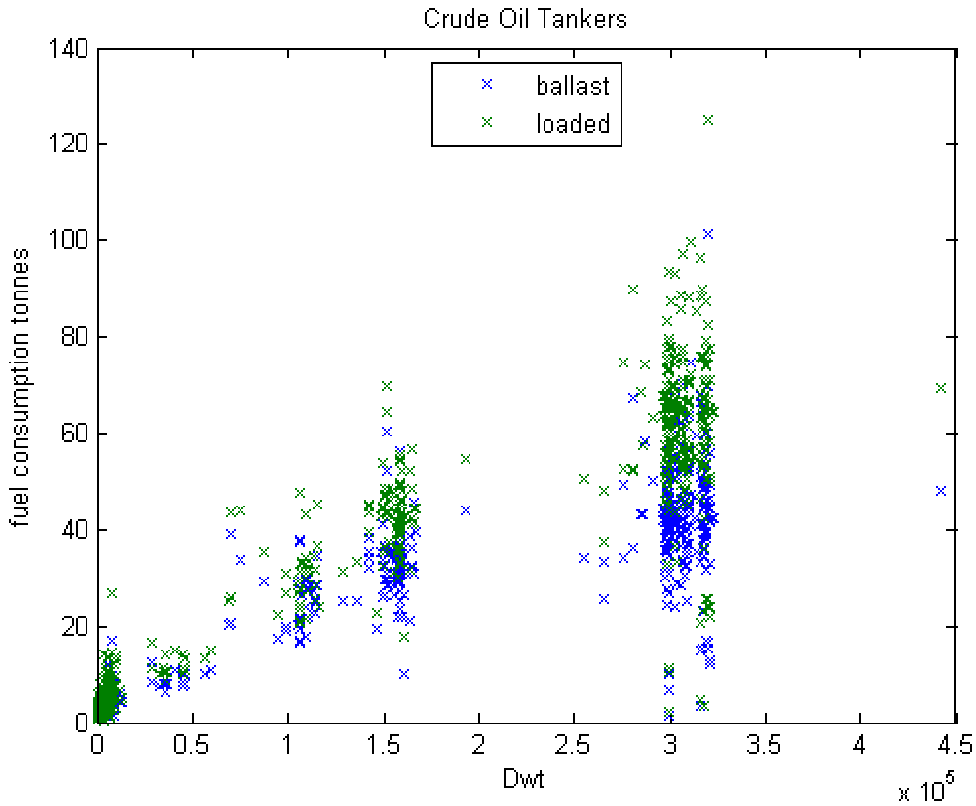

Figure 27: Average daily fuel consumption for all loaded and ballast days, crude oil tankers

The data for the gas bulk fleet, Table 26, are consistent with the relative uptake of slow steaming. The smallest LPG tanker size range was found to be operating at approximately the same speed as its design speed and therefore displays an increment in the fuel consumption (relative to the IMO 2nd GHG Study) which is consistent with the magnitude of the fouling and weather impacts on resistance.

Table 26: Main engine annual fuel consumption in the gas bulk fleets

	CBM (m3)		main engine fuel consumption ('000 tonnes pa)			
	>=	<	IMO	calculated (unfiltered)	calculated (filtered)	% difference
LPG	0	50000	1.9	2.4	1.8	24%
	50000	+	12.1	8.6	9.0	-29%
LNG	0	200000	31.1	22.8	22.4	-27%
	200000	+	28.5	21.8	22.7	-24%

The heterogeneity in the LNG tanker fleet's operating speed (Figure 23) is also shown in the average daily fuel consumption for the fleet, Figure 28 (these are total fuel consumptions, inclusive of both boil off gas and any HFO and MDO consumed).

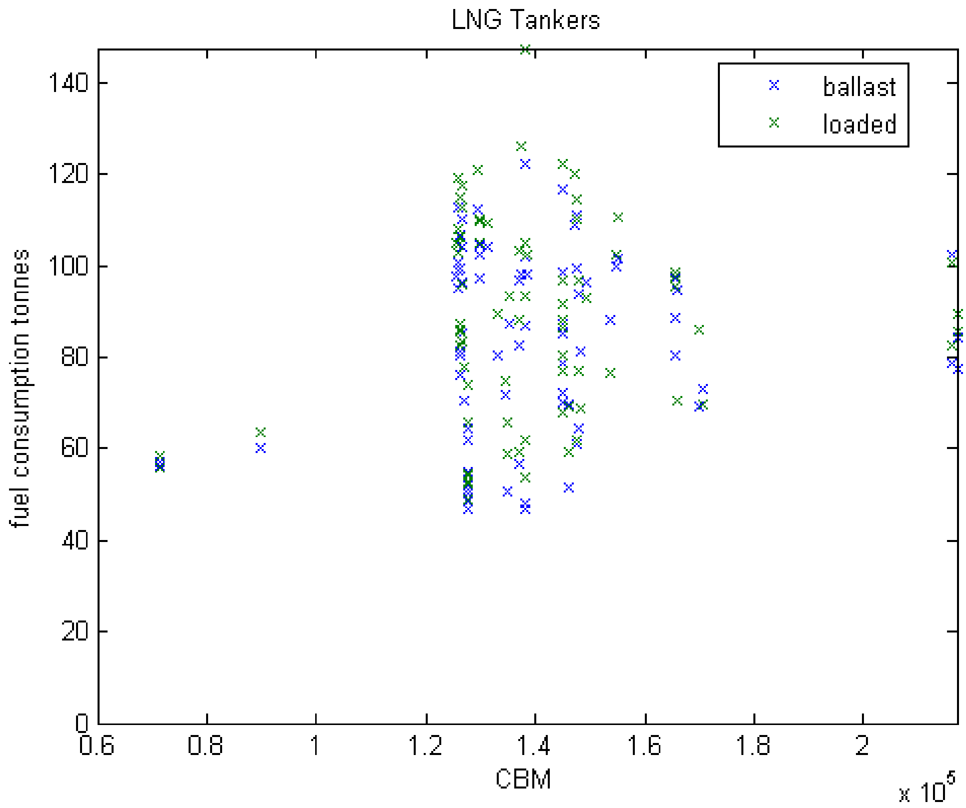

Figure 28: Average daily fuel consumption for all loaded and ballast days, LNG tankers

The container shipping fleet's fuel consumption (Table 27) show the extent that slow steaming is helping them to cut costs. Consistently, it appears that fuel consumption (and therefore fuel cost) is 40-60% lower than the assumption derived in the IMO 2nd GHG. Even the pure car carrier fleet, which only saw comparatively modest reductions in ship speed, shows significant reductions in fuel consumption (relative to the IMO 2nd GHG).

Table 27: Main engine annual fuel consumption in the container ship and car carrier fleets

	TEU equiv		main engine fuel consumption ('000 tonnes pa)			
	>=	<	IMO	calculated (unfiltered)	calculated (filtered)	% difference
container ships	0	1000	3.1	1.8	1.7	-43%
	1000	2000	9.7	5.0	5.0	-48%
	2000	3000	15.6	7.8	7.6	-50%
	3000	5000	25.2	12.2	11.4	-52%
	5000	8000	37.5	16.3	15.1	-57%
	8000	+	46.4	21.9	19.0	-53%
pure car carriers	0	4000	7.3	3.6	3.7	-51%
	4000	+	13.2	5.4	5.3	-59%

Figure 29 shows for container ships the equivalent to Figure 27, crude oil tankers. The separation between loaded and ballast days is not as meaningful since container ships typically spend so little of their time at sea in the ballast condition, however the graph does indicate the likely range of the fuel consumption of the fleet across different ship sizes.

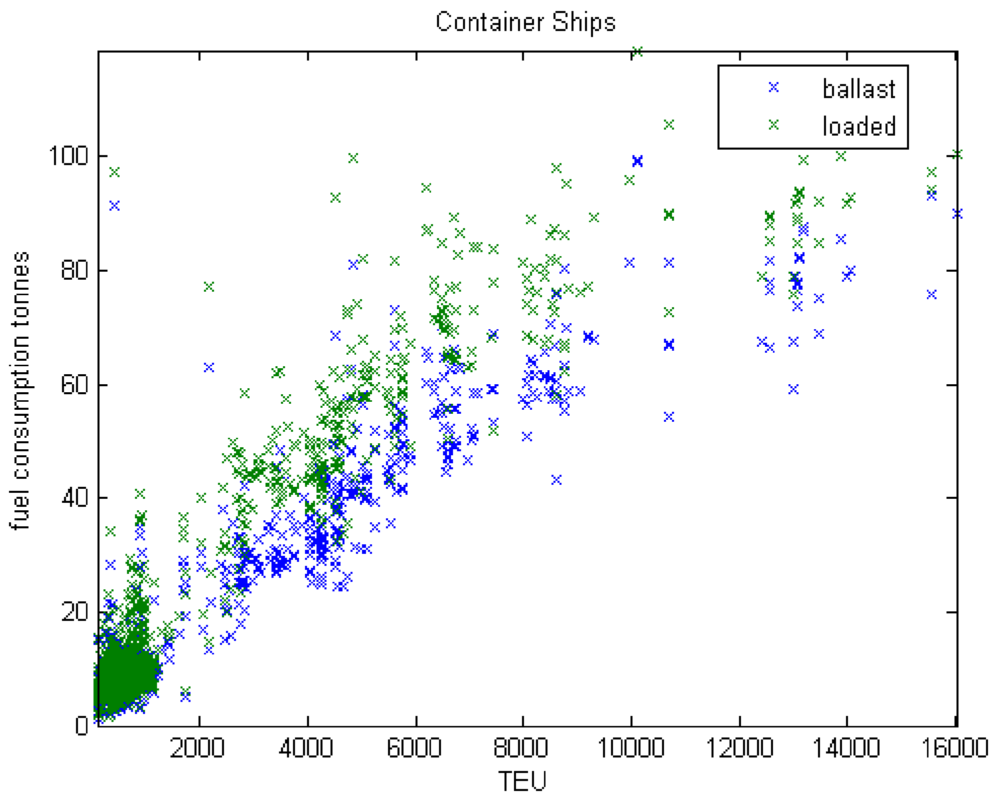

Figure 29: Average daily fuel consumption for all loaded and ballast days, container ships

2.6. CAPACITY UTILISATION AND TRANSPORT WORK

There are two key components to capacity utilization, ratio of loaded to ballast voyages and the average payload carried when loaded. Both of these variables can be estimated, with manageable uncertainty, using the draught data reported in the AIS dataset.

The transport work is defined in Section 1, Equation 5, incorporating the deadweight capacity, capacity utilization, total days at sea and vessel speed. It is important as it forms the denominator to the calculation of operational efficiency.

As the same assumptions for total days at sea that were used in the IMO 2nd GHG Study have been applied here, and for the majority of ship types and sizes the average capacity of ships in the size range is consistent, the main explanatory variables for differences in transport work per ship are differences in speed (known with low uncertainty) and capacity utilization (known but with high uncertainty). When reviewing specific data, it is important to bear in mind the relative fleet size that has passed through the filter. In the majority of cases, the filter has in excess of 30% of the observed fleet, which is deemed statistically significant and therefore adds validity to the extrapolation of the data to the whole fleet (size and type category). In a few cases (e.g. Aframax crude oil tankers), the filtered fleet is too small to be extrapolated with high confidence.

Table 28: Capacity utilisation and transport work in the wet and dry bulk fleets

	dwt (tonnes)		capacity utilisation (%)			transport work per ship ('000,000 t.nm)		
	>=	<	IMO	calculated (filtered)	% difference	IMO	calculated (filtered)	% difference
crude oil tankers	0	10000	0.48	0.47	-2%	91	153	68%
	10000	60000	0.48	0.24	-51%	1519	352	-77%
	60000	80000	0.48	0.40	-17%	2630	2038	-22%
	80000	120000	0.48	0.37	-23%	4418	3048	-31%
	120000	200000	0.48	0.37	-23%	7024	4791	-32%
	200000	+	0.48	0.34	-29%	14197	9052	-36%
product tankers	0	5000	0.45	0.23	-48%	38	28	-26%
	5000	10000	0.45	0.31	-30%	171	104	-39%
	10000	20000	0.5	0.50	-1%	464	398	-14%
	20000	60000	0.55	0.35	-36%	1334	789	-41%
	60000	+	0.55	0.32	-41%	3491	1597	-54%
chemical tankers	0	5000	0.64	0.65	2%	72	122	69%
	5000	10000	0.64	0.74	15%	383	388	1%
	10000	20000	0.64	0.75	18%	820	896	9%
	20000	+	0.64	0.69	8%	1832	1960	7%
dry bulk carriers	0	10000	0.6	0.39	-35%	68	89	31%
	10000	35000	0.55	0.46	-16%	1269	904	-29%
	35000	60000	0.55	0.44	-20%	2243	1782	-21%
	60000	100000	0.55	0.40	-28%	3821	2562	-33%
	100000	200000	0.5	0.37	-27%	7763	5267	-32%
	200000	+	0.5	0.38	-24%	10901	9032	-17%
general cargo	0	5000	0.6	0.36	-41%	116	42	-64%
	5000	10000	0.6	0.28	-53%	294	132	-55%
	10000	+	0.6	0.65	9%	900	665	-26%

Table 28 shows that in nearly all cases, the estimated values of capacity utilization in the wet and dry bulk fleets are lower in 2011 than the values assumed in the IMO 2nd GHG study. An exception to this is the chemical tanker fleet, which sees higher utilisation (between 2 and 18% on average). In most cases, the effect of lower capacity utilization is added to by slow steaming to create a further percent reduction in transport work supplied by each ship type and size. The aggregate impact on larger wet and dry bulk ships (Panamax and above) is for 20-40% less transport work to be performed than was estimated in 2007. The 200,000+ dry bulk fleet are a slight anomaly, which can be explained by a significant increase in average ship capacity for this sector since the 2007 analysis.

There are at least three plausible explanations for the differences between the IMO (2007) and this data (2011) and given the uncertainty of the input data used in the calculation, it is worth highlighting these here:

- The current market is in a state of over capacity; therefore operators are forced to compete harder for cargos resulting in a willingness to accept a greater number of part-load cargos and/or to steam longer distances in ballast for the sake of a fixture.
- There are methodological differences; IMO 2nd GHG data was derived largely by expert judgment, which might have been subject to prejudice or bias. These calculations are made from

AIS data, but in combination with an assumption on total days at sea per annum taken from the IMO 2nd GHG study.

- The draught data used in this study may be unreliable

Consistency in the results and the reasonableness of the first two of these possible explanations suggest that they could be the case, however at this stage definitive validation has not been obtained to ensure that the explanation is not the third possibility. Further discussion of the data's reliability is found below.

Common to the previous discussions on fleet size, speed and fuel consumption, the results for the smaller ship sizes are less consistent. Whilst in some cases, this could be genuine; it is likely that the variability is also closely related to the perceived inconsistency of ship type classification between the two studies.

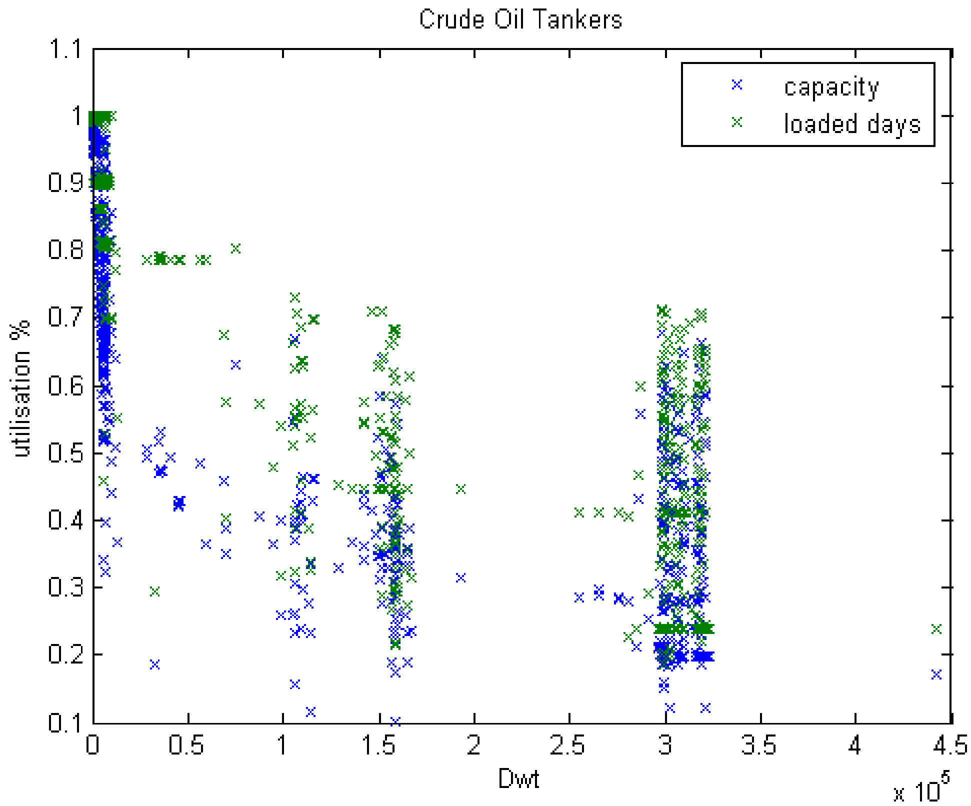

Figure 30: average capacity utilisation and ratio of loaded days to days at sea, crude oil tanker

Figure 30 shows the calculated utilization for the crude oil tanker fleet (all filtered data only). The 'loaded days' value represents the ratio of loaded days at sea to total days at sea, shown to vary for the larger (Panamax and above) between 20% and 70%. The capacity utilization is correspondingly the same or lower, because when loaded the ship is never more than 100% payload utilized and on average is shown here to be approximately 80% or less. In aggregate, these two figures contributed to the total capacity utilization figures in Table 28, which start at 40% for a Panamax ship and reduce to 34% for a VLCC. This trend of reduced capacity utilization with increase in ship size is important (because it can counter the gains in energy efficiency due to scale) and also apparent from the trend in Figure 30.

It is hard, without a validation data source, to speculate whether the heterogeneity observed in the data is genuine or a function of the uncertainty in the input data to this calculation (AIS reported draught).

Table 29: Capacity utilisation and transport work in the gas bulk fleets

	CBM (m3)		capacity utilisation			transport work per ship ('000,000 t.nm)		
	>=	<	IMO	calculated (filtered)	% difference	IMO	calculated (filtered)	% difference
LPG	0	50000	0.48	0.33	-32%	90	176	97%
	50000	+	0.48	0.33	-32%	2411	1633	-32%
LNG	0	200000	0.48	0.45	-5%	3797	3320	-13%
	200000	+	0.48	0.45	-6%	5672	4995	-12%

The data for the observed capacity utilization in the LPG and LNG fleet, Table 29, implies that there is good agreement of the calculated capacity utilization with the IMO 2nd GHG study for the LNG tankers, but that the agreement is not as good for the LPG tankers. Slow steaming contributes to a net further reduction in the annual transport work of the LNG tankers.

Figure 31 shows the distribution of capacity utilization and loaded days with ship size. There is generally a better agreement between the two than the agreement observed for the crude oil tanker fleet, which implies that the ships sail with close to 100% payload utilization.

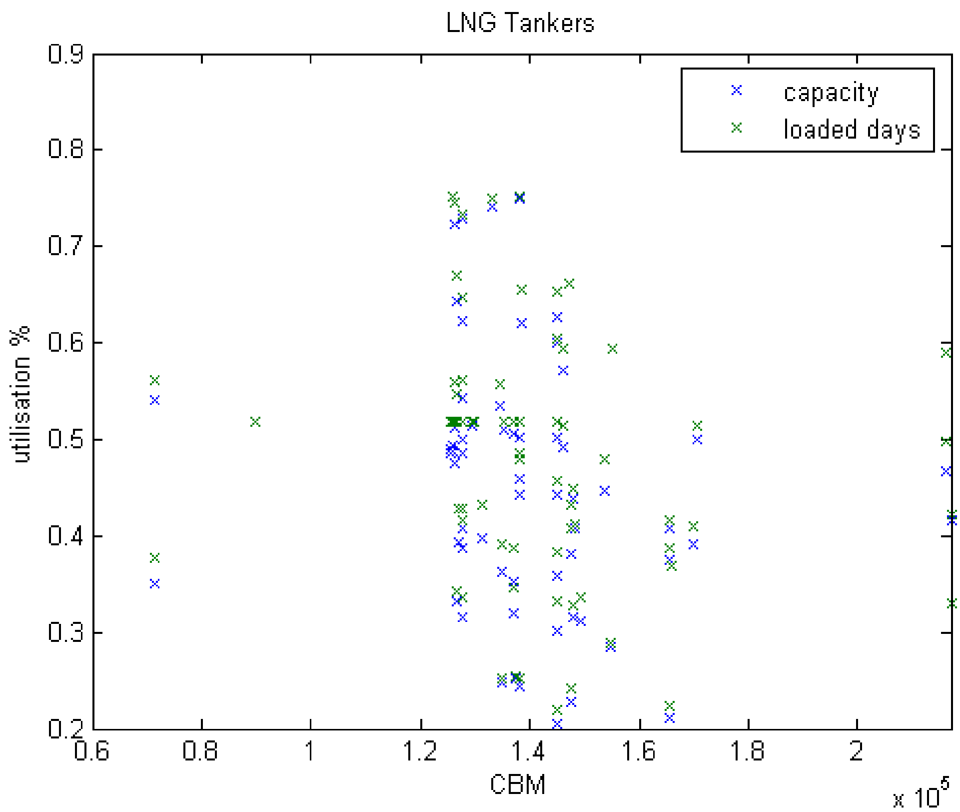

Figure 31: average capacity utilisation and ratio of loaded to ballast days, LNG tanker

Estimating utilization of the container and car carrier fleets presents the difficulty that the data used in the information (draught) can only relay the level of mass utilization and not volume utilization. A container ship could be at 100% volume utilization but if a low average weight per container, this could represent significantly less than 100% mass utilization. The IMO 2nd GHG assumed an average mass of cargo of 7 tonnes per TEU, and 1.5 tonnes per CEU. The total payload utilization (container and container cargo) was assumed to be 70% regardless of ship size, which allowing for 2 tonnes for the weight of the container itself, equates to an average of 55% deadweight utilization by cargo mass.

The container fleet, Table 30 has good coverage in the filtered dataset, and whilst it is impossible to infer the capacity utilization by volume or number of containers, it is possible to observe a consistent trend of lower utilization with increasing size of ship (as also seen for the wet and dry bulk fleets, and utilisations lower than those assumed in the IMO 2nd GHG (with the exception of the 1000-2000 TEU size range). The lower capacity utilization is supplemented by slow steaming to result in overall reductions in transport work per ship (after correcting to align with the IMO 2nd GHG assumption of 7 tonnes of cargo per container) which amount to a 20 to 60% reduction relative to IMO 2nd GHG data. The CEU to dwt and TEU to dwt ratios of each ship are used to calculate how the payload utilization in mass converts into TEU capacity utilisation, an assumption that is likely to be conservative (in estimating the actual transport work), but appropriate given the absence of more detailed data.

The car carrier fleet shows an increase in utilization (relative to IMO 2nd GHG Study) for the smallest size category and a decrease for the larger and corresponding differences in the estimate of total transport work done.

Table 30: Capacity utilisation and transport work in the container ship and car carrier fleets

	TEU equiv		capacity utilisation			transport work per ship ('000,000 t.nm)		
	>=	<	IMO	calculated (filtered)	% difference	IMO	calculated (filtered)	% difference
container ships	0	1000	0.7	0.44	-37%	180	135	-25%
	1000	2000	0.7	0.70	0%	578	708	22%
	2000	3000	0.7	0.64	-9%	1480	1163	-21%
	3000	5000	0.7	0.53	-25%	2820	1622	-42%
	5000	8000	0.7	0.48	-32%	4233	2218	-48%
	8000	+	0.7	0.36	-48%	6968	2829	-59%
pure car carriers	0	4000	0.7	0.89	27%	227	224	-1%
	4000	+	0.7	0.57	-19%	733	428	-42%

2.7. FLEET ENERGY EFFICIENCY DATA AND COMPARISON WITH IMO 2ND GHG STUDY

Operational energy efficiency is found by dividing the total carbon produced by the total transport work done (see Section 1). Therefore, the observations and explanations for each of these parameters (and their components, e.g. ship speed) above can now be used to understand discrepancies in operational efficiency calculated using the methods and data defined in Section 1 and those published in the IMO 2nd GHG (referred to as overall efficiency). For container ships and car carriers, a correction is applied such that the denominator in the calculations represents the IMO 2nd GHG assumption of 7 tonnes and 1.5 tonnes per TEU or CEU respectively to ensure consistency of comparison.

The technical efficiency is also shown, however before attributing any improvement to 4 year's technology development, there are important methodological differences, which need to be taken into consideration. The IMO 2nd GHG Study does not give a full description of the method used to calculate loaded efficiency, however it does state that the engine load is assumed to be 85% MCR, an operating output on average higher than the assumption applied in this study which is based on the assumed MCR design point of each ship type (see Annex 1, but also taken from the IMO 2nd GHG).

For operational efficiency, both the operational efficiency (calculated for the filtered dataset only) and the normalized operational efficiency (all data) are shown. For both calculations, the numerator is the same (the sum of CO_2 emissions produced annually from the main engine, auxiliary engine and boiler). For operational efficiency, the denominator is the transport work calculated using capacity utilization based on AIS observations of draught, whereas for normalized operational efficiency the IMO 2nd GHG assumption on capacity utilization is applied.

When comparing operational efficiency calculated in this method and the IMO 2nd GHG Study, it is important to bear in mind that discrepancies can arise because of methodological and data differences as well as because of changes in operation and technology that have occurred over the last 4 years.

Table 31: Technical and operational efficiency in the wet and dry bulk fleets

	dwt (tonnes)		technical efficiency $gCO_2/t.nm$		operational efficiency $gCO_2/t.nm$		
	>=	<	IMO	calculated	IMO	calculated OE, filtered	calculated NOE
crude oil tankers	0	10000	38.3	21.7	61.7	53.0	64.2
	10000	60000	9.6	7.4	16.9	32.2	18.9
	60000	80000	8.0	4.8	13.9	16.9	19.5
	80000	120000	5.6	3.8	10.9	12.8	10.8
	120000	200000	4.1	3.4	8.1	8.5	6.0
	200000	+	3.0	2.3	5.4	6.4	4.3
product tankers	0	5000	49.1	26.9	83.3	135.9	54.9
	5000	10000	27.4	16.9	54.1	66.4	52.6
	10000	20000	20.9	11.2	34.6	38.5	44.0
	20000	60000	13.3	5.7	19.1	24.8	19.5
	60000	+	6.1	4.4	10.6	16.9	13.0
chemical tankers	0	5000	34.4	20.7	41.1	24.9	26.1
	5000	10000	19.8	16.6	28.0	21.5	25.0
	10000	20000	13.5	11.7	20.0	15.4	16.5
	20000	+	10.6	8.4	15.6	12.0	12.3
dry bulk carriers	0	10000	42.4	19.6	54.1	44.3	19.3
	10000	35000	9.8	7.4	14.6	15.8	11.8
	35000	60000	7.0	5.2	10.6	10.8	8.0
	60000	100000	5.0	4.0	7.6	9.2	6.1
	100000	200000	3.3	2.7	5.6	6.6	4.5
	200000	+	2.8	2.3	4.6	5.2	4.0
general cargo	0	5000	21.2	20.7	27.0	49.4	21.9
	5000	10000	21.6	15.9	30.6	45.0	19.5
	10000	+	15.3	11.4	21.0	15.7	17.4

Table 31 lists the efficiency figures calculated for the wet and dry bulk fleets. Technical efficiency is also plotted in Figure 32 for crude oil tankers and Figure 36 for general cargo ships. Plotted on a log-log scale, the crude oil tankers show a clear linear trend with good correlation coefficient implying that within each size range there is relative consistency in specification and that economies of scale are being capitalized on in design.

For crude tankers, there are only a few data points that pass through the filter for the handy and Panamax fleets so this should be considered when considering the operational efficiency calculations and contrasting with normalized operational efficiency. Figure 33 provides further explanation for the tabular data, which demonstrates that the main explanatory variable for the differences between operational and normalized operational efficiency is the capacity utilization. For the 0-10,000 dwt crude oil tanker range, the higher than IMO capacity utilization estimate results in improvements relative to the normalized operational efficiency, whereas the lower capacity utilization calculated for the larger ships explains their comparatively poorer estimated operational efficiency. The high levels of heterogeneity for both operational and normalized operational efficiency can be attributed predominantly to the fleet's heterogeneity in speed, as the similarity in range (for a given ship size) between normalized and operational efficiency implies that the assumptions on capacity utilization are not having a dominant affect on the heterogeneity.

For Aframax, Suezmax and VLCC, the average operational and normalized efficiency lie either side of the IMO estimate of operational efficiency (e.g. +/- 20% in the case of the VLCC fleet), implying that despite the advent of slow steaming, the net benefit in terms of energy efficiency gain could be small.

Product tankers (Figure 35) and dry bulk carriers (Figure 36) show a similar trend in operational efficiency with size. The step changes in the IMO 2nd GHG Study capacity utilization between size ranges are clearly visible in the product tanker normalized operational efficiency calculations. The product tanker operational efficiency shows a consistent trend, adding credibility to the calculated capacity utilization.

Generally, product tankers appear to have worse operational efficiency (under both the operational and normalized operational efficiency calculations) than the IMO 2nd GHG Study estimate, whereas chemical tankers are consistently more efficiency (both calculations) that the IMO 2nd GHG Study estimates. As has already been suggested, these observations could be subject to inconsistencies in the classification of ship types between the studies.

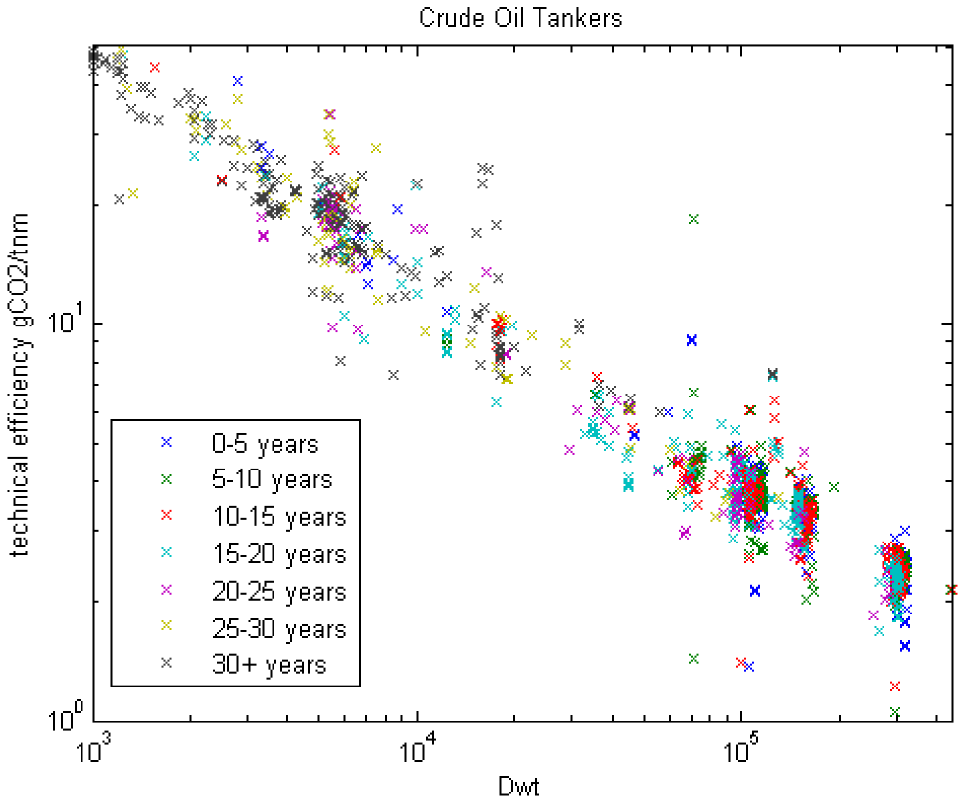

Figure 32: technical efficiency in the crude oil tanker fleet

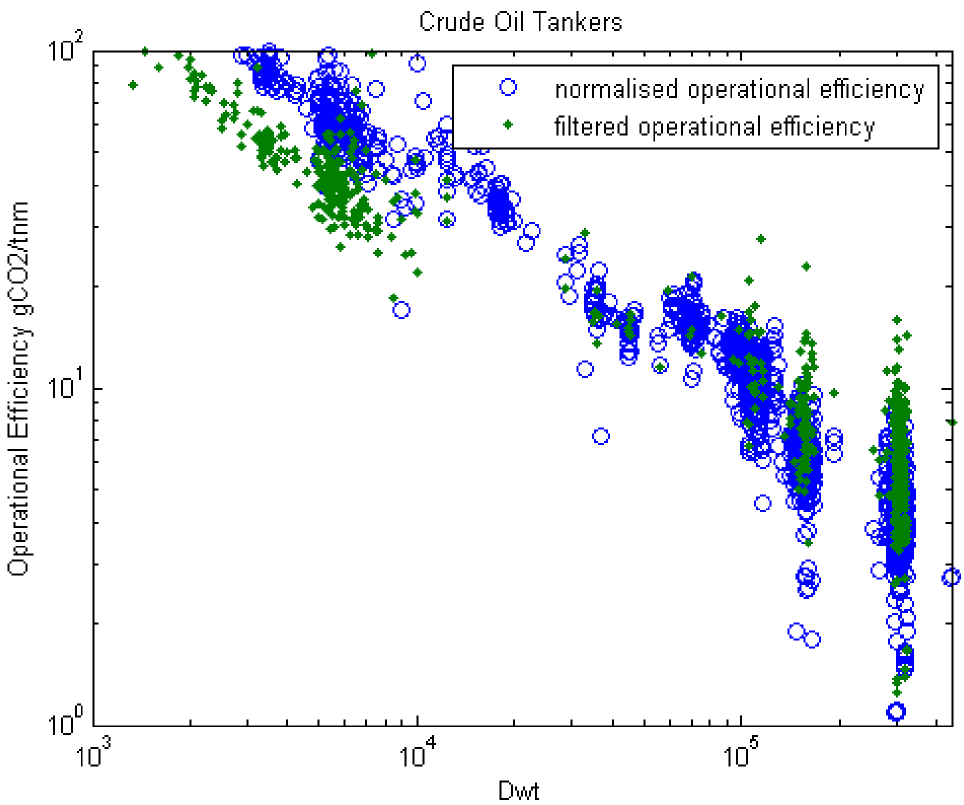

Figure 33: operational efficiency in the crude oil tanker fleet

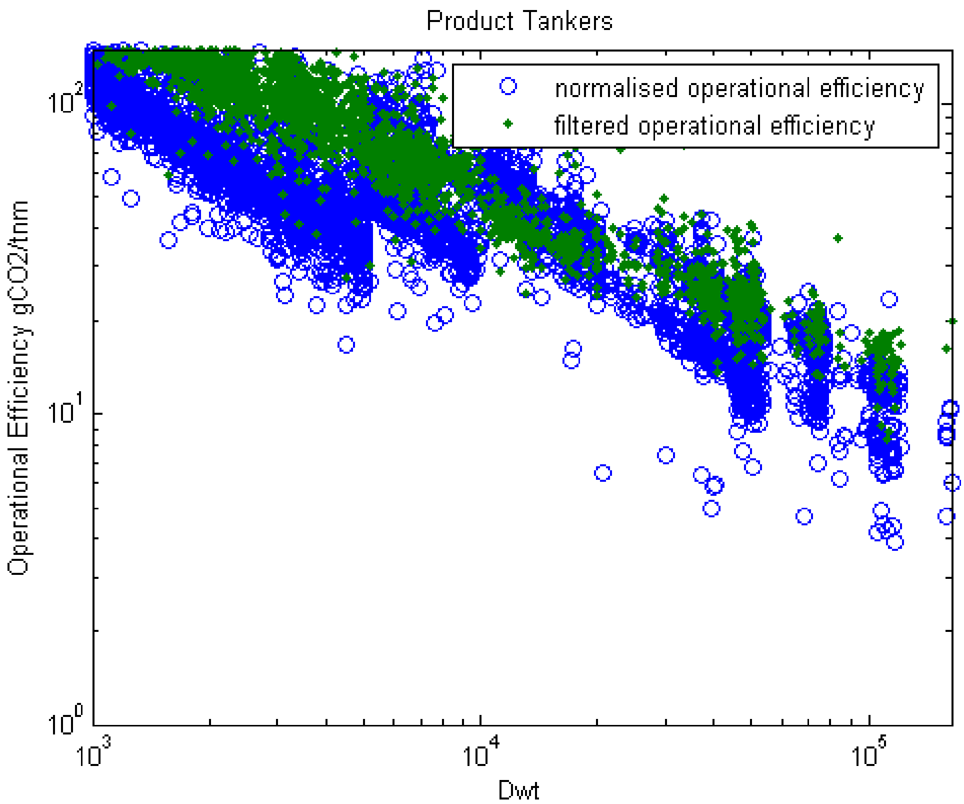

Figure 34: operational efficiency in the product tanker fleet

For dry bulk carriers, all but the smallest ship size show the same behaviour as the crude oil tanker fleet – normalized operational efficiencies are slightly higher than those estimated in the IMO 2nd GHG Study, whereas taking into account the draught derived capacity utilization leads to operational efficiencies which are slightly lower than those observed in the IMO 2nd GHG Study.

The General cargo fleet, Figure 36 and Figure 37, show some interesting behaviour. The fleet's technical efficiency appears significantly less tightly grouped (for ship size) than the other bulk fleets (possibly because of the limited dwt range of the fleet). There is also a step change in technical efficiency observable around 5,000 dwt tonnes. This also coincides with an increased presence in the fleet of general cargo ships that have the ability to mix bulk with unitized cargos (a separate category in the IMO 2nd GHG Study, but aggregated into the same categories in this report). The TEU carrying general cargo fleet typically has a higher design speed than the non-TEU carrying fleet, which appears consistent with this observation of the difference in the technical efficiency. The difference becomes even more pronounced in Figure 37, where the operational efficiency shows a clear negative trend with scale (reducing efficiency with ship size), in the 5-10,000 dwt range. The combined effects here are likely to be the increased operational speed of the TEU carrying fleet, and the lower mass capacity utilization (driven by limits on the volumetric or TEU capacity).

In the size range 0-10,000 dwt, the operational efficiency of general cargo ships is calculated to be lower than the IMO 2nd GHG study estimate, whereas the normalized operational efficiency is higher.

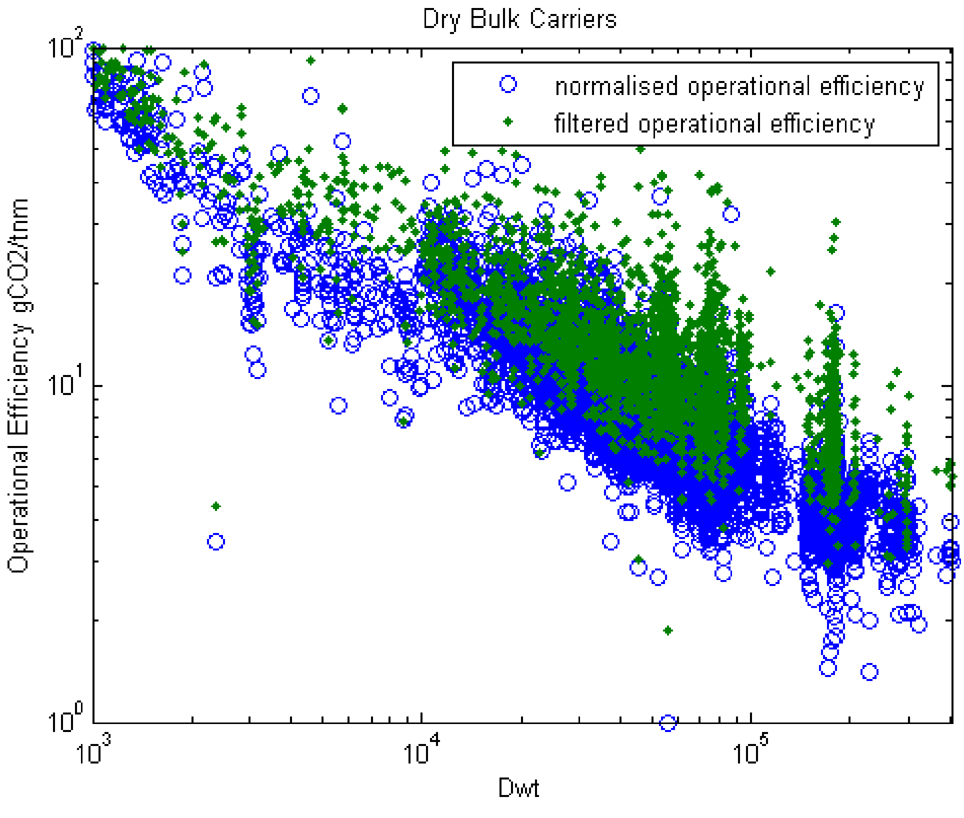

Figure 35: operational efficiency in the dry bulk fleet

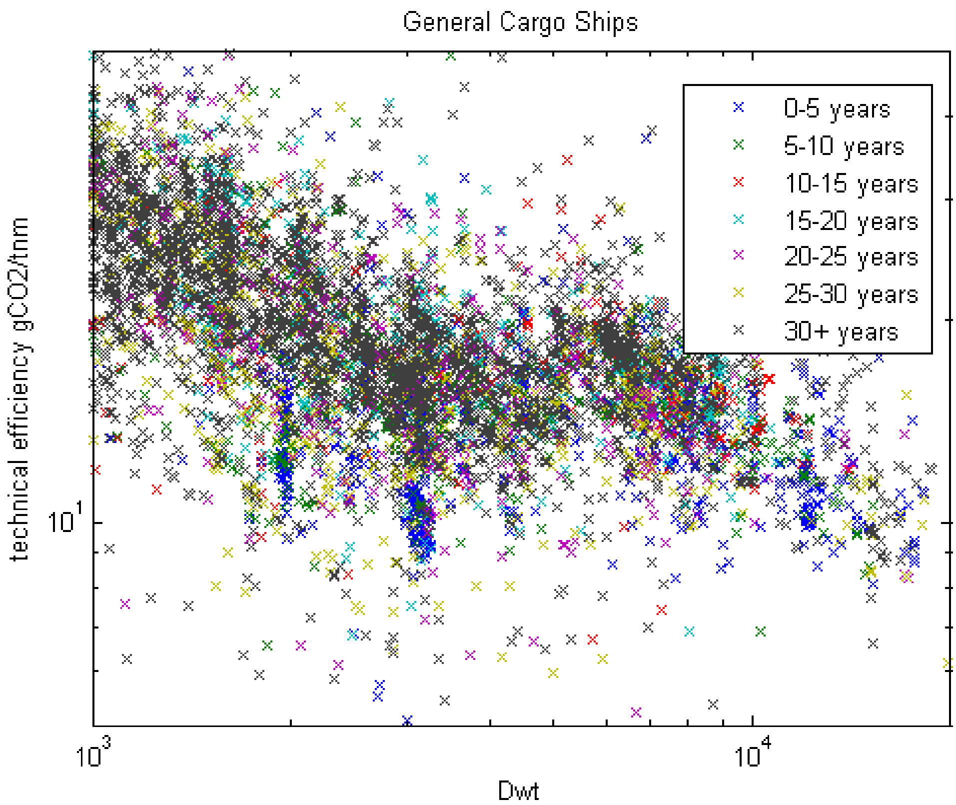

Figure 36: technical efficiency in the general cargo fleet

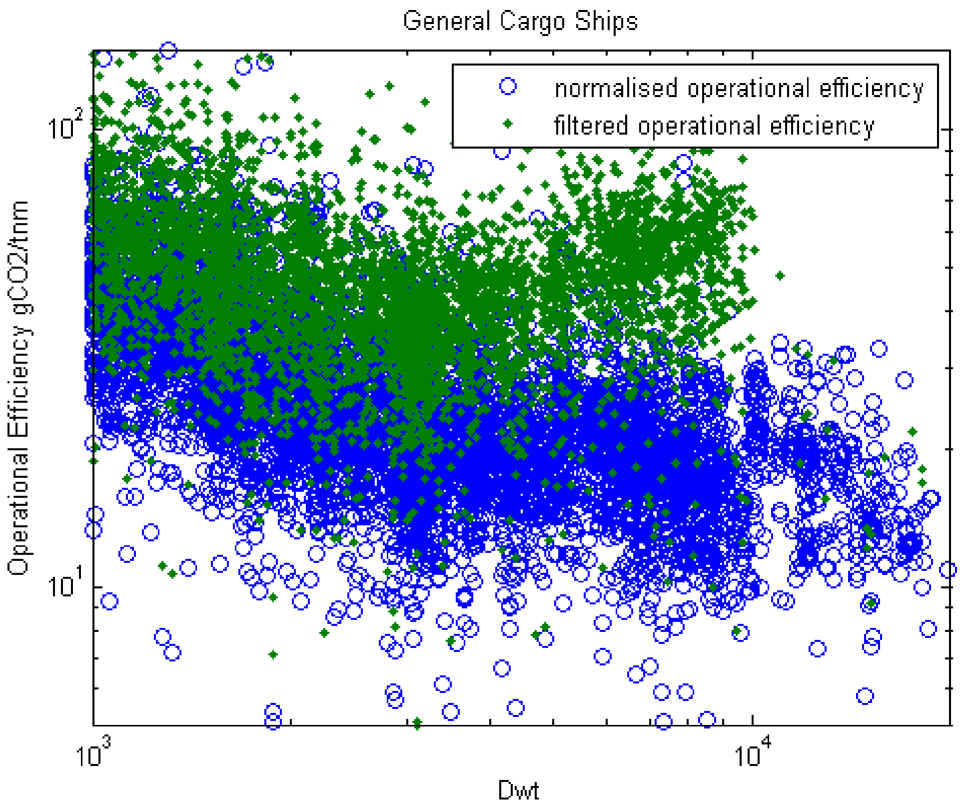

Figure 37: operational efficiency in the general cargo fleet

Table 32 lists the technical and operational efficiency as calculated for the LPG and LNG fleet. The operational efficiency of the LPG fleet differs in their agreement with the 2nd IMO GHG Study depending on the size range. The larger LPG ships show some agreement, with the lower capacity utilization applied in the operational efficiency resulting in a poorer efficiency compared to the IMO 2nd GHG. The smaller category of LPG ships shows only poor agreement (consistent with poor agreement found for the component parameters e.g. transport work).

The LNG fleet's operational efficiency is close to the values estimated in the IMO 2nd GHG Study, this is because the fuel savings due to slow steaming are being counteracted by the estimated reduction in transport work per ship. In the normalized operational efficiency calculation, the transport work remains high and so the values show a marked improvement relative to the IMO 2nd GHG Study.

Table 32: Technical and operational efficiency in the gas bulk fleets

	CBM (m3)		technical efficiency gCO_2/t.nm		operational efficiency gCO_2/t.nm		
	>=	<	IMO	calculated	IMO	calculated OE, filtered	calculated NOE
LPG	0	50000	50.0	16.5	80.6	63.4	33.3
	50000	+	9.6	6.4	16.7	22.4	12.8
LNG	0	200000	15.6	10.9	26.9	27.0	20.5
	200000	+	10.0	6.3	17.2	15.7	12.7

Figure 38 and Figure 39 show the technical and operational efficiency of the LNG tanker fleet. A clear distinction between ship size and age can be seen for LNG tankers in Figure 38, along with the superior technical efficiency of the Q-Flex and Q-Max ships. The operational and normalized operational efficiency show similar spread, which, just as in the case of wet and dry bulk, implies that the largest contributor to the heterogeneity of the operational efficiency is the speed of operation and not the capacity utilization.

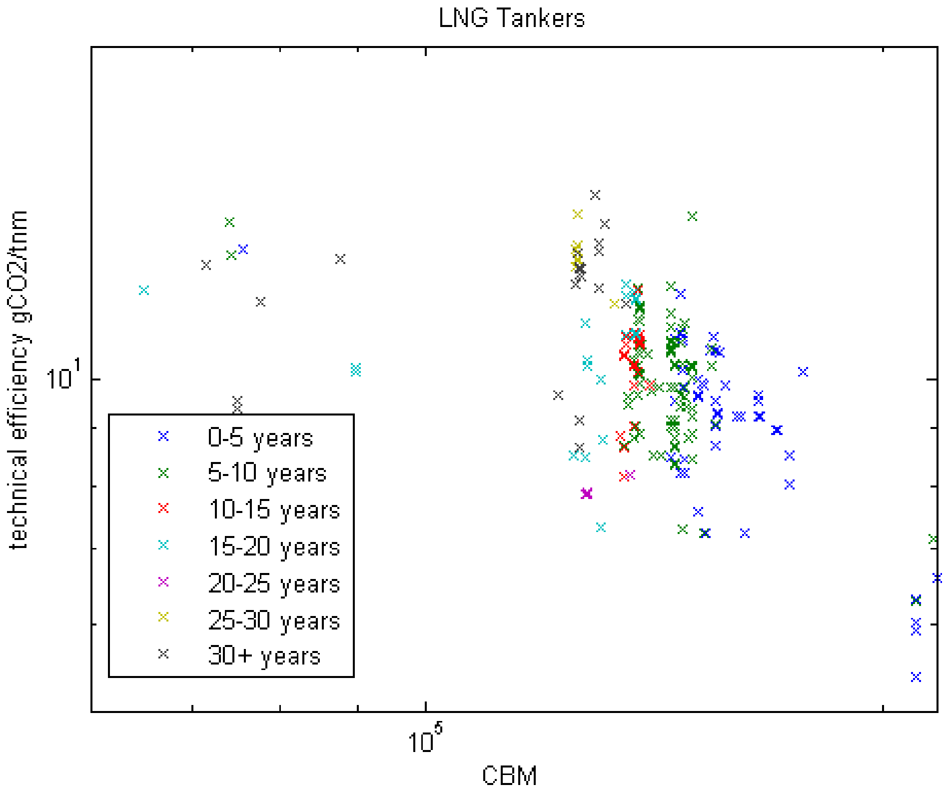

Figure 38: technical efficiency in the LNG tanker fleet

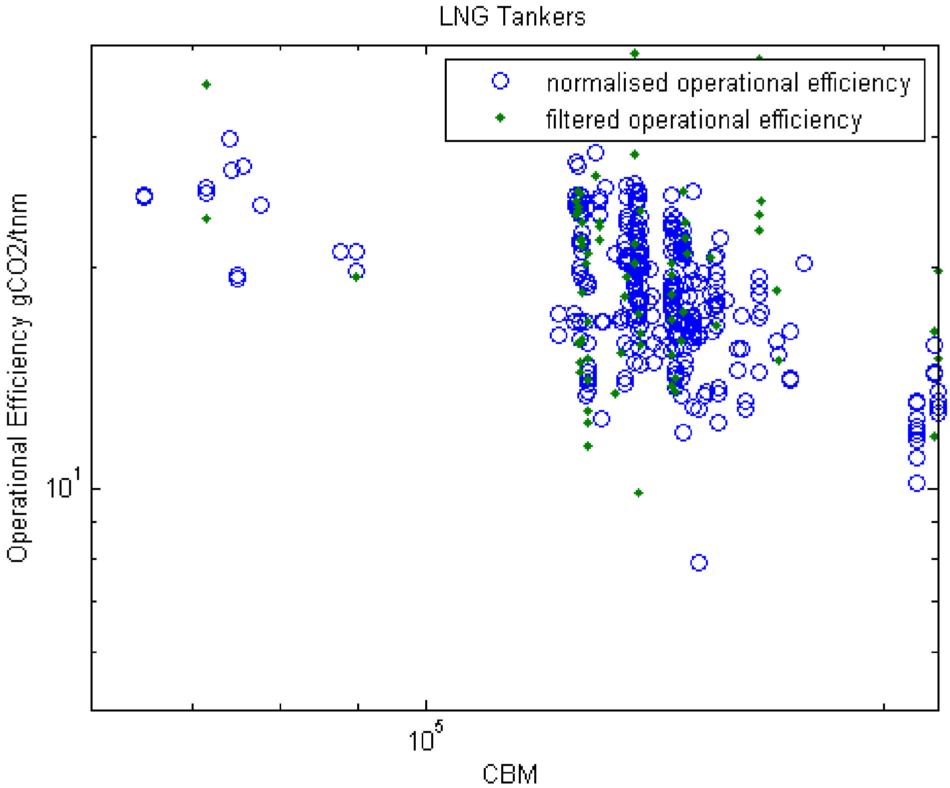

Figure 39: operational efficiency in the LNG tanker fleet

Table 33 lists the technical and operational efficiency of the container ship and car carrier fleets. For both technical and operational efficiency calculations, the transport work is corrected to be consistent with the IMO 2nd GHG Study assumption of 7 and 1.5 tonnes of cargo per TEU and CEU respectively. The container ship fleet showed the greatest uptake of slow steaming and this corresponded to a significant reduction of main engine fuel consumption (around 50% for the larger ship sizes, 3000 TEU and up). However, incorporating the AIS observed capacity utilization, the estimated operational efficiency does not show that fuel consumption benefit translating into a gain in efficiency, indeed in the 8000 + TEU category sector the operational efficiency is on average worse than the IMO 2nd GHG Study operational efficiency, in spite of s significant increase in the average ship size of this category. This trend is reversed for the smaller container ships with 1000-3000 TEU ships showing significant improvements relative to the IMO 2nd GHG Study assumption.

If the normalized energy efficiency values are adopted (with their higher capacity utilization), benefits are observed in the operational efficiency for all ship sizes, relative to the IMO 2nd GHG calculations.

For the car carrier fleet, both the operational and the normalized operational energy efficiency show substantial improvement relative to the 2nd IMO GHG Study calculations.

Table 33: Technical and operational efficiency in the container ship and car carrier fleets

	TEU equiv		technical efficiency gCO_2/t.nm		operational efficiency gCO_2/t.nm		
	>=	<	IMO	calculated	IMO	calculated OE, filtered	calculated NOE
container ships	0	1000	61.7	34.2	67.2	66.4	38.2
	1000	2000	54.4	25.8	59.4	31.7	30.6
	2000	3000	33.9	22.2	37.0	27.2	24.0
	3000	5000	28.2	20.7	30.7	29.1	21.5
	5000	8000	28.2	21.0	30.7	31.4	20.6
	8000	+	20.6	16.2	23.2	28.8	16.1
pure car carriers	0	4000	87.4	57.2	106.7	67.7	77.3
	4000	+	46.7	30.7	59.3	48.4	36.4

Figure 40, Figure 41 and Figure 42 show the variation in the technical and operational efficiency between individual ships and also size and age categories. Similar to the general cargo fleet, the container shipping fleet shows a significant level of heterogeneity in its technical energy efficiency and a move away from a linear trend at 3000 TEU capacity, which is consistent with the adoption of increased ship design speeds for the larger ships. That increase in ship design speeds erodes the energy efficiency benefit achieved through scale.

Figure 41 also shows an interesting trend with age. Within most of the size categories, the technical efficiency of container ships has got worse (higher) with time (a trend not observed in the wet and dry bulk fleets). Only for ships built in the last (0-5 years) is the trend starting to reverse. A possible explanation for this is the trend for higher speed services, which has incentivized newbuilds to exceed the design speeds of the ships they are built to supersede.

Figure 42 shows the operational efficiency trend with ship size, which also captures the step in the technical efficiency, trend in ship size around 3000 TEU. The discrepancy between the normalized and operational efficiency is apparent and explains the significant difference in the tabular results for fleet averages, depending on the calculation method used.

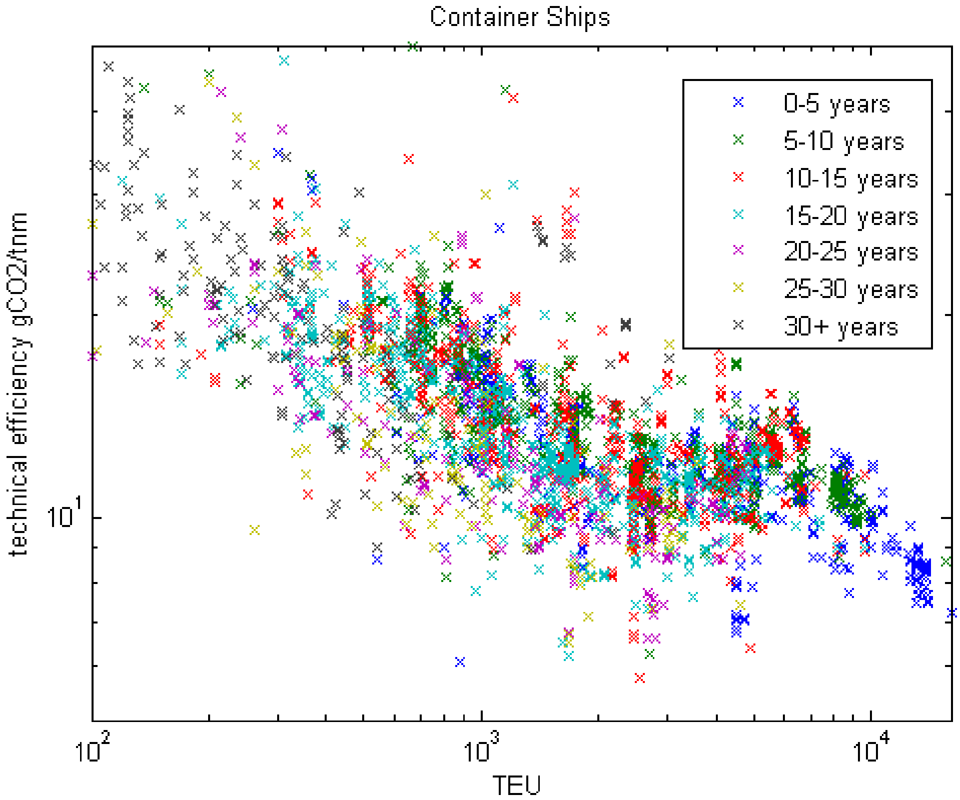

Figure 40: technical efficiency in the container ship fleet

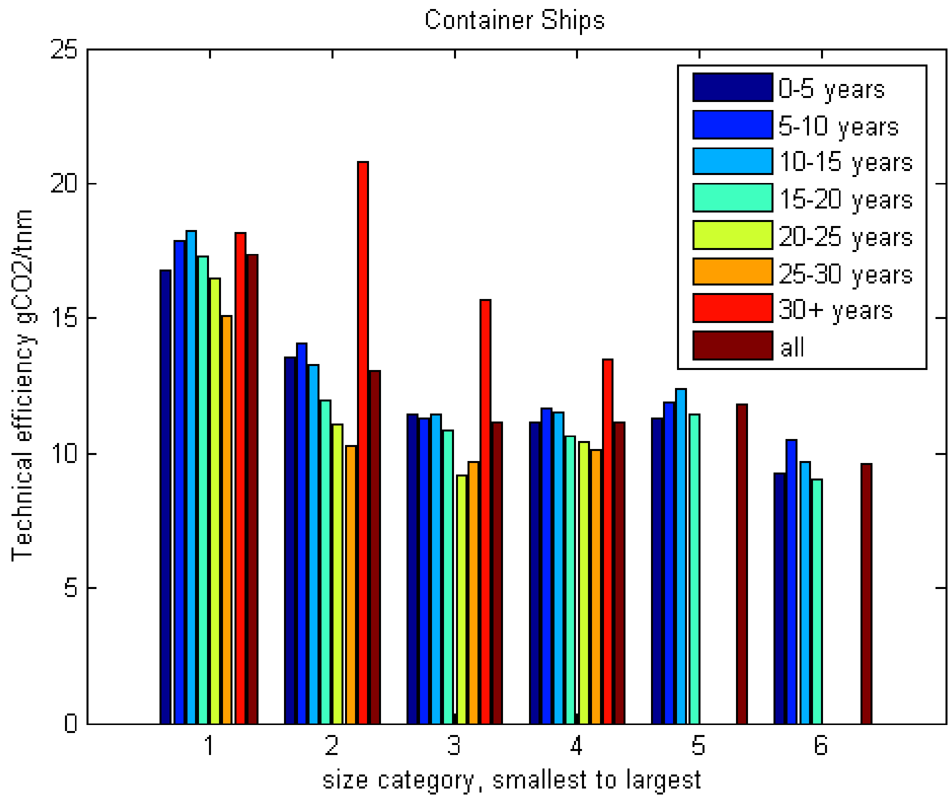

Figure 41: technical efficiency in the container ship fleet by size and age category

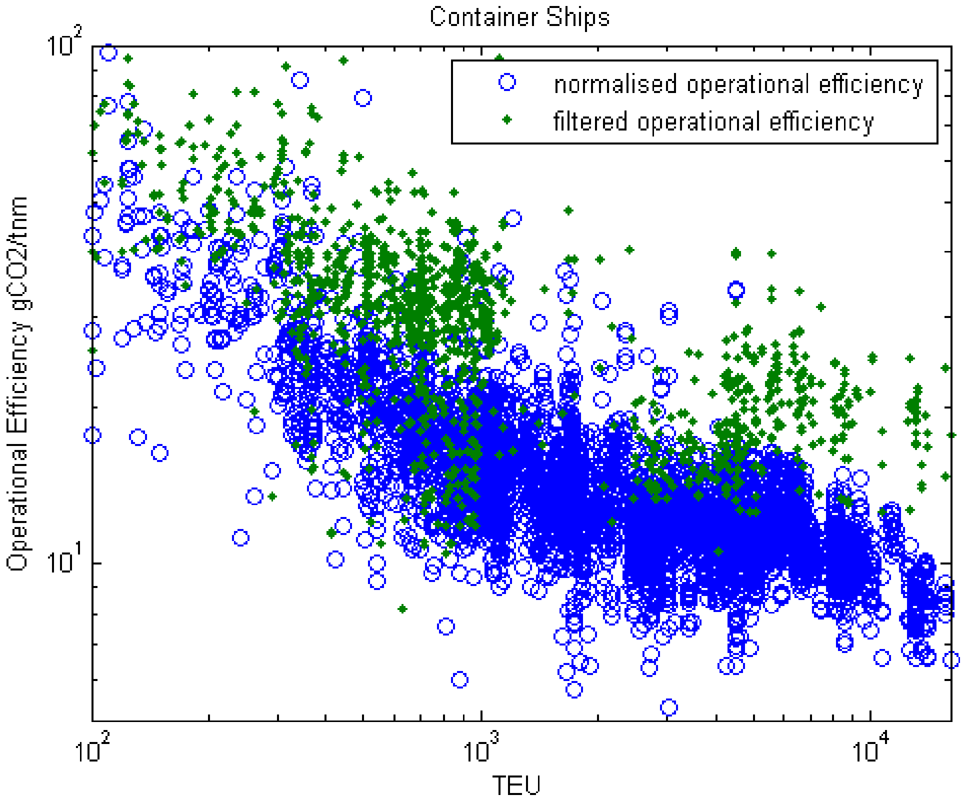

Figure 42: operational efficiency in the container ship fleet

2.8. SHIPPING ROUTES AND ENERGY EFFICIENCY

Using the method detailed in Section 1.4.4, the average energy efficiency of the fleet serving different regions can be estimated. Complete results are located in Annex 5. In nearly all cases, the North East Asia data field shows no ship movement, a feature that is possibly specific to the use of S-AIS data. This therefore appears as an anomalous void in most of the plots.

One example, Figure 43, displays the (filtered) operational efficiency of the dry bulk fleet. Most routes have an average above 10 gCO_2/t.nm except for those dominated by the iron ore trade, such as the Australia and Brazil to China routes. In these cases, vessel efficiencies are on average better, due to the typical use of larger vessels in these, cases the values average approx. 6 gCO_2/t.nm. Conversely, the shorter routes, particularly those dominated by smaller cargoes like grains and other agricultural goods, e.g. the USA to Canada route, the vessel efficiency reduces to reach up to 12gCO_2/t.nm.

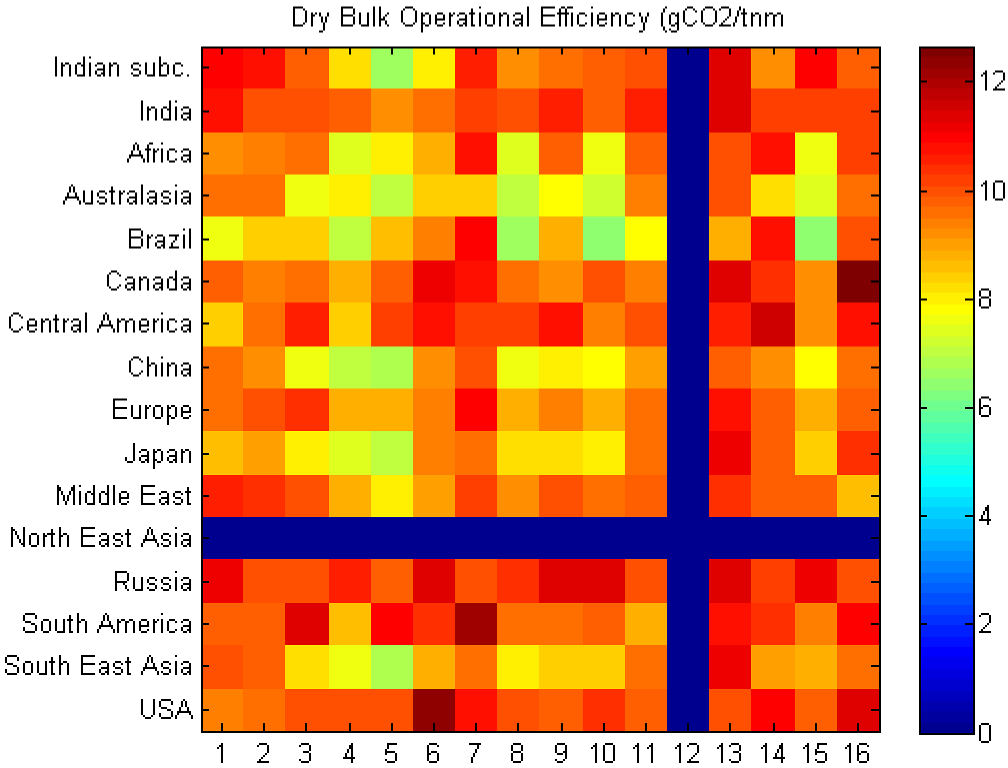

Figure 43: Route operational vessel efficiency for dry bulk, weighted by dwt on route. The numbering on the x-axis corresponds to region names on the vertical axis in top to bottom order. Zero values are on routes where no vessels have been recorded.

2.9. UNCERTAINTY

No calculation can be performed with 100% certainty, however every calculation should be performed with some estimate of the certainty or 'degree of confidence' with which the answer is known. Section 1 discussed qualitatively the level of reliability of the data used; this section will attempt to quantify the significance of this for an individual ship's calculation.

It should be noted that there are two key, different, types of uncertainty in this study: aleatory e.g. the uncertainty of randomness in the sample and epistemic e.g. uncertainty due to a lack of knowledge. For example, the main engine %MCR in the design condition could feature significant aleatory uncertainty. The consequence might be that there is a high variability between specific ships (even within the same size and type category), but that this variability 'averages' out so that a mean value can be applied to undertake meaningful aggregate analysis. This contrasts with epistemic uncertainty. Due to lack of knowledge of the specifics of coatings on different ships (and the many other parameters which are influential in the fouling growth on a ship e.g. time between dry docking, periodicity of maintenance) we have high epistemic uncertainty in the quantification of the condition impact parameter. The extent to which this results in an 'averaging' out in the results to some value appropriate for aggregate analysis is currently unable to be quantified.

In order to illustrate the significance of uncertainty, illustrative estimates of the uncertainty of individual parameters are listed below and deployed to calculate the combined compound worst case uncertainty, both for the technical, operational and normalized operational energy efficiency of an individual ship. The values are produced using expert judgment gained through the analysis of the input data used in this report. They are therefore not definitive nor can they be attributed confidence levels, however they can produce qualitative insights into the calculations produced in this report. It is not unreasonable to describe the uncertainty itself as uncertain, partly because this is one of the first attempts to deploy the source data for this purpose. In the IMO 2nd GHG study, the uncertainty of the different parameters is described qualitatively but no quantification is supplied, nor is there an estimate of the consequence of compounding the component parameter's uncertainty together in the formulation of the technical and overall efficiency. Therefore this study, and the detail available in the data that is used, has enabled a progression of the understanding of uncertainty, even if further work remains.

2.9.1. UNCERTAINTY IN AN INDIVIDUAL SHIP'S TECHNICAL EFFICIENCY ESTIMATE

Of the parameters applied in the technical efficiency calculation, the following are believed to have the highest uncertainty (an estimate of which is given in brackets) are:

- Main engine %MCR in the design condition at design speed, taken as the central assumption in the IMO 2nd GHG Study (10% on main engine fuel consumption, 9% on TE)
- Main engine sfc, taken from Clarksons World Fleet Register if available otherwise applies a default value (3% on main engine fuel consumption, 2.7% on TE)
- Capacity, taken from Clarksons World Fleet Register (5%, 5% on TE)
- Auxiliary engine %MCR in the design condition, taken as the central assumption in the IMO 2nd GHG Study (20% on auxiliary engine fuel consumption, 2% on TE)

As the main engine accounts for approximately 90% of the CO_2 emissions incorporated in the energy efficiency, the worst-case combination of these uncertainties is a total technical efficiency uncertainty of a given ship of approximately 20% (either side of the central value calculated using the data and method described in Section 1).

Taking the Suezmax crude oil tanker fleet as an example, e.g. a ship with the central value of 3.4 gCO_2/t.nm, applying this uncertainty creates an upper bound of the ship's technical efficiency of 4.1 gCO_2/t.nm and a lower bound value of 2.8 gCO_2/t.nm. The same range of values encompasses at least 80% of the world fleet (estimated from Figure 35). That is to say that the uncertainty of the technical efficiency of an individual ship is of a similar order to the variability observed naturally between ship specifications.

2.9.2. UNCERTAINTY IN AN INDIVIDUAL SHIP'S OPERATIONAL AND NORMALISED OPERATIONAL EFFICIENCY ESTIMATE

The following parameters are estimated to be of greatest uncertainty in the calculation of operational efficiency:

- Ship speed, taken from AIS but uncorrected for speed through water which will be subject to currents (5% over a year, 13.5% on OE)
- Loading condition, taken from AIS reported draught (30%, 30% on OE)
- Impact of hull fouling (50% on fouling, 4% on OE)
- Impact of wind and waves (30% on weather, 4% on OE)
- Aux engine %MCR, taken as the central assumption in the IMO GHG study (20% on aux fuel consumption, 2% on OE)
- Main engine sfc, taken from Clarksons World Fleet Register if available otherwise applies a default value (6% - allowing for uncertainty in wear, 5.5% on OE)

Excluding the loading condition uncertainty produces an overall worst case compound uncertainty of just over 30% which can be thought of as the uncertainty associated with the calculation of an individual ship's normalized operational efficiency. The loading condition uncertainty is hard to estimate so the 30% is only intended to be indicative of the magnitude of the uncertainty, although it seems credible (e.g. for a tanker believed to have a central estimate of capacity utilization of 50%, a 30% uncertainty on this would encompass capacity utilization of between 38% and 65%). Including the effect of loading condition uncertainty leads to a worst-case compound uncertainty for operational efficiency of an individual ship totalling 85%.

2.9.3. IMPLICATIONS OF INDIVIDUAL SHIP'S ESTIMATED UNCERTAINTY TO THE STUDY OF FLEET AGGREGATE STATISTICS

Using the above data and approach, the uncertainty associated with quantifications of technical, operational and normalized operational efficiency of any individual ship is 20%, 85% and 30% respectively (assuming that the central estimate of the capacity utilization used in the normalized operational efficiency has no uncertainty). It would be highly unlikely that errors occur in practice to compound the worst case uncertainty of every single parameter (e.g. all parameters are an extreme over-estimate or under-estimate), therefore the values calculated here are upper bound estimates on the compound uncertainty and in practice a meaningful uncertainty (e.g. corresponding to +/- 2 standard deviations could be significantly lower than these estimates).

Those magnitudes of uncertainty, and the significance of that magnitude relative to the variability observed in each of the technical, operational and normalized efficiency fleet statistics (due to variations in ship technical and operational parameters), shows that there is a large amount of further work needed before the input data sources used in this report (e.g. Clarksons World Fleet Register and S-AIS) can be used to more definitively quantify the relative efficiency of one ship versus another.

However, as the applications of the data and analysis in this report are focused on understanding the characteristics of aggregates of the fleet (type, size, age), and the production of aggregate statistics, the limitations of the data for understanding an individual ship's efficiency are less important. The fleet sizes, even when broken down into an individual type, size and age category, are in general believed to be large enough that at least the parameters with aleatory uncertainty will average out to allow conclusions to be drawn with confidence.

3. SHIP EFFICIENCY AND PRICES

The results presented in Section 2 show a significant degree of heterogeneity in many sectors of the industry (specific ship types and sizes). That is to say that the market contains ships deployed broadly for the same purpose, but with wide variations in both technical and operational energy efficiency. Particularly relevant to this, is the data describing trends in technical efficiency for ships of different ages (Figure 32, Figure 36, Figure 38, Figure 40 and Figure 41). Despite ships being ordered over a period of thirty years during which the oil price has risen significantly (albeit with relatively little discussion or regulation until more recent years on the importance of reductions in GHG emissions), the technical efficiency of many of the ship types (of a given size range) appears to be relatively constant both in terms of mean value and standard deviation.

The fuel costs associated with the operation of shipping, whilst varying in their proportion of overall costs between ship types and sizes, are consistently of high significance, and so it is reasonable to expect that the shipping markets might place some premium (in terms of price) on energy efficiency. However, there are also reasons why this might not be the case: there might be market barriers or failures (as has been suggested in other studies, CE Delft 2009, IMarEST, 2011). One example of a market barrier is if information deficiencies exist where the customer purchasing a ship or a shipping service (e.g. charter) might not have information of sufficient quality or trustworthiness with which to differentiate between two products. However, it could equally be the case that customers might be making decisions based on a variety of preferences (speed of service, reliability) in addition to energy efficiency, where these other preferences regularly outweigh any differentiation between two products based on energy efficiency alone.

The key question relevant to the discussion in the Introduction about the market behaviour and the need (or lack of need) for regulation that this section will answer is: do more energy efficient ships command higher prices? If the answer is no, then this provides good justification for Section 2's observed heterogeneity in energy efficiency – e.g. without a strong price signal there is no incentive to justify the investment in energy efficient ship specifications or to operate at maximum energy efficiency. If the answer is yes, then this implies that there are likely to be other drivers for the trends and scatter in the results observed in Section 2.

Section 2 presented results both for technical and operational efficiency, both showing a degree of heterogeneity. In addition to information about price, to further breakdown the drivers of the observed differences in operational efficiency between ships, information would be required on the nature of the cargos being transported, their origin and destination, the agents owning, managing and operating the ships and the charter-parties used as governing contracts between the agents. This is because all of these parameters are important to operational parameters such as speed, which have been shown in the data to be of such high significance to the differences in operational energy efficiency between ships. This level of detail is highly commercially sensitive and currently unavailable in the public domain datasets that are the primary sources of information in this study. So this Section will focus on understanding the relationship between technical efficiency and the different markets in the shipping industry (without addressing relationships between operational efficiency and prices). Questions that will be investigated include: is technical energy efficiency reflected in newbuild prices, second hand prices and the time charter day rate prices, and is there an observable relationship between scrapped ships and their technical efficiency. Unlike the analysis in Section 2, the analysis in this section is carried out for the time period 2007-2012 or in some cases 2009-2012 (depending on the availability of data). This allows the analysis to be tested for robustness to see if there is any consistency between years where the market had a similar dynamic (e.g. during the 2009-2012 period when oil prices were consistently high and freight rates consistently low relative to historical levels). The use of a time-series also allows, to a limited degree, the findings in two different markets (the 2007-2008 market of high freight rates and the 2009-2012 market of low freight rates) to be compared.

It should be noted that throughout this section, the quantification applied is the definition of technical efficiency formulated in this report (in Section 1). This definition broadly follows the EEDI formula, which is only one type of information available to customers who would like to assess energy efficiency and one which has only recently become widely available (e.g. in forms such as the Existing Vessel Design

Index, EVDI). The calculation of technical efficiency is uncertain, as is noted in Section 2.9.1 and there may be other information available to the purchaser of a ship or its services which is important to the calculation but unable to be included in this quantification (e.g. commercially sensitive information provided by a broker, prior experience gained during a previous charter, or technical information which is not captured in Clarksons World Fleet register such as details about the hull coating, the introduction of technical abatement technologies or the maintenance and management regime).

To ensure that the analysis of the markets is not by quantitative analysis alone, Section 3.1 discusses the importance of fuel efficiency in the shipping sector and the alleged possibility of the establishment of a two-tier market, where more energy-efficiency ships receive higher rewards compared to lower efficiency ships. In this section, which is mainly based on articles published the Lloyd's List; we quote several articles to show the depth and the breadth of the opinions being voiced in the industry. Interested readers are referred to the original sources where more information can be found. The following Section 3.2 discusses the rationale and the requisites for energy efficiency to be reflected in the market variables discussed above. Section 3.3 discusses the two methodological approaches, which are discussed in this study, namely regression analysis and comparison of mean values. Each of the next three sections (Sections 3.4, 3.5 and 3.6) discusses anecdotal evidence, as reported by the Lloyd's List, and the results we obtained in the time charter market, the newbuild and second-hand markets, and the demolition market, respectively. Once again, interested readers requiring more detailed information are referred to the original sources mentioned throughout these sections. Section 3.7 concludes.

3.1. IMPORTANCE OF EFFICIENCY AND ESTABLISHMENT OF A TWO-TIER MARKET

A major factor focusing operators' attention on energy efficiency is the high level of fuel prices, as the price of Heavy Fuel Oil has more than doubled in the last three years and is currently around 600 Dollars per tonne in Rotterdam (Clarksons, 2013). Despite future prices being highly uncertain and some authors pointing at a possible decrease in the oil price (Maugeri, 2012), the maritime sector is likely to experience high fuel prices in part due to increased oil scarcity and demand for oil from developing countries but also due to the introduction of sulphur regulations and increasingly stringent emission constraints. As bunker costs are estimated to represent approximately 60% of a ship's total costs (LL 26/11/2012a), high fuel prices are a strong incentive to focus on energy efficiency (LL 26/11/2012b). In market conditions characterised by high energy prices, low charter rates, and weak economic growth, fuel bills have become an item attracting operators' attention in order to increase profitability by reducing costs.

Energy efficiency of vessels is a complicated subject influenced by the vessel's design characteristics, their size and the way they are operated. Improved energy efficiency can be delivered through improved design, engine-related technologies and operational practices such as slow steaming[2]. The industry press has reported in a number of instances increased importance given to fuel efficiency by maritime operators. Several companies, for example, underline their efforts in ensuring the vessels they own or operate are being run as efficiently as possible (LL 31/10/2012). Technical departments in ship-owning companies are reported to take fuel management seriously, as the need to dampen the impact of rising fuel prices with operational and technological measures has increased (LL 06/03/2012). Similarly, the retrofit market shows increased sign of activity. DHT, for example, announced that they have retrofitted most of their fleet to increase fuel efficiency (LL 30/01/2013). Carbon War Room is set to launch a number of financial models aimed at facilitating the retrofitting of fuel-saving technologies on existing ships, one model being an agreement for the charterer to pay part of the upgrade or retrofit (LL 04/09/2012). Maersk Line has gone one step further by announcing that it would fund upgrades to make some of the ships they chartered-in more fuel efficient (LL 07/01/2013). Another project in this area is the Sustainable Shipping Initiative's Save As You Sail (SAYS), which is intended to improve access to retrofit finance, particularly where the period of payback for a retrofit technology is longer than the remaining time in a given time-charter.

[2] Another example of an operational measure is the Virtual Arrival system which incorporates weather analysis to calculate and agree a vessel arrival time that can enable a reduction in speed (LL 18/01/2013).

The importance acquired by energy efficiency is testified by shipyards and engineering firms using eco-efficiency as a marketing strategy in a bid to market their goods and services (LL 22/10/2012 and LL 05/06/2012), or differentiate their capabilities (LL 06/09/2012a). This has been highlighted by the response of Rongsheng, a Chinese shipbuilder, to a JP Morgan report claiming that large carriers built by the Chinese shipyards are 17% less efficient than those built by South Korean shipyards (LL 04/12/2012a and LL 04/12/2012b). Unfortunately, some of the fuel savings advertised by shipyards may be unlikely to materialise. Maersk, a shipping company, has joined a number of industry stakeholders in 'pouring cold water on' claims made by shipyards about fuel efficiency (LL 08/10/2012). Owners are increasingly outspoken and critical of newbuilding designs promising significant fuel-savings much higher than those made until recently (LL 22/10/2012). Lloyd's Register advised owners to be sceptical about fuel-saving claims from new eco-ship designs, as too many variables may influence operational fuel efficiency (LL 06/09/2012a). According to DNV, another classification society, promises from fuel-saving technologies may need to be played down due to tonnage in the water performing increasingly better than the benchmark used to describe newbuilds, as well as large variation in the performance of new designs and in the quality of the data used in their claims (LL 11/06/2012 and LL 27/11/2012). DNV recommend any potential buyer to have fuel consumption figures verified by an independent party (LL 27/11/2012). Similarly, IP, Napa and BMT recently called for independent assessment of claims from ship builders about fuel savings and the fuel consumption of eco-ships. If a transparent and independent standard methodology to assess fuel-savings is not agreed, IP, Napa and BMT argue that ship owners, operators and charterers will lack the confidence to make significant investment decisions (LL 22/10/2012). A group of manufacturers are also lobbying for the establishment of an independent benchmark (LL 01/10/2012).

The concept of a two tier-market has attracted considerable attention in the industry press although two different meanings have been attached to the phrase "two-tier market". One interpretation of a two-tier market is that of a split between the vessels optimised for slow steaming and those optimised for higher speeds of operation (LL 18/12/2012). More commonly, however, the phrase 'two-tier market' refers to a market split based on fuel efficiency. As fuel-efficient tonnage is more attractive, owners of the poorly performing vessels are suggested to be forced to accept lower rates or shorter contracts (LL 01/11/2012). Analysts have argued for some time that a two-tier market is emerging, as older and less fuel-efficient vessels lose out to modern tonnage (LL 01/06/2012). Oil companies are reported to prefer newer vessels even if they are a little bit more expensive (LL 29/03/2012) however, it is worth noting that in the case of oil tankers, the existence of a two-tier market could be partially motivated by issues of safety and the importance of the avoidance of spills. In the dry bulk and container sectors, the existence of a two-tier market seems more likely to be related to a greater extent to the efficiency of ships.

3.2. RATIONALE OF THIS STUDY

As indicated in the study of the literature on the concept of a two-tier market, energy efficiency should be an important parameter in the setting of prices in a number of the shipping markets: e.g. voyage charter, time charter, second hand, new build and demolition markets. In the first four markets, fuel efficiency, like any other desirable property of a vessel, can increase the demand for a particular ship which can take the form of lower transaction costs (e.g. more frequent charters or shorter time needed to sell a vessel in the second-hand or new-build market), or increase financial remuneration for the vessel (e.g. higher charter rates or prices in the second-hand market). However, the literature is based predominantly on anecdote or isolated example, and therefore fails to provide a rigorous assessment of whether the concept of a two-tier market is a genuinely widespread phenomenon and if so the extent of its influence on prices. The purpose of this part of the study is to apply regression analysis of market data in order to attempt to assess the extent to which the market is providing evidence to support the statements in the literature. In practice, the shipping markets involve complicated multi-stakeholder interactions (both in design and operation). Identifying and quantifying all these relationships, and then formulating them into a model which can be estimated based on available data is a challenging task The model applied here should be assessed bearing in mind the data available for this study, the resources available, and the fact that as far as we are aware, this is the first attempt to undertake rigorous analysis of the effect of energy efficiency on market variables. As with any model, there are numerous extensions and refinements that could be applied (data quality permitting) in order to explore the potential to achieve higher levels of fidelity in analysis output.

A conceptualization of the different shipping markets is given in Figure 45, showing the conceptual logic used in this study and a simple way in which the markets described above can be linked. In Figure 45, we identify value-creation markets, value-accumulation markets and reinforcing mechanisms. Figure 44 attempts to distinguish, in the case of value-creation markets, between ships operated by owners and those chartered in either from the voyage or time charter markets. In all cases, the value is created by fuel efficiency delivering lower fuel bills associated with the operation of a particular ship. What differs across the cases shown in Figure 45 is the likelihood of ship owners being rewarded for owning fuel efficient ships. In the case of owner-operated ships, case a) in the figure, higher fuel efficiency implies lower fuel expenditure for the owners, as ownership of the vessel guarantees the full appropriation of the monetary value of fuel savings. In the case of chartered ships the relationship between value-creation activity and the likelihood of owners being rewarded for owning efficient ships is more complicated, as benefits from fuel efficiency may be shared between the charterers and the owners.

It is interesting to notice that the implications of ships' fuel efficiency not being rewarded are very different in the two markets. In the time charter market, where the charterers pay for the fuel, fuel savings accrue entirely to the charterer if efficiency is not reflected in the charter rate, while in the voyage market, where the operator pays for the fuel, fuel savings would accrue entirely to the owner-operator. In practice, the relative numbers of charterer operated ships and owner operated ships may change over time, as the bargaining power shifts between the two parties. In the case of the time charters, case b) in Figure 45, one would expect higher demand from charterers for efficient ships, as they imply lower fuel bills, a fact that may well increase the charter rate charged by more fuel efficient ships. This implies charterers transferring some of the value of the fuel savings to owners, a process which may continue, depending on the relative importance of demand for and supply of efficient ships, up to a maximum where the whole amount of fuel savings are passed back to ship owners. Indeed, the premium in the day rates paid by charters could be even higher than the expected fuel savings if other factors such as reputational benefits and higher reliability (if this is indeed the case) of more energy efficient vessels add value. In the case of the voyage charter market, case c) in Figure 45, the fact that owners of more efficient ships enjoy higher profits if fuel efficiency is not reflected in the voyage rate may lead either to charterers demanding a lower price on contracts for more efficient ships or owners offering a lower rate to attract more business. Like in the time charter market, this process may continue, depending on the relative importance of demand for and supply of efficient ships, up to a maximum where the full value of the fuel savings is transferred to charterers.

Whether the final market allocation of the fuel savings implied by more energy efficient ships will be closer to either extreme (fuel savings completely appropriated by owners or charterers) depends on a number of factors such as market conditions, number of ships competing for a certain contract, ability to verify information provided by the other party, and importance of reputation. Leaving particular conditions of the market or market segment aside, one can conclude that fuel efficient characteristics are most likely to be rewarded in the case of owner-operated ships, followed by voyage chartered ships and finally time chartered ships. Among these three types of operational arrangements, this study decided to focus on time chartered ships, as this is the least likely case where energy efficiency is valued.

When ship owners are rewarded for owning more energy efficient ships, they should find efficient ships more attractive, due to the extra revenues, and this may result in them willing to pay a higher price for efficient newbuilds. This higher price arises from the potential owners' expectations of higher revenues, suitably discounted, accruing over the whole lifespan of a more energy efficient ship. By doing so, some of the rewards of fuel efficiency enjoyed by ship owners are essentially transferred to ship builders. Bearing in mind that the value is created by the ship being energy efficient and that the likelihood of owners being rewarded for fuel efficient ships depends on the chartering conditions, if any, Figure 44 summarizes the conditions required for more energy efficient newbuilds to be paid a higher price. In the case of owner-operators, the justification of a higher price for newbuilds is reliant on the ability of potential owners to verify the true savings associated with allegedly more efficient designs. This is not by any means simple, but at least no extra analysis is demanded from the owners. If the ship delivers financial savings they can be confident that they will benefit from them, as they operate the ships themselves. The premium paid for more fuel efficient ships will then depend on the relative negotiating power of potential owners and shipyards. In the case of potential owners planning to offer the newly purchased ships on the charter markets, higher price for newbuilds requires not only an assessment of the potential savings from more efficient designs claimed by shipyards but also of whether these fuel efficiencies will ultimately be rewarded through the prices paid by the charterers. The latter requires charterers to be able to verify the efficiency claims made by ship owners, in the same way owners need to assess the fuel saving claims made by the shipyards. The premium paid for more fuel efficient ships in the case of chartered ships will then depend on the relative negotiating power of potential owners and shipyards, and the relative negotiating power of owners and potential charterers. The ultimate outcome of such negotiations may also depend on a number of other factors, including the appetite of both shipyards and owners to take on new, unfamiliar technology.

Owner operated ships

- Ability to verify efficiency claims made by shipyards
- Negotiating power between potential buyers and shipyards

Chartered Ships

- Ability to verify efficiency claims first made by shipyards and then by owners
- Negotiating power between
    - potential buyers and shipyards
    - owners and potential charters

Figure 44 Conditions required for more efficient newbuilds to be paid a higher price.

In Figure 45 one can see two reinforcing mechanisms of the logic described above, one focused on the second-hand market, the other on the demolition market. As the process and the conditions required for second hand price to reflect the value of energy efficiency is analogous to the one for newbuilds, it will not be discussed any further. It is important to notice, however, that the possibility that energy efficiency is rewarded in the second-hand market provides a further incentive for potential owners of a newbuild to pay a higher price for more efficient ships, i.e. in the knowledge that they will receive a higher price should they sell their ships before the end of its economic life. The likelihood of more efficient newbuilds being sold at higher prices may also be reinforced by activities in the demolition market. If less fuel efficient ships have a shorter economic life, which is likely to happen if the choice of the ships sent for demolition is influenced by their level of efficiency (i.e. less efficient ships are more likely to be scrapped), more efficient ships not only are rewarded with a higher charter rate (or are able to deliver fuel savings in case of ship owners) but they will be operating for a longer period of time, therefore increasing the net present value of the revenues occurring through the longer lifespan of the ship. A higher net present value is then likely to be reflected in higher prices for newbuilds.

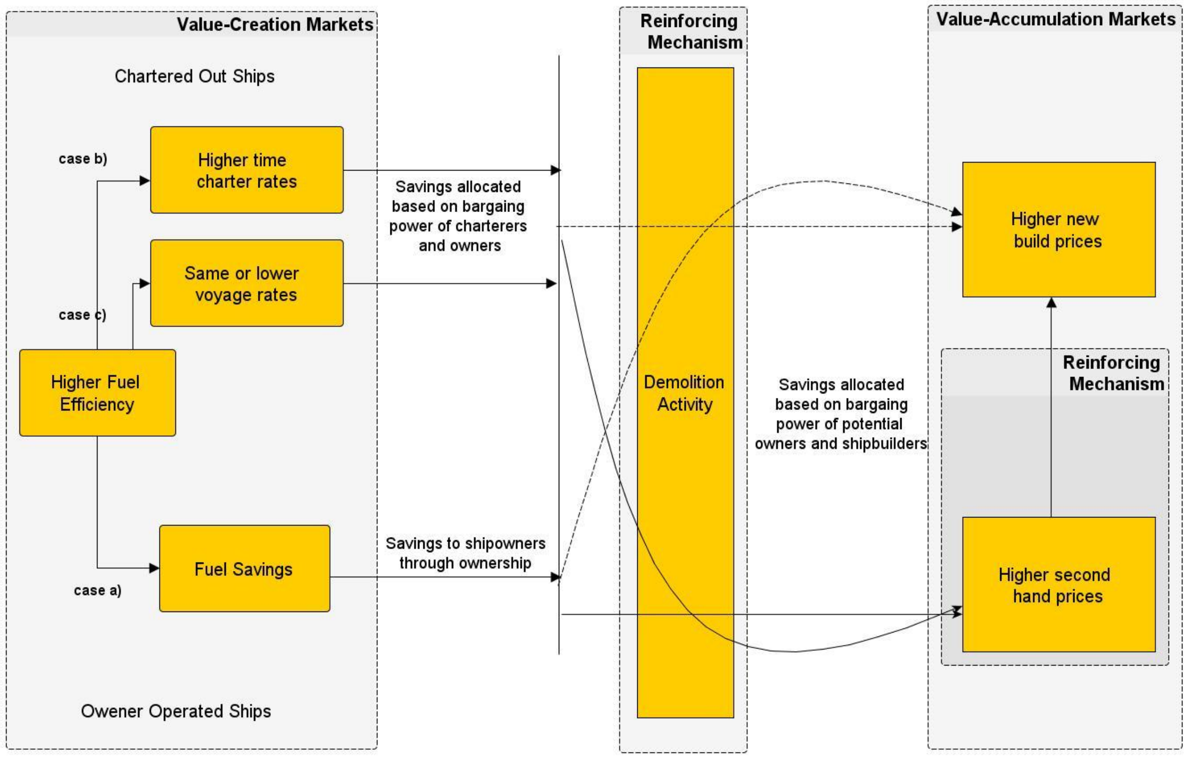

Figure 45 Logic of the value chain discussed in this study.

3.3. METHODOLOGICAL APPROACH AND GUIDE FOR INTERPRETING TABULAR RESULTS

In this study we assess the extent to which prices (i.e. time charter rates, newbuild and second-hand prices) take into account the energy efficiency of the ships transacted in each market through both a mean comparison and by performing regression analysis. In the case of the demolition market we implement the first methodology only. Data have been taken from transaction specific information found in the Clarksons World Fleet Register and Clarksons Shipping Intelligence Network. As data availability varies depending on the size of the ship, the shipping markets and the variables of interest, each of the sections presenting our results on a particular variable of interest also discuss any specifics of data availability.

3.3.1. MEAN COMPARISON

When comparing average prices paid for ships of different energy efficiency, in order to ensure comparability across different transactions, we split the sample into a maximum of four periods, depending on data availability, i.e. the first comprising all observations from 2007 and 2008, the second observations from 2009 and 2010, the third comprising observations from 2010 to 2011 and the fourth from 2011 to 2012. The sample in each time period used in the analysis is then further split on the basis of the fuel efficiency of the ships (high and low) and, when applicable, on the basis of their age (old and new) by identifying the median of the two variables. For each period, we identify the observations belonging to the four groups originated from the partition above (namely: i) old highly efficient ships; ii) old less efficient ships; iii) new highly efficient ships; and iv) new less efficient ships), and we compute the average value of the variable of interest for these groupings. Averages are then compared across values of energy efficiency, e.g. the average for old ships with low energy efficiency is compared to the average paid for old ships with higher energy efficiency. By doing so we take into account the effect of the ship age on the value of the variable of interest. Comparison of average is obtained through the well-known Welch test which allows for the two groups for which the average is computed to have a different number observations and different values of variance[3]. The hypothesis that we test is:

$$H_0: X_{h,t,a} > X_{l,t,a}$$

where *X* may indicate the time charterers paid in the fixture, the new build price or the second hand price paid for the ship. The indicators 'h' and 'l' indicate the group of ships with high and low efficiency, respectively, 't' the period in which the two groups of observations fall and 'a' the age of ship. The comparison above would imply, for example, to compute the average time charters paid in 2007-08 for new ships with high efficiency $TC_{h,\ 2007\text{-}08,\ new}$ and compare it to the average time charter paid in the same time period for new ships with low efficiency, i.e. $TC_{l,\ 2007\text{-}8,\ new}$.

In the tables presented in the section discussing the results from the analysis of mean values, cells are formatted so that:

- A dark green cell indicates that the hypothesis of energy efficiency being incorporated in the variable of interest, e.g. time charters, is accepted by the data at least at the 90% confidence level;
- A light green cell indicates that the null hypothesis above cannot be rejected by the data at a confidence level below 90%;
- A pink cell indicates that the computed average for more efficient ships is lower than the average for less efficient ships, although we cannot conclude that there is any significant difference between the two values at a confidence level higher than 90%;
- A red cell indicates that the computed average for more efficient ships is lower than the average for less efficient ships and that the difference between the two averages is significant at a confidence level higher than 90%.

In simplified terms, dark green and light green cells indicate that the average we computed for more efficient ships is higher than the value computed for less efficient ships (hypothesis that energy efficiency is reflected in price is supported). In the case of dark green cells, the difference between the averages is so high, when taking into account the variability in the samples and their size, that we can confidently conclude that the average in the fuel efficient portion of the fleet is higher than the average in the remaining portion of the fleet (statistically significant). Pink and red cells, on the other hand, indicate that the computed average for more efficient ships is lower, contrary to the expectation of the hypothesis, than the value computed for less efficient ships. However, only in the case of red cells is the difference between the two averages big enough that we can confidently conclude that the average in the fuel efficient portion of the fleet differs from the average in the remaining portion of the fleet (statistical significance) For each year the tables below present the computed averages and the number of observations corresponding to each grouping, and the outcome from our analysis. In the case of the light and dark green cells we also present, in parentheses, the difference between the two averages expressed as a percentage of the overall average price paid for the ships of that age and year category.

3.3.2. REGRESSION ANALYSIS

Regression analysis has been implemented by estimating the effect of a number of factors on the price related to purchasing and chartering transactions contained in the sample used in this study. Variables used as explanatory factors include the installed power of the ship's main engine, its quoted speed of operation, bunker capacity and a measure of the size of the cargo that can be transported, either in DWT or TEU depending of the ship type. It is worth mentioning that the factors above are design characteristics of the ship rather than specifics of their operation. The list of explanatory variables also included the operational measure of energy efficiency described in Section 1 (Equation 2), in some cases multiplied by the fuel price in order to create a variable reflecting the fact that energy efficiency is likely to get more attention when prices are high, as well as the length of the negotiated contract in the case of time charters, and age of the ship when sold in the case of second hand prices. Finally, we included, as an explanatory factor, an index describing the average value of the relevant variable observed in the market to take into account of the wider conditions of the economy and shipping sector on the value of the

[33] The variance is estimated separately for both groups and degrees of freedom are modified accordingly.

relevant variable observed for a specific transaction. By doing so, the other factors listed above are expected to explain the difference between the value of the relevant variable for a specific transaction and the average value in the market when the transaction occurred.

The impact of energy efficiency on time charter rates, new build and second-hand prices has been computed by taking into consideration a two-tier market, as described above. First we computed the effect of energy efficiency by multiplying the value observed in each transaction by the estimated coefficient. We then divided the estimation sample in two halves based on the value of energy efficiency and computed the average impact of this factor in these two subsamples. We finally computed the impact of energy efficiency by subtracting the average for energy efficiency for the less efficient half of the sample from the average obtained for the remaining ships. The result, expressed in US dollars, is then divided by the average value of the relevant variable, i.e. time charter rates, new build and second-hand prices, in the overall sample, to convert it into a percentage metric.

3.4. IMPACT OF ENERGY EFFICIENCY ON THE TIME CHARTER MARKET

3.4.1. EVIDENCE FROM THE INDUSTRY PRESS

The time charter market is the area of the shipping industry, which has seen the highest level of debate about energy efficiency in the industry press. Charters responsible for fuel expenditure of the ships they employ are taking a strong interest in using fuel-efficient vessels and are reported to be looking at new partnerships with owners, as issues of fuel management become critical (LL 02/04/2012). The reason of the interest is thought to be associated with the high fuel price and low time charter rates implying a high contribution of the fuel bill to the total cost of chartering a ship. In fact, as pointed out by Cargill, a large dry-bulk charterer, any owner who thinks cargo charterers are not interested in fuel efficiency, despite being responsible for paying for the fuel, is at best naïve (LL 30/03/2012).

According to Intercargo, taking fuel efficiency into account before chartering vessels is not a recent development but a characteristic of the industry (LL 02/10/2012). A number of commentators underlined the increasing scrutiny charterers placed to fuel efficiency while a number of charters explicitly encouraged ship-owners to increase the fuel efficiency of the ships they charter or to get involved in fuel-efficiency programmes. Taiwan's Evergreen, for example, has launched a bonus incentive to assess fuel efficiency among chartered vessels and reward ship-owners outperforming Evergreen Line's expectations (LL 06/11/2012). Maersk Line is scoring all the vessels they charter based on their fuel efficiency performance (LL 29/10/2012), to attempt to ensure that they use the most fuel-efficient vessels in both the case of owned and chartered ships. Norden, another shipping company with their own performance indicator, have encouraged owners of chartered-in tonnage to install instrumentation and reporting of their indicator on-board (LL 29/10/2012) while Maersk line has gone one step further as they warned that they may find it hard to do business with owners who opt out of their in-house fuel efficiency programme (LL 29/10/2012).

From the industry press it seems clear that more fuel-efficient vessels receive longer contracts or attract more competition for their services. In the container market, several liner operators are said to take in more fuel-efficient vessels first (LL 01/11/2012). In the dry-bulk market Cargill announced it would refrain from taking in poor performing dry bulk vessels when it could (LL 01/11/2012). In some cases, older vessels are reported as facing tougher challenges to secure employment due to their fuel efficiency failing to match that of modern ships (LL 06/09/2012b). On the other hand, probably unsurprisingly, some liner operators and bulk charterers are less forthcoming as to whether they are willing to pay higher rates for more fuel-efficient vessels. It must be said, however, that higher time charter rates for more efficient vessels have been noticed, for example in the Panamax container market (LL 05/06/2012). A recent fixture involving MCC-Maersk was reported to have attracted a clearly higher rate than those seen for similar vessels with brokers speculating that it might be due to the fuel efficiency (LL 12/07/2012).

Some bulk-charters are open about their intention of rewarding owners of more fuel-efficient vessels. Cargill, for example, denied claims that charterers are not prepared to pay extra for more efficient tonnage (LL 02/04/2012). Confirming the fact that a two tier market had already developed, older ships either are chartered at a discount or find it difficult to find employment, due to lower fuel efficiency, especially in the Panamax segment (LL 10/10/2012), while modern vessels with greater fuel efficiency can achieve a premium over average rates (LL 20/03/2012). There is a view that a strong preference for newer vessels, which comply with new environmental regulation and display greater fuel efficiency, translates into higher charter rates than those paid for older ships (LL 29/03/2012). On the other hand, ship owners are concerned that they will not reap the rewards from investing in fuel-efficiency measures, a possible solution consisting in charter agreements being reworded to better meet the demands of fuel management.

Considering fuel efficiency across the fleet, the gap between earnings is substantial and one should not be surprised that charters may want to pass some of the fuel savings back to the owners in order to encourage higher fuel efficiency. New Very Large Crude Carriers, for example, can earn around $18,000 per day more than older vessels booked at the same spot market rate, believed in part to be due to higher fuel efficiency (LL 01/06/2012). Unfortunately, difficulty in sharing information about fuel efficiency, measurement, and credibility of the claims on fuel savings make it difficult for owners to be certain that they will reap rewards from investing in fuel-efficiency measures (LL 02/04/2012).

3.4.2. RESULTS FROM MEAN COMPARISON AND REGRESSION ANALYSIS

Data for the time charter markets were sourced from the Clarkson Shipping Intelligence Network, which contains information on fixtures in a number of shipping markets. Information about individual fixtures has been matched to information describing the ship in that economic transaction obtained from the Clarkson World Fleet Registry and its deployment to estimate the ship's efficiency, as described in Section 1. Fixtures missing data for any of the variables used in the analysis were discarded. Due to data availability limitations, only the Capesize, Panamax and Handymax markets in the dry bulk sector were analysed, along with the Subpanamax, Handy and Feedermax markets of the container sector.

Results from the comparison of means are fairly strongly in favour of energy efficiency being incorporated in the time charter rate, therefore confirming anecdotal evidence from the industry press discussed above. In the case of the bulk sector, Table 34 displays eight instances where the mean for more efficient ships is lower than the mean computed for less efficient ships but in none of them one can conclude that the difference between the means are statistically significant. The opposite result is found in ten instances, and more importantly, in three of these ten instances the computed means are so different that we can confidently conclude that the average in the more efficient part of the fleet is also lower. This happens only when comparing time charters for relatively new ships. From the percentages reported in the green cells one can however notice that the premium paid to efficient ships is about 10% in the case of the statistically significant cases (dark green cells) while it tends to be much lower in the other cases.

In the case of the container sector there is stronger evidence that time charters incorporate a premium for energy efficiency. Table 35 displays only two instances where the computed mean for more efficient ships is lower than the mean computed for less efficient ships. The opposite result is found in ten instances. More importantly, in six of these ten instances the computed means are so different that we can confidently conclude that the average in the more efficient part of the fleet is also lower. Confirming the results for the dry bulk sector, this happens mostly in the case of relatively new vessels.

Table 34 Average time charter prices ($) paid in the in the dry bulk sector.

			2007-08			2009-10			2011-12		
	Age	**Efficiency**	**Average ($)**	**Sample**	**Outcome**	**Average ($)**	**Sample**	**Outcome**	**Average ($)**	**Sample**	**Outcome**
Capesize (100,000 270,000 dwt)	New	High	116,965 (21%)	65	Efficiency rewarded (Statistically significant)	39,674 (9%)	23	Efficiency rewarded (Statistically significant)	13,653 (6%)	16	Efficiency rewarded (Non-statistically significant)
	New	Low	94,671	50		36,390	50		12,874	37	
	Old	High	87,053 (2%)	68	Efficiency rewarded (Non-statistically significant)	33,508	38	Efficiency not rewarded (Non-statistically significantly)	12,667	18	Efficiency not rewarded (Non-statistically significantly)
	Old	Low	85,086	47		33,596	26		13,231	18	
Panamax (60,000 100,000 dwt)	New	High	58,262	251	Efficiency not rewarded (Non-statistically significantly)	24,792 (6%)	128	Efficiency rewarded (Statistically significant)	14,609 (4%)	42	Efficiency rewarded (Non-statistically significant)
	New	Low	59,715	345		23,298	250		14,093	87	
	Old	High	58,701	263	Efficiency not rewarded (Non-statistically significantly)	22,740	226	Efficiency not rewarded (Non-statistically significantly)	14,422 (2%)	94	Efficiency rewarded (Non-statistically significant)
	Old	Low	58,783	132		23,150	111		14,135	70	
Handymax (40,000 60,000 dwt)	New	High	45,796	105	Efficiency not rewarded (Non-statistically significantly)	19,712	63	Efficiency not rewarded (Non-statistically significantly)	13,530 (0%)	27	Efficiency rewarded (Non-statistically significant)
	New	Low	46,105	70		20,991	70		13,491	40	
	Old	High	46,427 (1%)	44	Efficiency rewarded (Non-statistically significant)	19,122 (0%)	58	Efficiency rewarded (Non-statistically significant)	12,591	37	Efficiency not rewarded (Non-statistically significantly)
	Old	Low	45,910	72		19,107	54		13,067	27	

Table 35 Average time charter prices paid in the container sector.

	Age	Efficiency	2009-10			2011-12		
			Average ($)	**Sample**	**Outcome**	**Average ($)**	**Sample**	**Outcome**
Subpanamax (2,000-3,000 TEU)	New	High	12,053 (18%)	10	Efficiency rewarded (Statistically significant)	9,688 (2%)	146	Efficiency rewarded (Non statistically significant)
	New	Low	10,100	12		9,517	140	
	Old	High	9,760	10	Efficiency not rewarded (Non statistically significant)	9,266 (2%)	141	Efficiency rewarded (Non statistically significant)
	Old	Low	9,942	12		9,077	136	
Handy (1,000-2,000 TEU)	New	High	8,506 (6%)	35	Efficiency rewarded (Statistically significant)	8,098 (6%)	253	Efficiency rewarded (Statistically significant)
	New	Low	8,004	37		7,630	398	
	Old	High	7,658 (2%)	51	Efficiency rewarded (Non statistically significant)	7,685 (3%)	377	Efficiency rewarded (Statistically significant)
	Old	Low	7,517	32		7,461	249	
Feedermax (500-1,000 TEU)	New	High	5,897 (10%)	15	Efficiency rewarded (Statistically significant)	5,695 (6%)	130	Efficiency rewarded (Statistically significant)
	New	Low	5,367	36		5,385	189	
	Old	High	4,780 (0%)	32	Efficiency rewarded (Non statistically significant)	4,876	188	Efficiency not rewarded (Non statistically significant)
	Old	Low	4,768	20		5,002	120	

Regression analysis confirms the results from mean comparison discussed above. Surprisingly, considering the number of instances in which our hypothesis is rejected by the comparison of means, the best results in the case of regression analysis are obtained in the dry bulk sector. The fact that in the container sector, only the Subpanamax shows results which conform to our hypotheses is probably due to the sample spanning only a relatively short time period, as we could not access data prior to 2009.

Table 36: Results from the regression analysis for time charters.

Sector	Ship Size	Average Effect of Energy Efficiency (Dollars)	Percentage
Container	Subpanamax **(2,000-3,000 TEU)**	200	2.1%
Dry Bulk	Capesize (**100,000 270,000 dwt)**	1,700	2.7%
Dry Bulk	Panamax (**60,000 100,000 dwt)**	800	2.0%
Dry Bulk	Handymax (**40,000 60,000 dwt)**	500	1.7%

3.5. IMPACT OF EFFICIENCY ON THE NEW AND SECOND HAND MARKETS

3.5.1. EVIDENCE FROM THE INDUSTRY PRESS

We could find very few articles in the industry press about whether new build and second hand ship prices take into account the fuel-efficiency of a vessel. From an economics perspective, if more efficient vessels are rewarded through higher charter rates, it would seem natural that higher revenue streams are capitalised through a higher sale price, as argued in section 3.2. Oceanbulk Maritime, a Greek shipping company, was quoted recently saying that they keep a close eye on fuel savings in order to consider what price level is justified for a vessel (LL 11/10/2012). Norden, a Danish shipping company, recently announced that they would no longer order vessels with older designs, as fuel efficiency had become one of the key challenges (LL 15/08/2012). As more and more companies take a similar stance, we would expect decreased demand for less efficient designs to translate into lower prices. SPP building, a South-Korean building yard, has recently announced that fourteen 50,300 dwt vessels they recently won an order for have been priced about $1m higher than current market prices, the differential reflecting the vessels' more sophisticated design and greater fuel efficiency (LL 06/12/2012). In the case of second-hand prices, recent research concluded that the prices of second hand Panamax bulk fleet vessels have failed to grasp the difference in earnings between fuel-efficient newbuildings and existing vessels, leading to second hand vessels being overvalued (LL 15/11/2012). It is interesting to notice that overvalued second hand prices seem to occur despite shipping companies advocating the purchase of newbuildings over second-hand vessels (LL 19/11/2012). On the other hand, it can also be argued that overvalued second-hand prices, when compared to new eco designs may simply reflect potential buyers discounting the fuel-efficiency claims from the latter, as discussed above.

3.5.2. RESULTS FROM MEAN COMPARISON AND REGRESSION ANALYSIS

Data for the newbuild and second-hand markets were sourced from the Clarkson World Fleet Register. In the case of newbuild prices, data availability let us compare a wide array of ship sizes in the dry-bulk and container markets, but unfortunately we could analyse only two ship sizes in the wet bulk market. In the case of second-hand prices, data availability confined most of the analysis to the dry bulk sector, with the exception of the Handy size in the container sector.

Results from the comparison of means show a mixed picture for the hypothesis that fuel efficiency commands a premium. In the case of the dry bulk sector, Table 37 shows a similar number of instances, three and two respectively, in which our hypothesis can be accepted (dark green cells) and rejected (red cells) at a high confidence level. Similarly, the table shows three instances where the hypothesis of a price premium for efficiency is accepted (light green) and two where it is rejected (pink) at a lower confidence level. The instances where the hypothesis is accepted with a high confidence level occur all from 2009 onwards, probably pointing to a recent increase in the interest for energy efficiency. In the case of the wet bulk sector, evidence is preponderantly contrary to the hypothesis. In Table 38 the average price of efficient newbuild ships is higher than the price for the remaining ships in only one instance although there is no statistically significant difference between the averages. In the remaining three cases, the average price of efficient newbuild ships is lower than the price of the remaining ships, although in only one instance is the difference between the prices statistically significant. Results from the container sector – see Table 39 - are much more encouraging with the exception of the Handy ship size where the hypothesis of a price premium is clearly rejected. Leaving this ship size aside, the average price of efficient newbuild ships is higher than the average price in seven instances, in six of which the difference between the averages is statistically significant. In only four cases is the average price of efficient newbuild ships lower than the price for the remaining ships, although the difference between the averages is statistically significant in only two instances.

Table 37 Average new build prices in the dry bulk sector.

		2007-08			2009-10			2011-12		
	Efficiency	**Average ($)**	**Sample**	**Outcome**	**Average ($)**	**Sample**	**Outcome**	**Average ($)**	**Sample**	**Outcome**
Capesize (100,000-270,000 dwt)	High	n.a.	n.a.	n.a.	70.6	10	Efficiency not rewarded (Statistically significantly)	87.4 (20%)	22	Efficiency rewarded (Statistically significantly)
	Low	n.a.	n.a.		83.3	36		71.2	23	
Panamax (60,000-100,000 dwt)	High	32.7 (0.5%)	15	Efficiency rewarded (Non-statistically significant)	50.3 (6%)	30	Efficiency rewarded (Non-statistically significant)	46.3 (9%)	28	Efficiency rewarded (Statistically significantly)
	Low	32.6	19		47.5	30		42.5	70	
Handymax (40,000-60,000 dwt)	High	32.5 (7%)	21	Efficiency not rewarded (Non-statistically significantly)	36.6 (4%)	71	Efficiency rewarded (Statistically significantly)	36.4	58	Efficiency not rewarded (Statistically significantly)
	Low	30.2	25		35.2	52		39.7	49	
Handy (10,000-40,000 dwt)	High	n.a.	n.a.	n.a.	28.2	50	Efficiency not rewarded (Non-statistically significantly)	32.3 (2%)	34	Efficiency rewarded (Non-statistically significant)
	Low	n.a.	n.a.		30.6	39		31.8	37	

Table 38 Average new build prices in the wet bulk sector.

		2007-08			2009-10		
	Efficiency	**Average ($)**	**Sample**	**Outcome**	**Average ($)**	**Sample**	**Outcome**
VLCCs (250,000-460,000 dwt)	High	110.3 (8%)	9	Efficiency rewarded (Non-statistically significant)	111.4	12	Efficiency not rewarded (Statistically significantly)
	Low	101.5	11		121.1	24	
Aframax (100,000-120,000 dwt)	High	59.5	7	Efficiency not rewarded (Non-statistically significantly)	61.2	9	Efficiency not rewarded (Non-statistically significantly)
	Low	61.0	5		63.2	10	

Table 39 Average new build prices in the container sector.

		2007-08			2009-10			2011-12		
	Efficiency	**Average ($)**	**Sample**	**Outcome**	**Average ($)**	**Sample**	**Outcome**	**Average ($)**	**Sample**	**Outcome**
Postpanamax I (8,000-14,000 TEU)	High	127.7 (8%)	8	Efficiency rewarded (Statistically significantly)	157.1 (21%)	22	Efficiency rewarded (Statistically significantly)	152.4 (18%)	64	Efficiency rewarded (Statistically significantly)
	Low	118.2	30		127.7	25		125.6	11	
Postpanamax II (5,000-8,000 TEU)	High	96.3 (12%)	22	Efficiency rewarded (Statistically significantly)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a
	Low	85.3	13		n.a.	n.a.		n.a.	n.a.	
Panamax (3,000-5,000 TEU)	High	61.5 (1%)	56	Efficiency rewarded (Non-statistically significant)	65.5 (4%)	61	Efficiency rewarded (Statistically significantly)	n.a.	n.a.	n.a.
	Low	61.2	48		62.9	40		n.a.	n.a.	
Subpanamax (2,000-3,000 TEU)	High	46.8 (5%)	21	Efficiency rewarded (Statistically significantly)	47.5	4	Efficiency not rewarded (Non-statistically significantly)	n.a.	n.a.	n.a.
	Low	44.3	4		48.5	5		n.a.	n.a.	
Handy (1,000-2,000 TEU)	High	28.4	39	Efficiency not rewarded (Statistically significantly)	26.5	10	Efficiency not rewarded (Non-statistically significantly)	18.5	5	Efficiency not rewarded (Non-statistically significantly)
	Low	33.3	31		28.5	15		26.7	8	

Regression analysis overall confirms the container sector as the market valuing energy efficiency the most. In four out the five ship sizes we assessed, energy efficiency has an impact on new build prices, the extent varying between 4% and 8% of the average new build price. In the case of the ship sizes from the dry and the wet bulk sectors shown in Table 40, the effect of energy efficiency is slightly smaller ranging between 2% and 3.5% of the average newbuild price.

Table 40: Results from the regression analysis for new build prices.

Ship Type	Ship Size	Average Effect of Energy Efficiency (Thousand Dollars)	Percentage
Dry bulk	Capesize **(100,000-270,000 dwt)**	3,400	3.5%
	Panamax **(60,000-100,000 dwt)**	500	2%
Container	Postpanamax I **(8,000-14,000 TEU)**	10,300	7.4%
	Postpanamax II **(3,000-5,000 TEU)**	5,300	5.3%
	Subpanamax **(2,000-3,000 TEU)**	3,100	7.8%
	Handy **(1,000-2,000 TEU)**	700	4%
Wet bulk	VLCC **(250,000-460,000 dwt)**	3,700	3.4%
	Aframax **(100,000-120,000 dwt)**	900	2%

Considerable evidence supporting the existence of a premium for energy efficiency could be found in the second hand market. As shown in Table 41, the average price of efficient second hand dry bulk ships is higher than the price of the remaining ships in fifteen instances, eight of which show a statistically significant difference. In the remaining nine cases the average price of efficient ships is lower than the price for the remaining ships, although only in two instances is the difference between the prices statistically significant. The Handy size from the container sector shows more balanced results with regard to the existence of a premium for efficiency, as can be seen in Table 42, probably due to the relatively small sample available for this ship size.

Table 41 Average second hand prices in the dry bulk sector

			2007-08			2009-10			2011-12		
	Age	**Efficiency**	**Average ($)**	**Sample**	**Outcome**	**Average ($)**	**Sample**	**Outcome**	**Average ($)**	**Sample**	**Outcome**
Capesize (100,000 270,000 dwt)	New	High	113.3	6	Efficiency rewarded (Non-statistically significant)	44.0	8	Efficiency not rewarded (Statistically significantly)	42.6	4	Efficiency rewarded (Non-statistically significant)
	New	Low	100.4	17		58.0	16		37.3	17	
	Old	High	49.5	25	Efficiency rewarded (Non-statistically significant)	22.7	17	Efficiency rewarded (Non-statistically significant)	13.7	17	Efficiency not rewarded (Non-statistically significantly)
	Old	Low	43.2	8		20.6	15		18.3	6	
Panamax (60,000 100,000 dwt)	New	High	57.1	45	Efficiency not rewarded (Non-statistically significantly)	33.4	36	Efficiency not rewarded (Statistically significantly)	24.3	9	Efficiency not rewarded (Non-statistically significantly)
	New	Low	61.8	30		39.4	29		26.9	21	
	Old	High	41.8	29	Efficiency not rewarded (Non-statistically significantly)	17.8	37	Efficiency rewarded (Statistically significantly)	12.5	28	Efficiency rewarded (Statistically significantly)
	Old	Low	44.3	37		14.5	40		9.0	23	
Handymax (40,000 60,000 dwt)	New	High	53.8	44	Efficiency rewarded (Statistically significantly)	32.3	53	Efficiency rewarded (Non-statistically significant)	23.7	21	Efficiency not rewarded (Non-statistically significantly)
	New	Low	47.6	35		31.0	24		25.0	16	
	Old	High	30.6	31	Efficiency rewarded (Non-statistically significant)	11.5	34	Efficiency not rewarded (Non-statistically significantly)	8.8	34	Efficiency not rewarded (Non-statistically significantly)
	Old	Low	30.1	30		13.6	56		9.6	49	
Handy (10,000-40,000 dwt)	New	High	38.4	41	Efficiency rewarded (Statistically significantly)	20.4	68	Efficiency rewarded (Non-statistically significant)	16.8	49	Efficiency rewarded (Statistically significantly)
	New	Low	29.8	71		19.0	54		10.3	30	
	Old	High	16.9	39	Efficiency rewarded (Statistically significantly)	5.5	66	Efficiency rewarded (Statistically significantly)	5.2	59	Efficiency rewarded (Statistically significantly)
	Old	Low	11.6	50		3.5	69		3.7	38	

Table 42 Average second hand prices in the container sector

<table>
<tr><th></th><th></th><th></th><th colspan="3">2008</th><th colspan="3">2010</th><th colspan="3">2012</th></tr>
<tr><th></th><th>Age</th><th>Efficiency</th><th>Average ($)</th><th>Sample</th><th>Outcome</th><th>Average ($)</th><th>Sample</th><th>Outcome</th><th>Average ($)</th><th>Sample</th><th>Outcome</th></tr>
<tr><td rowspan="4">Handy (1,000-2,000 TEU)</td><td>New</td><td>High</td><td>33.3</td><td>22</td><td rowspan="2">Efficiency rewarded (Non-statistically significant)</td><td>14.6</td><td>12</td><td rowspan="2">Efficiency not rewarded (Non-statistically significantly)</td><td>n.a.</td><td>n.a.</td><td rowspan="2">n.a</td></tr>
<tr><td>New</td><td>Low</td><td>29.9</td><td>21</td><td>17.7</td><td>26</td><td>n.a.</td><td>n.a.</td></tr>
<tr><td>Old</td><td>High</td><td>n.a.</td><td>n.a.</td><td rowspan="2">n.a</td><td>8.2</td><td>20</td><td rowspan="2">Efficiency rewarded (Statistically significantly)</td><td>5.7</td><td>30</td><td rowspan="2">Efficiency not rewarded (Non-statistically significantly)</td></tr>
<tr><td>Old</td><td>Low</td><td>n.a.</td><td>n.a.</td><td>5.7</td><td>16</td><td>5.8</td><td>20</td></tr>
</table>

The table below shows the results from the regression analysis. Overall, we noticed more instability with regard to the value of the coefficients, a fact that was imputed to the size of the dataset and to the variables capturing only a subset of the factors influencing the price of second-hand[4]. Only in the case of dry bulk Panamax, Handymax and Handy size did the coefficient on technical efficiency conform to our expectation of a negative sign.

Table 43: Results from the regression analysis for Second-Hand Prices.

Ship Type	Ship Size	Average Effect of Energy Efficiency (Thousand Dollars)	Percentage
Dry bulk	**Panamax (60,000 100,000 dwt)**	600	3.3%
	Handymax (40,000 60,000 dwt)	700	5.0%
	Handy (10,000-40,000 dwt)	1,000	9%

3.6. IMPACT OF ENERGY EFFICIENCY ON THE DEMOLITION MARKET

3.6.1. EVIDENCE FROM THE INDUSTRY PRESS

Vessels with lower fuel efficiency and therefore higher fuel consumption may also be candidates for early scrapping, especially in a market characterised by low charter rates, vessels' oversupply, high bunker prices and a number of technology challenges. Even though each of the three current major technology challenges — ballast water, sulphur emissions and fuel efficiency — are unlikely individually to cause early scrappage of a vessel, some commentators believe that combined they may compel owners to scrap or sell vessels when survey dates are due rather than spending the sums of money required to remain compliant (LL 20/12/2012). In fact, Ningbo Marine, a dry bulk operator, confirmed upon selling a Panamax vessel to demolition yards that the sale was part of their objective to get rid of vessels with low fuel efficiency (LL 21/06/2012). Some commentators go even further by calling on governments to encourage scrapping of inefficient and old vessels at a national level, as done in Italy about 15 years ago (LL 07/06/2012). Some others notice that the establishment of a two-tier market, implying a difference in earnings between new and older vessels, will contribute to calls for more scrapping of older tonnage (LL 01/06/2012). Intercargo commented that the demolition market was taking care of poor-performing tonnage with around 400 bulk vessels scheduled to be recycled this year alone. According to Intercargo, fleet modernisation and operational measures were already having an impact (LL 02/10/2012).

3.6.2. RESULTS FROM MEAN COMPARISON

Results from the comparison of means are strongly in favour of the hypothesis that owners tend to demolish ships with lower energy efficiency. In thirty out of thirty-eight instances, demolished ships are less energy efficient than those in the fleet, the difference between the averages being statistically significant in eighteen of the thirty cases above. Demolished ships are more energy efficient than those in the fleet in eight cases, but only in one case is the difference between the averages statistically significant.

For each ship size in each market, the tables below show the energy efficiency and capacity of the ships being demolished and those left in the fleet with an age ranging between the newest and the oldest demolished ship, the average age of the demolished ships and the number of ships being demolished in each year. Demolished ships tend to be smaller than those left in the fleet, therefore showing owners' preference for bigger ships. This trend may have some implications for the efficiency of the demolished ships, as bigger ships tend to be more efficient, although it is not thought to have preponderant effect on the results, as we can observe a number of instances where energy efficiency of demolished ships is lower despite their average size being bigger than those in the fleet – see for example Handy dry bulk in 2009

[4] One would expect second-hand prices, for example, to be influenced by factors such as the conditions of the engine, the hull, and the general wear and tear of the ship, which we could not take into account in our analysis due to lack of data.

and 2012, Feedermax container in 2009, 2010 and 2012 and Subpanamax container in 2010. The number of demolished ships increased in 2012 across sizes and shipping sectors while the age of demolished ships decreased.

Table 44: Selected characteristics of demolished ships and those operating in the dry bulk fleet

		2009	2010	2011	2012
Capesize (100,000 270,000 dwt)	Technical Efficiency of Demolitions (gCO_2/t.nm) / Fleet	n.a.	3.17 / 2.63	2.85 / 2.58	2.59 / 2.66
	Dwt of Demolitions (tonnes) / Fleet	n.a.	144,462 / 181,179	157,178 / 181,594	169,975 / 183,112
	Average Age of Demolitions	n.a.	28.2	26.4	23
	Sample	n.a.	17	62	64
	Are demolished ships less efficient?		Yes Significantly.	Yes Significantly.	No. Non significantly.
Panamax (60,000 100,000 dwt)	Technical Efficiency of Demolitions (gCO_2/t.nm) / Fleet	5.88 / 5.07	n.a.	5.12 / 4.74	5 / 4.62
	Dwt of Demolitions (tonnes) / Fleet	66,261 / 74,269	n.a.	68,590 / 76,187	67,947 / 77,111
	Average Age of Demolitions	28.6	n.a.	29.2	28.7
	Sample	27	n.a.	66	100
	Are demolished ships less efficient?	Yes Significantly.	n.a.	Yes Significantly.	Yes Significantly.
Handymax (40,000 60,000 dwt)	Technical Efficiency of Demolitions (gCO_2/t.nm) / Fleet	6.41 / 6.27	n.a.	6.41 / 6.26	6.29 / 6.04
	Dwt of Demolitions (tonnes) / Fleet	48,186 / 49,349	n.a.	46,806 / 51,158	45,557/ 51,768
	Average Age of Demolitions	30.6	n.a.	30	27
	Sample	26	n.a.	44	80
	Are demolished ships less efficient?	Yes Non-significantly.	n.a.	Yes Non-significantly.	Yes. Significantly.
Handy (10,000-40,000 dwt)	Technical Efficiency of Demolitions (gCO_2/t.nm) / Fleet	10.27 / 9.99	10.67 / 9.93	10.71 / 9.56	9.52 / 9.46
	Dwt of Demolitions (tonnes) / Fleet	27,137 / 26,975	25,961 / 27,364	25,607 / 27,885	29,135 / 28,093
	Average Age of Demolitions	31.9	32.4	32.3	30.1
	Are demolished ships less efficient?	Yes. Significantly.	Yes Significantly.	Yes Significantly.	Yes Non-significantly.
	Sample	198	98	191	213

Table 45: Selected characteristics of demolished ships and those operating in the wet bulk fleet.

		2009	2010	2011	2012
VLCC (250,000-460,000 dwt)	Technical Efficiency of Demolitions (gCO_2/t.nm) / Fleet	n.a.	2.35 / 2.51	n.a.	n.a.
	Dwt of Demolitions (tonnes) / Fleet	n.a.	265,635 / 303,645	n.a.	n.a.
	Average Age of Demolitions	n.a.	19.8	n.a.	n.a.
	Sample	n.a.	33	n.a.	n.a.
	Are demolished ships less efficient?	n.a.	No. Non significantly.	n.a.	n.a.
Suezmax (120,000-190,000 dwt)	Technical Efficiency of Demolitions (gCO_2/t.nm) / Fleet	n.a.	3.48 / 3.34	n.a.	3.41 / 3.3
	Dwt of Demolitions (tonnes) / Fleet	n.a.	145,974 / 155,533	n.a.	150,507 / 156,220
	Average Age of Demolitions	n.a.	21.2	n.a.	20.6
	Sample	n.a.	11	n.a.	18
	Are demolished ships less efficient?	n.a.	Yes Non significantly.	n.a.	Yes Non significantly.
Aframax (100,000-120,000 dwt)	Technical Efficiency of Demolitions (gCO_2/t.nm) / Fleet	4.23 / 3.89	4 / 4.08	4.16 /4.18	4.5 / 4.08
	Dwt of Demolitions (tonnes) / Fleet	95,998 / 105,325	92,806 / 105,903	97,518 / 106,479	97,378 / 106,732
	Average Age of Demolitions	22.7	24.4	20.7	20.3
	Sample	13	13	23	15
	Are demolished ships less efficient?	Yes Significantly.	No. Non significantly.	No. Non significantly.	Yes Significantly.

Table 46: Selected characteristics of demolished ships and those operating in the container fleet.

		2009	2010	2011	2012
Panamax (3,000-5,000 TEU)	Technical Efficiency of Demolitions (gCO_2/TEU.nm)/ Fleet	135.79 / 152.80	145.61 / 153.61	n.a.	145.93 / 155.81
	TEU of Demolitions / Fleet	3577 / 4092	3437 / 4124	n.a.	3391 / 4137
	Average Age of Demolitions	22.8	23.5	n.a.	22.5
	Sample	36	13	n.a.	17
	Are demolished ships less efficient?	No. Significantly.	No. Non significantly.	n.a.	Yes Significantly.
Subpanamax (2,000-3,000 TEU)	Technical Efficiency of Demolitions (gCO_2/TEU.nm)/ Fleet	176.6 / 166.3	171.7 / 165.5	180.9 / 163.1	168 /165.2
	TEU of Demolitions / Fleet	2420 / 2540	2653 / 2539	2577/ 2541	2421 / 2548
	Average Age of Demolitions	26.3	27.1	27	25.2
	Sample	39	11	10	32
	Are demolished ships less efficient?	Yes Significantly.	Yes Significantly.	Yes Significantly.	Yes Non significantly.
Handy (1,000-2,000 TEU)	Technical Efficiency of Demolitions (gCO_2/TEU.nm)/ Fleet	237.3 / 202.4	225.8 /205.6	233.1 / 192.2	198.5 /
	TEU of Demolitions / Fleet	1448 / 1408	1384 / 1414	1306 / 1415	1468 / 1408
	Average Age of Demolitions	28.1	29.9	28.9	21.4
	Sample	62	19	19	47
	Are demolished ships less efficient?	Yes Significantly.	Yes Significantly.	Yes Significantly.	Yes Non significantly.
Feedermax (500-1,000 TEU)	Technical Efficiency of Demolitions (gCO_2/TEU.nm)/ Fleet	321.4 /255.1	298.7 / 248	n.a.	260.2 / 247.2
	TEU of Demolitions / Fleet	742 / 731	744 / 713	n.a.	748 / 650
	Average Age of Demolitions	28.5	28.1	n.a.	25.9
	Sample	33	14	n.a.	13
	Are demolished ships less efficient?	Yes Significantly.	Yes Significantly.	n.a.	Yes Non significantly.
Feeder (100-500 TEU)	Technical Efficiency of Demolitions (gCO_2/TEU.nm)/ Fleet	429.9 / 402.7	423.1 / 417.6	377.4 / 385.2	378.5 /429.8
	TEU of Demolitions / Fleet	368 / 315	314 / 315	380 / 310	369 / 312
	Average Age of Demolitions	30.1	30	31.1	30
	Sample	13	18	11	18
	Are demolished ships less efficient?	Yes Non significantly.	Yes Non significantly.	No. Non significantly.	No. Non significantly.

3.7. SUMMARY OF FINDINGS

This section investigated whether technical energy efficiency commands a premium in the shipping markets and whether it has any role to play in the selection of the ships being sent for demolition. In relation to both questions we could find some anecdotal evidence in the literature but no rigorous quantitative analysis. In order to add to the evidence base provided by the literature, this section used two methodologies, one based on a simple comparison of average market prices, the other based on regression analysis.

We found that the strength of the evidence supporting the existence of a premium for energy efficiency varies across markets, shipping sectors and age of the ships. Some of the specifics for each of the markets studied are described below, however the overall impression provided by the analysis in Section 3 is that whilst there is quantitative evidence that answers the questions posed in the introduction "do more efficient ships command higher prices?" the answer is "yes, somewhat". The qualification for this is that whilst there is a premium in price it appears to be no more than 3-6% of the value of the contract (e.g. the newbuild ship's price, the second hand ship's price, the price paid for the time-charter contract). To place some of this in context – if the fuel cost is 50% of the total costs paid by a time charterer (the remainder being the time-charter cost), and there is a difference in technical energy efficiency of 20% between a high efficiency and a low efficiency ship, then the fuel savings differential between the high and low efficiency ship equate to 10% of the value of the time-charter contract. Given the uncertainty associated with the estimation of a ship's technical efficiency, and the importance of operational parameters in determining a ship's fuel consumption (which have not been included here), 3-6% is therefore an encouraging indication of rational behaviour in some of the markets.

However, the fact that the findings are not consistent (for some ship types, there is little strong evidence, or even results that contradict the expectation that there will be a premium associated with energy efficient ships) provides some evidence to support the observations in Section 2: without a strong signal from the market (e.g. significant price differential), then it is understandable for there to be some significant heterogeneity in the technical efficiency of the fleet.

In the time charter market, our findings suggest strong evidence of a premium for energy efficiency in the container sector and for relatively recently built ships. In the container sector, more energy efficient ships are paid higher average rates in 10 out of the 12 cases we analysed, the difference between average time charters for efficient and less efficient ships being statistically significant in 6 of the 10 instances above. In the case of recently built ships, energy efficient ships are paid higher average charter rates in 12 out of the 15 cases (individual ship sales) we analysed, the difference between average time charters for efficient and less efficient ships being statistically significant in 8 of the 12 instances above. These findings confirm anecdotal evidence from the industry press discussed in the sections above in relation to energy efficient ships receiving higher charter rates; containers being the most appreciative sector of energy efficiency, as indicated by several operators such as Maersk and Norden being strong advocates on this topic; and shipping operators more likely to pay a premium for efficiency in recently built ships. Although we found considerable evidence supporting the existence of a premium for energy efficiency in the time charter market, the impact seems rather limited. Based on regression analysis we conclude that the value of energy efficiency is around 3% of the average time charter rate. Based on the average time charter paid for dry bulk Panamax in 2012, the effect of energy efficiency on time charter prices can be quantified as being in the region of 200 dollars per day, although this is expected to rise if market conditions improve and time charters become more expensive.

Our findings, however, suggest that clear quantitative evidence for a premium for efficiency in new build prices may exist in the container sector only. In this sector, newbuild prices of energy efficient ships are higher in 7 out of the 11 cases we analysed, with the difference between average newbuild prices paid for efficient and less efficient ships being statistically significant in 6 out of the 7 cases above. We point out that no evidence supporting a premium for energy efficiency could be found in the case of the handy container ships which is responsible for 3 out of 4 cases where average newbuild prices for efficient ships are lower than averages prices for less efficient vessels. In the dry bulk sector evidence supporting the existence of a premium was almost as frequent as the evidence against it. In the wet bulk sector, evidence against the existence of a premium is more frequent than evidence supporting it, 3 instances and 1 instance respectively. Regression analysis confirmed the containerships as the sector where energy efficiency is valued most, its effect on price estimated at about 6%. This premium is equivalent to approximately 3 million dollars in the case of Subpanamax containerships delivered in 2011 and 2012.

Contradicting evidence from the comparison of average prices, a premium for more efficient ships is also found for Capesize and Panamax ships in the dry bulk sector and VLCC and Aframax ships in the wet bulk sector. In these cases the premium, which can be imputed to efficiency, is about 3%, half the size estimated in the container sector. These mixed findings confirm the fact that anecdotal evidence supporting the existence of an energy efficient premium is fairly scarce although it has been advocated by a number of shipping operators in the industry press.

Our findings suggest that energy efficiency is incorporated in the second-hand prices. Dry bulk second hand prices have a better reflection of the value of energy efficiency than new build prices. Second hand prices for energy efficient dry bulk ships are higher in 15 out of the 24 cases we analysed, with the difference between the average second-hand price paid for efficient and less efficient ships being statistically significant in 8 out of the 15 cases above. Unfortunately, not enough data were available to thoroughly analyse the container market, which is the market most appreciative of energy efficiency in the case of newbuild prices. Evidence for the Handy containerships sector shows a mixed picture, two instances where average prices of energy efficient ships are higher than the remaining ships and two instances where they are lower. However, this is an encouraging result if one bears in mind that the Handy size showed considerable evidence against the existence of a premium for more energy efficient ships incorporated in the newbuild price. Based on regression analysis, the share of second hand prices, which can be imputed to energy efficiency, varies considerably across ship types, the average being close to 5%. This corresponds to about 700,000 dollars in the case of the second-hand Panamax sold in 2011 and 2012. These findings contradict our expectations on the existence of an energy efficient premium in second hand prices. As industry press articles on the premium for efficiency in the second-hand market are extremely rare, we had not expected efficiency to be rewarded in this market.

In terms of the factors influencing the selection of demolished ships, our findings suggest that energy efficiency plays an important role in determining which ships are demolished. Average energy efficiency of demolished ships is higher in 30 out the 38 cases we analysed, the difference between the averages of demolished ships and those left in the fleet being statistically significant in 18 of the 30 cases above. These findings confirm anecdotal evidence in the industry press and are supportive of the concern for high fuel bills diffused among shipping operators, as discussed in a number of industry press articles referenced above. It also implies that energy efficient ships have a longer economic life therefore providing better revenue streams for their owners.

4. CONCLUDING REMARKS

4.1. SUMMARY OF FINDINGS

This report seeks to improve upon previous estimates of ship efficiency characteristics in a number of different ways: (1) attention to the underlying physics that influence the performance of ships (Section 1); (2) attention to the uncertainties associated with input data sources and the sensitivity of efficiency quantifications to the different input parameters (Section 2); (3) incorporation of new and far richer data sources (particularly Satellite Automatic Identification System, or AIS) to describe the operational variables of shipping (Section 2). The analysis updates previous shipping industry analyses to address some of the major shifts that have occurred in the shipping industry, particularly to do with ship speed, that have occurred in the 2007-2011 timeframe. Using the estimation of the fleet's technical efficiency, this data is then used to explore whether there is evidence in the markets (time charter, newbuilds, second hand and scrappage) to support the idea that more efficient ships attract a price premium (Section 3).

4.2. OBSERVATIONS ON THE ESTIMATED TECHNICAL AND OPERATIONAL EFFICIENCY

One overarching conclusion from the work is that the richness of the global AIS data allows for detailed assessments of particular questions about ship efficiency characteristics. Table 47 indicates this study's overall statistics on the number of ships and their activity, alongside the summary CO_2 emission findings. The analysis is based upon detailed data of about 36,000 ships covering approximately 61,000 billion tonne-nm of transport supply. The analysis categorizes ships into nine primary categories, each of which has greatly differing characteristics about their activity and their efficiency.

The average transport-supply-weighted CO_2 emission characteristics are presented in Table 47 (See Section 2 for more detailed analyses broken down by ship size category) for the nine ship types that constitute this study. It should be noted that for Container Ships and Pure Car Carriers, the capacity used in the following several figures (Table 47, Figures 46 through 48) is the deadweight; it has not been generated using the assumptions in the IMO 2nd GHG Study for mass per container (TEU) or car (CEU). Much of the difference between the ship types can be attributed to the difference in average ship capacity, since ship size is such a significant driver of energy efficiency, design speed is also an important parameters and explains the relative high values for weighted average technical efficiency in relation to ship size for LNG carriers, container ships and Pure Car Carriers. There is also some observable difference between ship type's ratios of normalized operational to technical efficiency. Some of this can be explained through differences in capacity utilization between ship types, however the extent to which the ship type has taken up slow steaming also contributes to the differences. Container ships, the sector showing the greatest uptake of slow steaming and a sector with a comparatively high capacity utilization show the lowest values. Product tankers have a notably high normalized operational efficiency and high value for the ratio of operational vs. technical efficiency. This ship type is dominated by smaller ships (<10,000 dwt tonnes), which have proportionately high values for the boiler fuel consumption (see Table 3). For the smaller ships the boiler consumption according to this data is of the same order as the main engine fuel consumption. The boiler therefore makes a significant contribution to the total carbon emissions component of the calculation of normalized operational efficiency, whereas this contribution is currently not included in the calculation of technical efficiency. For future work, this justifies obtaining information from a wider range of sources on product tanker boiler fuel consumption, and for considering inclusion of boiler fuel consumption in the calculation of Technical efficiency.

Table 47: Summary of ship characteristics and average efficiency by ship type from this analysis

Ship type	Ship type characteristics				CO_2 related characteristics		
	Number of ships in the dataset	Average per-ship capacity (deadweight tonne)	Average per-ship distance (nm/year)	Age (years)	Technical efficiency (gCO_2/t.nm)	Normalized operational efficiency (gCO_2/t.nm)	Ratio of operational vs. Technical efficiency
Crude Tanker	2,129	210,452	81,387	8.2	3.0	7.4	1.97
Product Tanker	6,506	56,163	52,787	7.4	6.6	23.5	3.44
Chemical Tanker	1,185	25,488	78,133	9.8	10.7	16.1	1.24
Dry Bulker	9,180	109,743	82,740	9.0	4.1	6.9	1.66
General Cargo	10,001	8,545	62,138	21.1	16.2	23.8	1.93
LNG tanker	314	75,175	106,404	14.4	10.6	20.5	1.78
LPG tanker	1,039	41,201	87,103	12.2	9.1	18.7	1.62
Container ship	5,094	69,082	105,747	7.8	11.3	12.0	1.10
Pure Car Carrier	720	17,373	83,632	9.4	16.3	20.3	1.38
Average	36,168	113,283	85,993	8.7	6.2	10.0	1.70

[A] assumes 7 tonnes per TEU for container ships and assumes 1.5 tonnes per CEU car carriers for this high-level summary

Beyond the average characteristics of the ships, the more detailed data show just how broadly the ships' energy efficiencies within these ship types vary. Figure 46 shows a bimodal distribution for the normalized operational efficiency, with peaks occurring at 5 gCO_2/t.nm and 12 gCO_2/t.nm, coincident with the peaks in the bulk (wet and dry) and container fleets respectively). Generally the ships with higher CO_2 emissions in the right tail of the distribution is associated with smaller ships and higher speeds – there is little evidence in the data (Section 2) that ship age is a significant driver for poor energy efficiency, except where it is coincident with a trend for smaller ship size.

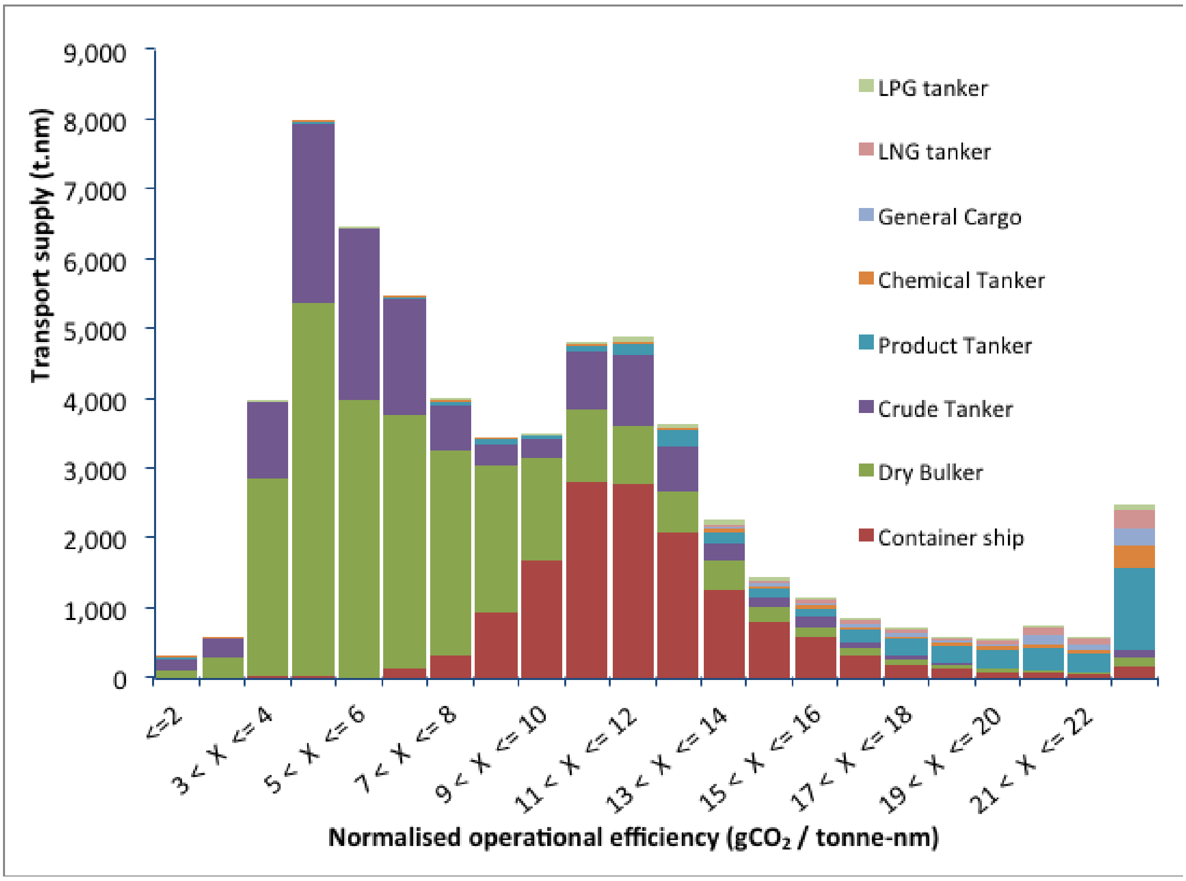

Figure 46: Ship transport supply at given normalised operational efficiency levels

As already mentioned, it is anticipated that one of the core underlying reasons for variation in operational efficiency is the variation in the average speed at which the ships are operating. Figure 47 shows the amount of transport activity across average ship speeds, as observed using the Satellite AIS data deployed in this study. The results indicate that ships tend to be operated, in 2011, at an average of 15% below their design speed. Some ship types are found to operate at lower relative speeds (e.g., container ships at 23% below design speed), whereas others are at higher relative speeds (e.g., chemical tankers, dry bulkers, and LPG tankers at about 10% below design speed). Within ship types, the variation among ships is quite wide (and is described in detail in Section 2). Although these figures indicate that container ships are the ship type with the lowest average relative speed, 23% below design speed, their actual operation speed, at an average of 17.8 knots, is also the highest among the nine types.

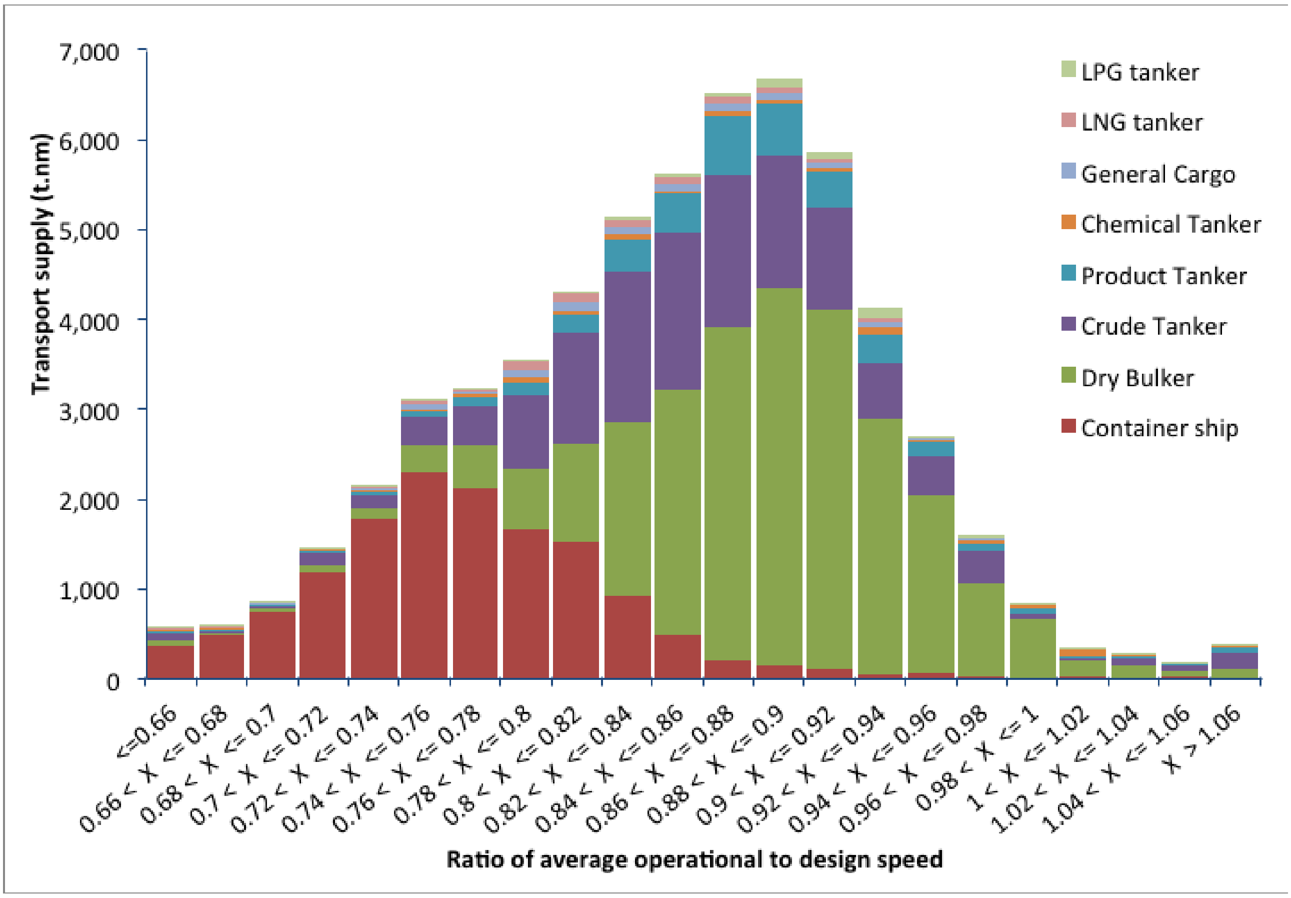

Figure 47: Ship transport supply at given operation-to-design speed ratios

Figure 48 is another presentation of the study's results on technical and operational efficiency. As shown in the figure, if ships operated at their technical efficiency, their CO_2 emissions would be reduced by about 36% on average – but by about 8% (for container ships) and as high as 71% (for product tankers). Additional results from this analysis give an indication of how much higher the efficiency and lower the CO_2 emissions are for the most efficient ships. For each ship type, the 90th and 95th percentile for most efficient ship transport activity (based on annual averages of all the ships in the analysis and normalized capacity utilisation) reveal how much lower CO_2 emissions could be, using existing technology and current operational practices. This is remarkable considering that, relative to the operational efficiency estimated in the IMO 2nd GHG study; the normalized operational efficiencies in this study are already lower (due to the take up of slow steaming). These 10% and 5% lowest-CO_2 vessels by each ship type are on average 46% and 53% lower CO_2 emission per ship capacity than the average for their segment. As a result, in eight of the nine ship types, the 10% and 5% lowest CO_2 emission ships are operating with lower CO_2 emissions than their technical efficiency.

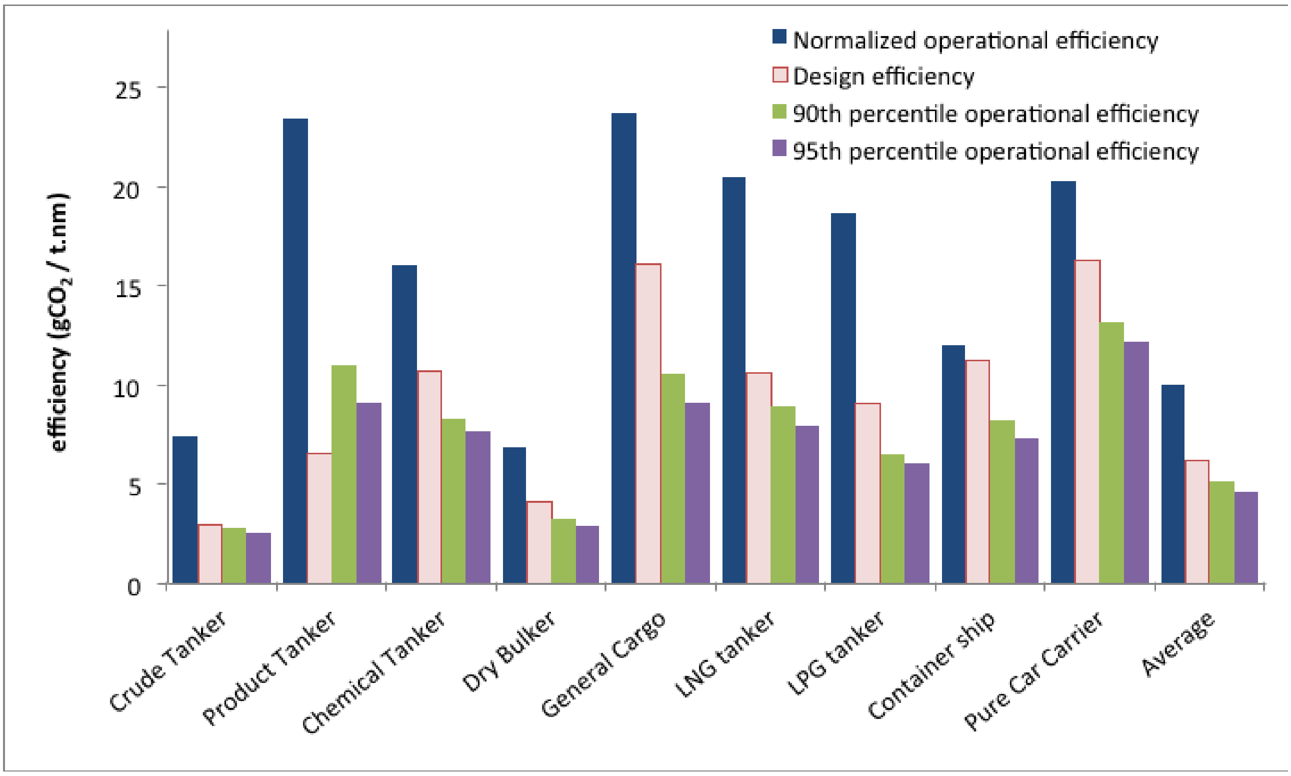

Figure 48: Operational, technical, 90th percentile, and 95th percentile energy efficiency

Figure 49 gives a more direct indication of the variation of CO_2 emission rates and ship efficiency within one given ship type: Container ships. This figure specifically shows only ships between 3000 and 8000 twenty-foot equivalent unit capacity, to take out the much smaller and larger container ships. These 3000-8000 TEU ships represent 72% of the TEU.nm transport supply of container ships from this global analysis. As shown in the figure, the lowest efficiency ships, representing 5% of transport supply, have annual average CO_2 emission rates of 192 gCO_2/TEU.nm or greater. The highest efficiency ships, also representing 5% of transport activity by container ships, have annual average emissions of 118 gCO_2/TEU.nm or lower. The low-CO_2 ships are about 21% better than the average CO_2 emissions of all container ships, whereas the high-CO_2 ships are about 28% higher than the industry average.

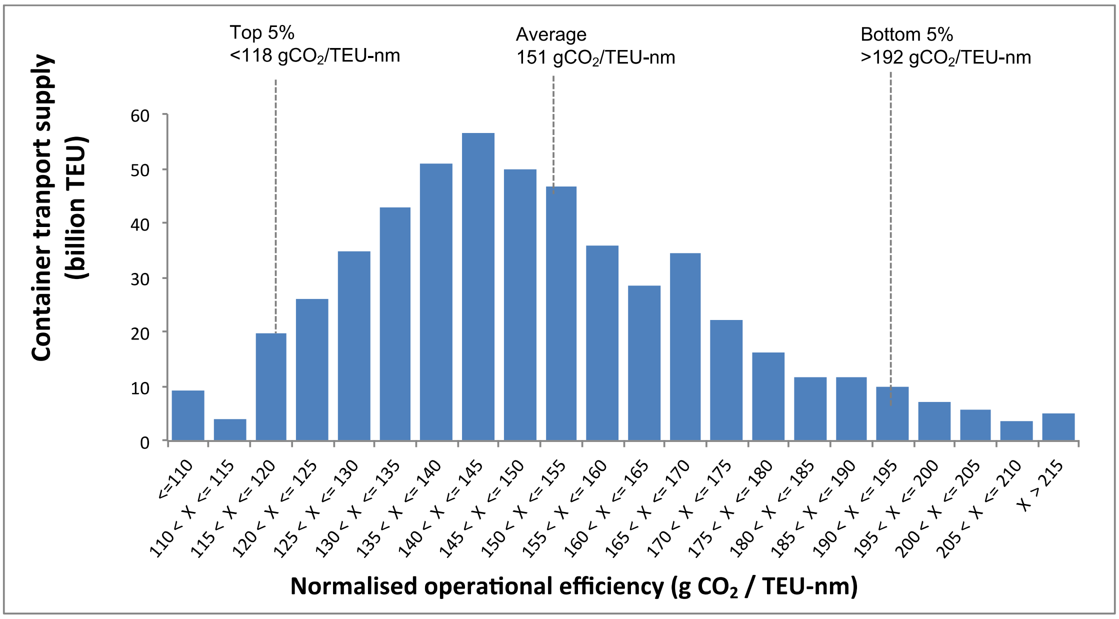

Figure 49: Container ship transport supply by 3000-8000 TEU container ships by ships average annual CO_2 emission rate

Figure 50 shows an aggregated summary of how the data from this study compare to that of the IMO 2nd GHG study. This analysis provides normalized operational efficiency rates to account for the ship type fleet composition (numbers and specifications of ships) in 2011, 2011 ship activity, 2011 routes, and changes in vessel speed, and adjustments for IMO conventions on the payload capacity (see Section 1). Whilst every attempt was made to ensure comparability, there are known to be some differences in how ship types have been classified (see Section 2), and this work is based on global satellite data on ship movements, whereas the IMO 2nd GHG study relied on a different source of information and differing assumptions for the effects of fouling and weather, as a result some element of the difference observed in the results could be an artefact of methodology difference and not a difference in reality. The data tables throughout Section 2 provide many direct and detailed comparisons from this study's findings to that of the 2nd IMO GHG Study on the 2007 fleet's characteristics. As shown in the aggregate data, the findings of this study suggest that the average efficiency has improved, thereby giving generally lower CO_2 emission rates per unit of transport supply than those of the 2nd IMO GHG study. It is suggested, based on the analysis in Section 2, that the main explanation for the differences is the operating speeds of the fleet in 2011, relative to those in 2007.

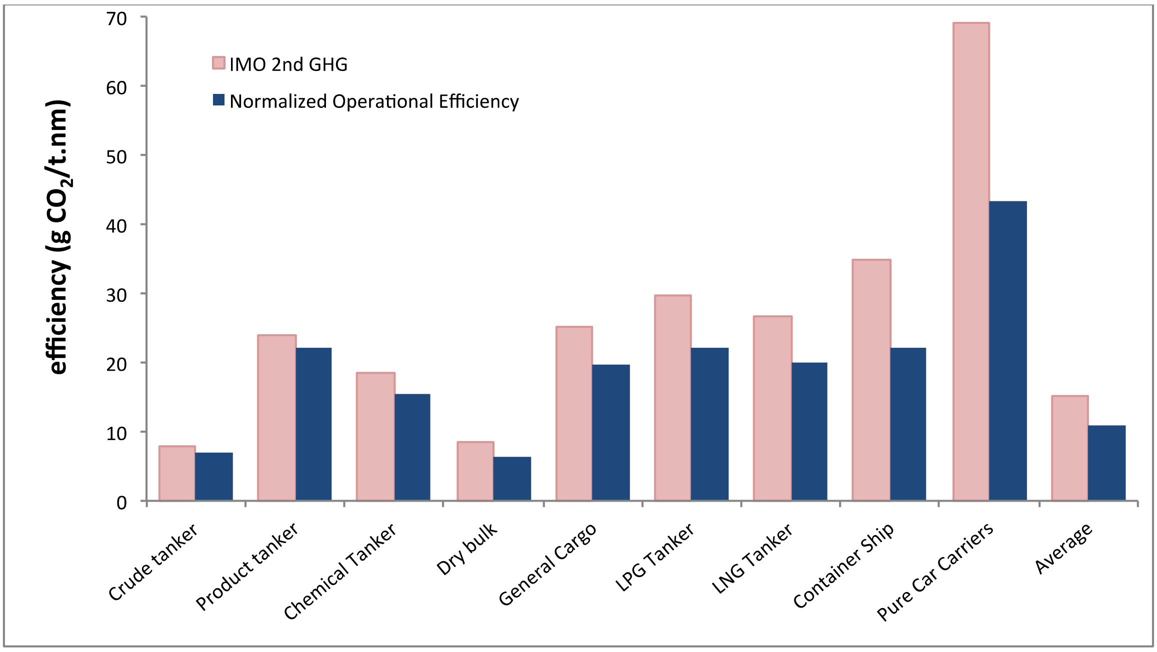

Figure 50: Comparison between the estimations of normalised operational efficiency in this report and the operational efficiency data in the IMO 2nd GHG Study

In this summary of findings, it is noteworthy to mention which vessels are not covered in the assessment. A number of vessel segments were outside the scope of this assessment. The segments that are excluded from this analysis include passenger (e.g., ferry, cruise), service (e.g., dredgers, tugs), ro-ro, refrigerated, dry bulk, specialized tankers, bunkering vessels. In many of these sectors, the approaches described in Section 1 were not thought applicable without substantial further work. Many of these sectors also have large auxiliary energy demands relative to the propulsion energy demand and this would introduce uncertainty in a study primarily focused on changes in propulsion energy demand, and many of these sectors are also those where the activity is predominantly coastal and therefore in many places poorly covered using Satellite AIS data. From the perspective of understanding the shipping industry's CO_2 emissions and fuel consumption, their omission can be justified by the fact that the ship types that have been included represent the majority share (74.6% of the sector's total emissions, as calculated in the IMO 2nd GHG Study).

It is also observed that global satellite data provides a richness of data than can be utilized in more detailed ways than conveyed here in this report. This could include route specific calculations that more provide insights about trade routes and regional trade and how their associated energy demands and CO_2 emissions differ. Figure 51 provides an illustration of how given routes can have greatly varying CO2 emissions intensities (red are the highest CO_2, yellow are lower CO_2, green is lowest CO_2 per TEU.nm). To aid clarity, the figure is derived from only a several-week sample of container ship activity, but nonetheless gives an indication about how route-specific data could inform more detailed analysis of the geography of energy efficiency and ultimately not just the analysis of the fleet, but also the supply chains carrying maritime trade.

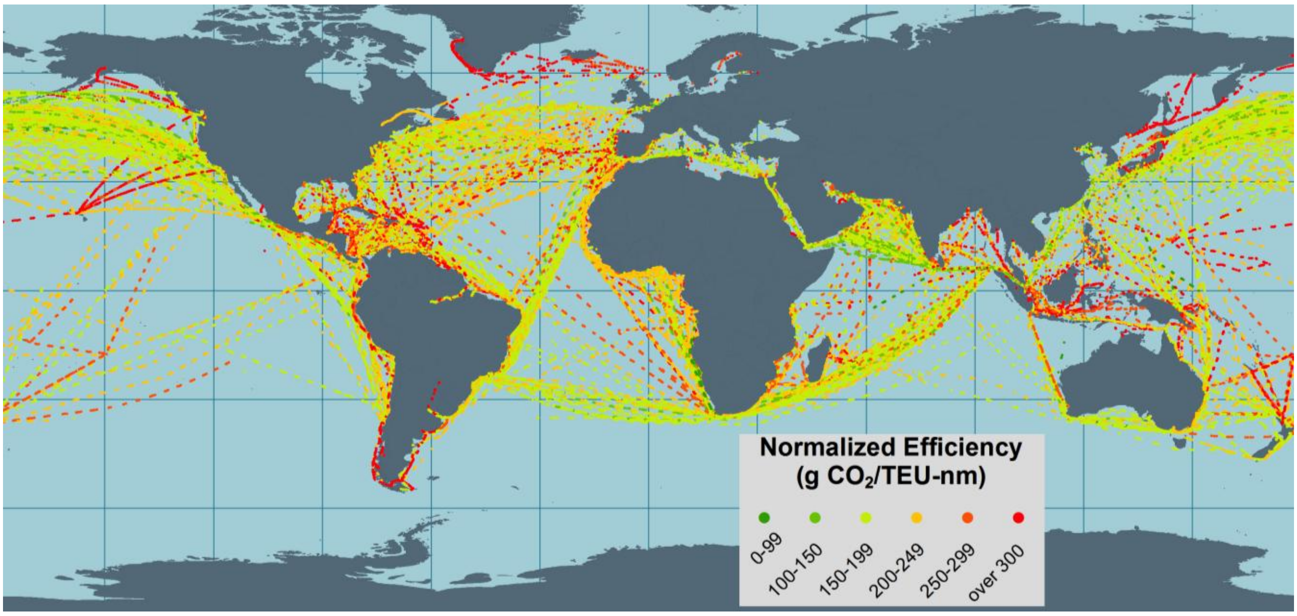

Figure 51: Illustration of annual average container ship normalised energy efficiency per route, where green is better energy efficiency, red is lower

4.3. OBSERVATIONS ON THE ESTIMATED RELATIONSHIP BETWEEN EFFICIENCY AND PRICES

As far as we are aware, this report has presented the first comprehensive analysis of the effect of ships' energy efficiency on time charter rates, newbuild and second hand prices and demolition activity. Our findings confirm anecdotal evidence from the industry press on energy efficiency being reflected in the time charter rates, especially in the recently built vessels, but our quantitative analysis shows that the effect, which can be imputed to energy efficiency, is limited, i.e. about 3% of the average time charter rates. Evidence of newbuild prices containing an energy efficiency premium is less strong, with the exception of the container sector. Its possible that this is a reflection of the fact that whilst the newbuild data is for the same, post financial crisis period as the data for other markets, newbuild 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 the ships being demolished. With regard to the sectors we assessed in this study, we conclude that as a percentage of prices, the container sector appears the most price sensitive to energy efficiency as shown by the existence of a premium both in the case of time charter rates and newbuild prices, although perhaps this is to be expected for a sector which has proportionately higher fuel costs to begin with due to the higher speeds of the 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 maximize 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 at 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 to 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 in 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 establishment of databases documenting the performance of vessels across time and in different weather conditions.

In concluding, it is important to emphasize that any of the figures on the impact of energy efficiency computed in this study are dependent on the specific definition of energy efficiency that has been applied here. The set of variables used in the analysis, the way we have taken into account factors from the shipping industry, the economy assumed to affect all transactions in the same way and our decision of comparing the average effect in the more energy efficient half of the fleet to the average effect in the remaining portion of the fleet. For these reasons, this should not be seen as a definitive assessment of the impact of energy efficiency on the markets, more a first attempt using the best data that is available to try and understand the problem and issues. On the other hand, there is robust evidence to conclude that energy efficiency is being incorporated in the markets, although the percentage effect seems to be relatively small. The analysis of technical efficiency of the existing fleet and the heterogeneity that it shows needs to be placed in the context of the energy prices associated with that era and the absence of any policy, which might have placed attention on energy efficiency. Bearing in mind the increased attention given to energy efficiency in recent years, not just by the shipping industry's owners and operators but also the wider stakeholder community and the supply chain it serves, we would expect its impact on the shipping market to grow, especially with the ongoing debates on the subject in the industry press and the policy making bodies, and with a prolonged exposure to historically high energy prices and low revenues.

4.4. INFERENCES FROM THE ANALYSIS OF EFFICIENCY

4.4.1. ENERGY EFFICIENCY DESIGN INDEX

In January 2013, the IMO's Energy Efficiency Design Index (EEDI) regulation came into effect, stipulating minimum efficiencies for newbuild ships. Albeit retrospectively, the evidence in this report supports the concept of a minimum energy efficiency regulation as there is not a strong trend appearing in the technical and operational efficiency statistics to show improvements in efficiency with ship age, and the analysis of the newbuild market prices did not show a consistent or strong premium attached to energy efficiency. Furthermore, the data demonstrate that there is heterogeneity in the technical efficiency of ships in all sectors of the fleet, regardless of age, and that this implies that there is potential to increase efficiency using technology and designs, which exist today.

However, there will always be exceptions to the generalisations above. There are good reasons, for certain cargos and routes, to optimize ships in a way, which might score them poorly on technical efficiency whilst in practice achieving high operational efficiency. Ultimately, it is the operational efficiency of a ship that is the driver of emissions and it is important that EEDI does not have a perverse effect on the emissions of the industry, forcing the adoption of designs, which are optimized for a condition in which they are rarely operated in practice. The data shows how for a fleet (ship type and size category, e.g. VLCC tankers) where the technical efficiency might vary from 90th to 10th percentile by +/- 20%, the corresponding range of normalized operational efficiency can be + / - 50% or more (in the year studied here – 2011). That indicates that progress towards technically efficiency ships can easily be lost in the variability of operational practices.

An initial test of the significance of these risks to the efficacy of the EEDI regulation can be seen by inspecting the data in this report for a correlation between technical and operational efficiency: do more technically efficient ships have lower operational efficiency? Figure 52 shows, for two example fleets, the dry bulk and container fleet that there is a correlation between technical and operational efficiency, but in many instances there are ships that do not fit this rule. The coefficients of determination, R^2, have been calculated for both the dry bulk and container fleet, with the container fleet demonstrating a weaker correlation. In both instances, it appears that the evidence of a correlation diminishes as the efficiency of increases (gets worse). A fairer assessment might be achieved by inspecting the correlation for individual size ranges (which would be more consistent in technical and operational efficiency) and this could be the subject of further work, however even at this stage it appears that the efficacy of EEDI in bringing about genuine emission reductions might be greatest for the larger ship sizes (more efficient) and less good for the smaller ship sizes.

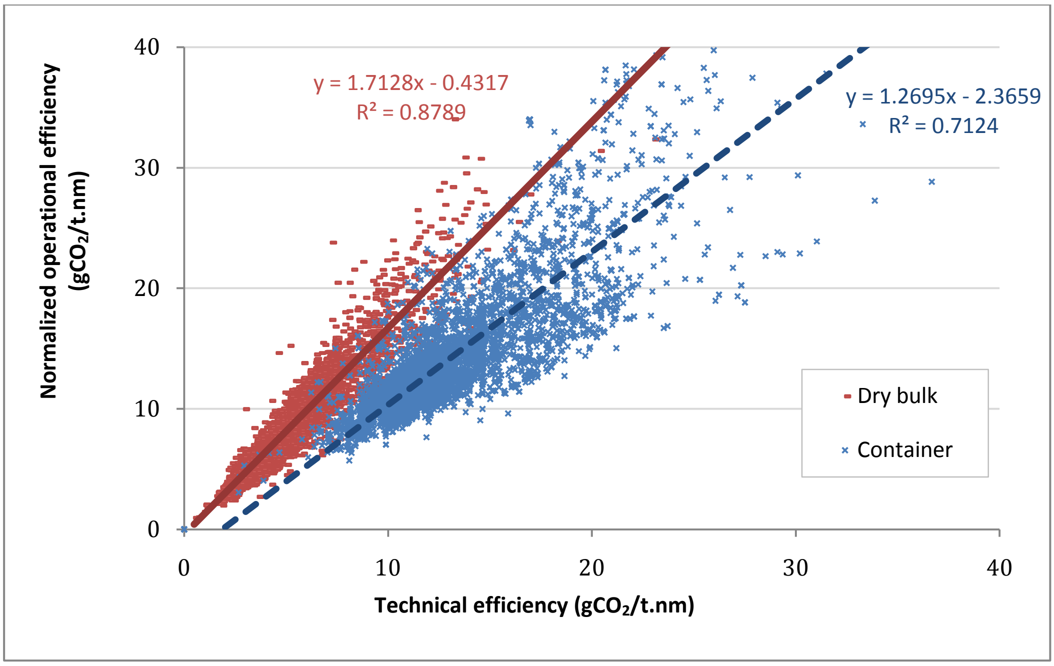

Figure 52: Relationship between technical and operational efficiency of the dry bulk and container shipping fleets

4.4.2. THE NEED TO UNDERSTAND THE OPERATIONAL EFFICIENCY AND THE DRIVERS OF OPERATIONAL EFFICIENCY

A notable finding, which has been enabled by the use of Satellite AIS data, is the large heterogeneity in the operational efficiency (both when applying a normalization to capacity utilization and when using AIS derived draughts) of the fleet. This heterogeneity implies a large potential for improvement (Figure 48), albeit one which it is hoped the introduction of the Ship Energy Efficiency Management Plan (January 2013) will start to address. However, because operational efficiency is so important for the emissions of the sector and because this analysis shows that there is a potential for improvement, there are a number of important points that this raises: (1) that there is a need for further work to refine the methods deployed in this study, to reduce the uncertainty associated with the estimation of an individual ship's energy efficiency by reducing the reliance on generalized assumptions (e.g. on hull fouling and weather) and to increase the levels of validation (2) that there should be further use of the data (or equivalent) to try and understand the drivers of energy efficiency.

With regard to (1), this should occur over time as research expertise in this area improves and greater data for validation becomes available. The current discussions on Monitoring Reporting and Verification, both at IMO and the EC, could result in important validation datasets being created, should there be some mechanism for their availability for this purpose. This study has attempted to address the issue of capacity utilization, through the use of AIS reported draught data, however an inability at present to validate these estimates of capacity utilization led the report to resort to the use of normalized operational efficiency for much of the data discussed in these conclusions. Given the significance of capacity utilization to the calculation of operational efficiency (operational efficiency is directly proportional to capacity utilization), it is important that the uncertainty in this relatively understudied variable is addressed.

Implying significant potential for improvement and there being significant potential for improvement are two different things. The gap can only be closed between these two states with a greater understanding of the drivers for the heterogeneity in the operational efficiency data. A simplistic observation would be that the variability in the operating speeds of the fleet are the cause for the heterogeneity, which therefore leads onto the question what are the drivers for the variability in operating speeds, are these for sound commercial reasons (e.g. economically rational behaviour) or is the variability a function of market barriers or failures. The analysis undertaken in this report has not been able to assess the drivers for speed, however the data presented here, combined with other types of data, has the potential to explore whether there are connections between ships travelling at certain speeds, their chaterparty type, the supply chains they operate in, the cargo they are carrying, fuel costs and fuel savings potential, the route they are travelling on etc. and this may in turn help to develop important understanding into what the gap is between implied potential and actual potential for further operational efficiency improvement.

4.4.3. MARKET BASED MEASURES DISCUSSION AND TECHNO-ECONOMIC ANALYSIS

A market based measure typically uses a price signal (e.g. carbon price) to incentivize behaviour. In theory, when applied using techno-economic analysis such as a Marginal Abatement Cost Curve, the price signal creates a technical or operational change, which reduces carbon intensity and ultimately emissions. The fundamental principle behind both is that the carbon cost savings (often obtained through increased energy efficiency) provide payback for an upfront investment or other cost. However, for this to work in practice, the market must function in such a way that the carbon cost savings are passed back to the party that bears the cost. The multi-stakeholder nature of the shipping industry (ship yard, owner, time charterer, voyage charterer, cargo owner etc.) and the difficulty of obtaining rigorous and transparent quantifications of energy efficiency and carbon intensity, could obstruct the passage of cost savings back to the stakeholders taking upfront risk. The consequence of this being that if a market based measure were badly designed, it could have little impact on in-sector carbon emissions (albeit generating revenue which could in turn purchase out of sector emissions reduction), whilst having significant negative impacts on the cost of shipping.

Without unpicking whether there was either a split-incentive, an information deficit or another explanation, Section 3 found that the premiums associated with energy efficiency in the different markets (time charter, second hand, newbuild and scrappage) support the concept of market based measures. However, the relative magnitude of the premiums to the fuel cost savings of individual vessels imply that there is evidence of market barriers and failures which would reduce the efficacy of a market based measure (relative to the assumptions often used in analysis at the moment – that all the carbon cost savings can be counted as capital for investment in abatement interventions), and that there are some significant differences in the different markets. Its therefore important that work continues not just to identify market barriers but to try and quantify the extent of market barriers and failures, and that analysis used to argue the cost-benefit of market based measures is not naive to their existence and magnitude. This finding also implies that there could be significant emissions savings produced just by using policy (or even voluntary initiatives) to remove market barriers and failures (e.g. making rigorous and transparent data on energy efficiency widely available) in order to ensure that the price premium of energy efficiency is strengthened.

4.5. FURTHER WORK FOR IMPROVING ESTIMATES

As this study is one of the first attempts to deploy Satellite-AIS data to understand the world fleet's energy efficiency, a number of areas for further work have been identified.

4.5.1. ESTIMATING SHIPPING ACTIVITY AND OPERATIONAL PARAMETERS USING AIS

Coverage of shipping's activity in congested seaways and ports appears to be poor with Satellite-AIS. This presents difficulties with the use of the data to estimate shipping's days at sea and days at port, key variables in the estimation of transport work done. With time, it is expected that Satellite-AIS improves both with respect to its global coverage (more satellites) and the algorithms used to handle data in congested sea areas. However, in the meantime, improvements can be achieved by splicing together Satellite-AIS data with Shorebased-AIS data. It is likely that this would still lead to imperfect coverage (there are times when ships turn off their transponders, e.g. when near piracy zones), however any increases in coverage will help to reduce some of the key uncertainties (particularly days at sea/port).

To compensate for any shortcomings in coverage, models and logic for shipping activity, if rigorously verified could help "fill in the gaps". As deployed in the 2nd IMO GHG Study, shortest path algorithms could be developed to estimate the missing shipping activity and this would allow greater fidelity for the port identification module. The main reason this was not inclusion in this iteration was time and computational limitations.

Ideally, the generation of training data (e.g. fixture data) used for the allocation of ship movements to port-to-port trade could be automated. This would significantly benefit the model and allow for identification of dependence between variables rather than the naïve Bayes assumptions of independence. This would also allow the extension to the use of a dynamic model in which Markov processes (dependence between subsequent AIS messages) could be included.

Using the modelled network, it would be possible to identify port traffic and therefore identify efficiency of the fleet entering the port. However, as outlined previously, this may be unreliable for some ports in dense traffic areas. Such an analysis would benefit greatly from the addition of a shoreside AIS dataset as discussed above. Ship's loading conditions on specific voyages were identified as a key uncertainty and a reason for the inclusion of normalised operational efficiency. Further investigation of alternative sources of loading condition information, either for direct substitution in the methods used here or as a means to verify or filter the AIS reporting of draught, would greatly benefit the confidence with which the operational efficiency estimate can be interpreted.

4.5.2. ESTIMATING FUEL CONSUMPTION FOR TECHNICAL AND OPERATIONAL PARAMETERS

This study uses established theoretical methods (e.g. Holtrop and Mennen) to calculate the resistance and fuel consumption for a ship in a specific condition. However, these methods were originally intended for use in design. More sophisticated models (e.g. computational fluid dynamics) can be used but require significant computational resource to deploy. It is unlikely that it will be feasible to deploy for all ships and a sufficient number of operational states that could capture voyage level fuel consumption. Therefore, rather than proposing a switch to a more sophisticated computational model, further work could help validate the use of these simpler models by rigorously testing and quantifying the uncertainties associated with the study's range of ship specifications and operational conditions.

The impact of weather on the fuel consumption is likely to be route and voyage specific (the wind, waves and current encountered by a ship are not the same in every ocean), despite the availability of information on the vessel's position in time, in this study a global average estimate is applied. There are datasets describing hindcast weather conditions (e.g. NOAA, Met Office) with a degree of accuracy and geographical specificity that could be combined with theoretical models for the estimation of fuel consumption in a specific set of environmental conditions. Whilst it is likely that there would remain a moderate degree of uncertainty associated with such estimates, particularly in more extreme weather conditions, this should present an improvement over the current global average estimate.

The specificities of marine coatings and information on fouling have been simplified to a consistent average applied to all ships (regardless of age). Should a database matching details of coating type to individual ships be available it would be of significant benefit to improve the specificity of the theoretical model, and if feasible expand on the level of detail applied in the estimation of how the condition changes through time.
In combination with further work validating the individual components of the theoretical model of fuel consumption, validation of the approach could also be gained through comparison against aggregate fuel consumption data assembled by ship operators or other third party organisations.

4.5.3. LONGITUDINAL ANALYSIS

This study has primarily focused on analysing the efficiency of the fleet in 2011. The methods used involve a large number of differences, both on sources of input data and methodology, relative to the previous work in the field (i.e.,. the IMO 2nd GHG Study). Public information on ships' technical and operational efficiency is limited. Shipping's emissions can be reduced either by reducing transport demand or increasing operational efficiency. To minimize negative impacts on transport demand, it is therefore key to understand the drivers of operational efficiency and indeed this is one of the aims of this report. However, to understand the 'levers' and the influence that external drivers (policy, fuel price, freight rates, technology availability) have on shipping's efficiency, it is crucial that more work is done that can look at changes in efficiency over time (e.g. longitudinal analysis). 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.

Furthermore, longitudinal analysis of trends in efficiency could be used to monitor the consequences of the introduction of certain policies and validate claims made in the scenario analysis and forecasting of the efficacy of those policies. For example: Can we observe changes in technical efficiency of the fleet due to the introduction of EEDI? Does this also result in improvements in operational efficiency? Is SEEMP generating the impact that it was expected to have?

There are limitations to the extent that the methods described in this study can be deployed in longitudinal analysis, because the coverage of Satellite-AIS is significantly worse before 2011 and non-existent before 2008. However, it should be possible to conduct a calibration of equivalent methods (e.g. using LRIT, Long Range Identification and Tracking, or equivalent data as a substitute to Satellite-AIS) in order to get a more detailed analysis of the trends in the efficiency and the leading order components of efficiency over time.

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ANNEX 1 – ASSUMPTIONS BY SHIP TYPE

Ship Category		Size	Size Unit	Main Engine Load	Auxiliary Engine Load	days at sea per year	Yearly Capacity utilisation	Annual boiler consumption	Boiler consumption per loaded day	Condition impact on fuel consumption	Weather impact on fuel consumption (15% for ocean going, 10% for coastal)
Crude oil	tanker	200,000+	dwt	73%	63%	274	48%	1300	10	109%	115%
Crude oil	tanker	120,000–199,999	dwt	80%	63%	271	48%	900	7	109%	115%
Crude oil	tanker	80,000–119,999	dwt	80%	63%	254	48%	3000	25	109%	115%
Crude oil	tanker	60,000–79,999	dwt	70%	56%	238	48%	3000	26	109%	115%
Crude oil	tanker	10,000–59,999	dwt	70%	56%	238	48%	1500	13	109%	115%
Crude oil	tanker	0–9,999	dwt	65%	56%	180	48%	500	6	109%	110%
Products	tanker	60,000+	dwt	80%	63%	171	55%	3600	38	109%	115%
Products	tanker	20,000–59,999	dwt	66%	63%	171	55%	3000	32	109%	115%
Products	tanker	10,000–19,999	dwt	70%	56%	183	50%	1800	20	109%	115%
Products	tanker	5000–9,999	dwt	75%	56%	177	45%	900	11	109%	110%
Products	tanker	0–4999	dwt	65%	56%	175	45%	300	4	109%	110%
Chemical	tanker	20,000+	dwt	80%	63%	251	64%	0	0	109%	115%
Chemical	tanker	10,000–19,999	dwt	80%	56%	246	64%	0	0	109%	115%
Chemical	tanker	5000–9999	dwt	76%	56%	246	64%	0	0	109%	110%
Chemical	tanker	0–4999	dwt	65%	56%	180	64%	0	0	109%	110%
LPG	tanker	50,000+	cbm	70%	63%	273	48%	0	0	109%	115%
LPG	tanker	0–49,999	cbm	65%	56%	180	48%	0	0	109%	110%
LNG	tanker	200,000+	cbm	70%	63%	260	48%	0	0	109%	115%
LNG	tanker	0–199,999	cbm	70%	56%	274	48%	0	0	109%	115%
Other	tanker			65%	56%					109%	110%
Bulk		200,000+	dwt	71%	76%	281	50%	0	0	109%	115%
Bulk		100,000-199,999		70%	76%	279	50%	0	0	109%	115%
Bulk		60,000–99,999	dwt	70%	76%	271	55%	0	0	109%	115%
Bulk		35,000–59,999	dwt	70%	72%	262	55%	0	0	109%	115%
Bulk		10,000–34,999	dwt	70%	79%	258	55%	0	0	109%	115%
Bulk		0–9999	dwt	65%	68%	180	60%	0	0	109%	110%
General	cargo	10,000+	dwt	80%	69%	260	60%	0	0	109%	115%
General	cargo	5000–9999	dwt	80%	69%	272	60%	0	0	109%	110%
General	cargo	0–4999	dwt,	65%	54%	180	60%	0	0	109%	110%
General	cargo	10,000+ dwt	100+TEU	65%	58%	240	60%	0	0	109%	115%
General	cargo	5000-9999 dwt	100+TEU	65%	54%	180	60%	0	0	109%	110%
General	cargo	0–4999 dwt	100+TEU	65%	75%	180	60%	0	0	109%	110%
Other dry	Reefer			69%	61%					109%	110%
Other dry	Special			65%	61%					109%	110%
Container		8000+	TEU	67%	101%	241	70%	0	0	109%	115%
Container		5000–7999	TEU	65%	101%	247	70%	0	0	109%	115%
Container		3000–4999	TEU	65%	85%	250	70%	0	0	109%	115%
Container		2000–2999	TEU	65%	85%	251	70%	0	0	109%	115%
Container		1000–1999	TEU	65%	76%	259	70%	0	0	109%	110%
Container		0–999	TEU	65%	68%	180	70%	0	0	109%	110%
Vehicle		4000+	ceu	76%	59%	284	70%	0	0	109%	115%
Vehicle		0–3999	ceu	73%	51%	271	70%	0	0	109%	115%
Roro		2000+	lm	65%	51%	219	70%	0	0	109%	115%
Roro		0–1999	lm	65%	51%	180	70%	0	0	109%	110%

ANNEX 2 – FLEET DISAGGREGATION CATEGORIES

Function	LCS	WFR main heading	WFR subheadings	IMO (approx share total CO2)	Included in this project?
Merchant vessels	wetbulk	Oil tankers	bunkering vessel	other tanker (0.2%)	no (insufficient data on specifics and
			fleet replenishment vessel		
			chemical and oil carrier	products (3.9%)	yes
			produ/chem carrier		
			product carrier		
			product carrier/heavy lift		
			product carrier/ro-ro		
			shuttle tanker	crude oil (10.1%)	yes
			tanker		
		Parcel Tankers	chemical parcel tanker	chemical tanker (5.7%)	yes
		Spec. Tankers	asphalt and bitumen carrier	other tanker (0.2%)	no (insufficient data on specifics and very small sector)
			chemical and LPG carrier		
			edible oil carrier		
			fruit juice carrier		
			methanol carrier		
			molten sulphur carrier		
			oil and liquid gas carrier		
			palm oil carrier		
			phosphoric acid carrier		
			slop reception vessel		
			sukphuric acid carrier		
			waste disposal carrier		
			water carrier		
			wine carrier		
	drybulk	Bulkers	bulk carrier	bulk (15.9%)	yes
			cement carrier		
			chip carrier		
			forest product carrier		
			gypsum carrier		
			limestone carrier		
			miscellaneous dry bulk		
			open hatch carrier		
			ore and sulphuric acid carrier		
			ore carrier		
			slurry carrier		
			stone chip carrier		
			urea carrier		
		Reefers	reefer	other dry (reefer) (1.7%)	no (insufficient data on auxiliary energy requirements)
			reefer fish carrier		
			reefer/container		
			reefer/fleet replen.		
			reefer general cargo		
			reefer/pallets carrier		
			reefer/pass/ro-ro		
			reefer/ro-ro cargo		
		Combos	Bulk/oil	other dry (special) (0.1%)	no (insufficient data on specifics and very small sector)
			ore/oil		
		MPP	multi-purpose		
			multi-purpose / heavy lift cargo		
		Gen Cargo	barge carrier	gen cargo (8.6%)	yes
			bulk carrier		
			cement carrier		
			chip carrier		
			general cargo liner		
			general cargo tramp		
			heavy lift cargo vessel		
			limestone carrier		
			livestock carrier		
			minibulker		
			miscellaneous cargo		
			miscellaneous dry bulk		
			ore carrier		
			ore/oil carrier		
			unknown general cargo		
			urea carrier		
	gasbulk	LPG	Ethylene	LPG tanker (1.3%)	yes
			Ethylene/LPG		
			Ethylene/LPG/Chemical		
			LPG carrier		
			LPG/chemical		
			LPG/oil		
		LNG	LNG carrier	LNG tanker (3%)	yes
			LNG/Ethylene/LPG		
			LNG/Regasification		
	unitised	Containerships	Fully Cellualar Container	container (23.6%)	yes
		Ro-Ro	Naval Ro-Ro logistics vessel	Ro-Ro (1.6%)	yes if possible
			Ro-Ro		
			Ro-Ro freight/passenger		
			Ro-Ro/container		
			Ro-Ro/Lo-Lo		
		PCC	Pure car carrier	vehicle (2.5%)	yes if possible

ANNEX 3 – COUNTRY-TO-REGION MAPPING

Country	Region
Algeria	Africa
Angola	Africa
Benin	Africa
Botswana	Africa
Burkina Faso	Africa
Burundi	Africa
Cameroon	Africa
Cape Verde	Africa
Central African Rep.	Africa
Chad	Africa
Comoros	Africa
Congo	Africa
Cote d'Ivoire	Africa
Dem. Rep. of the Congo	Africa
Djibouti	Africa
Egypt	Africa
Equatorial Guinea	Africa
Eritrea	Africa
Ethiopia	Africa
Gabon	Africa
Gambia	Africa
Ghana	Africa
Guinea	Africa
Guinea-Bissau	Africa
Kenya	Africa
Lesotho	Africa
Liberia	Africa
Libya	Africa
Madagascar	Africa
Malawi	Africa
Maldives	Africa
Mali	Africa
Mauritania	Africa
Mauritius	Africa
Mayotte	Africa
Morocco	Africa
Mozambique	Africa
Namibia	Africa
Niger	Africa
Nigeria	Africa
Reunion	Africa
Rwanda	Africa
Sao Tome and Principe	Africa

Senegal	Africa
Seychelles	Africa
Sierra Leone	Africa
Somalia	Africa
South Africa	Africa
Sudan	Africa
Swaziland	Africa
Togo	Africa
Tunisia	Africa
Uganda	Africa
United Rep. of Tanzania	Africa
Western Sahara	Africa
Zambia	Africa
Zimbabwe	Africa
American Samoa	Australasia
Australia	Australasia
Christmas Isds	Australasia
Cocos Isds	Australasia
Cook Isds	Australasia
Fiji	Australasia
FS Micronesia	Australasia
Guam	Australasia
Heard Island and McDonald Islands	Australasia
Kiribati	Australasia
Marshall Isds	Australasia
Montserrat	Australasia
Nauru	Australasia
New Caledonia	Australasia
New Zealand	Australasia
Niue	Australasia
Norfolk Isds	Australasia
Pitcairn	Australasia
Samoa	Australasia
Solomon Isds	Australasia
Tokelau	Australasia
Tonga	Australasia
Tuvalu	Australasia
Vanuatu	Australasia
Wallis and Futuna Isds	Australasia
Brazil	Brazil
Canada	Canada
Antigua and Barbuda	Central America
Aruba	Central America
Bahamas	Central America
Barbados	Central America

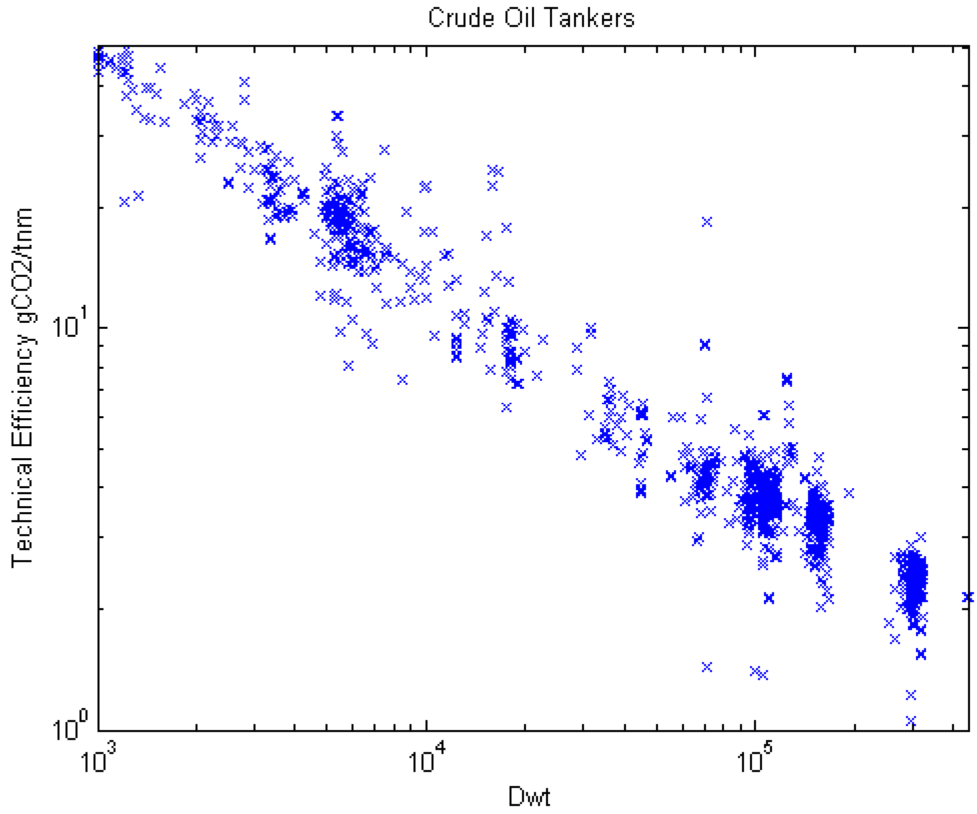
Belize	Central America
Bermuda	Central America
Caribbean, nes	Central America
Cayman Isds	Central America
Cuba	Central America
Dominica	Central America
Dominican Rep.	Central America
Grenada	Central America
Guadeloupe	Central America
Guatemala	Central America
Haiti	Central America
Honduras	Central America
Jamaica	Central America
Martinique	Central America
Mexico	Central America
N. Mariana Isds	Central America
Neth. Antilles	Central America
Nicaragua	Central America
Panama	Central America
Saint Helena	Central America
Saint Kitts and Nevis	Central America
Saint Kitts, Nevis and Anguilla	Central America
Saint Lucia	Central America
Saint Pierre and Miquelon	Central America
Saint Vincent and the Grenadines	Central America
South Georgia and the South Sandwich Islands	Central America
Trinidad and Tobago	Central America
Turks and Caicos Isds	Central America
China	China
Albania	Europe
Andorra	Europe
Austria	Europe
Belarus	Europe
Belgium	Europe
Bosnia Herzegovina	Europe
Bulgaria	Europe
Croatia	Europe
Cyprus	Europe
Czech Rep.	Europe
Denmark	Europe
Estonia	Europe
Faeroe Isds	Europe
Finland	Europe
France	Europe

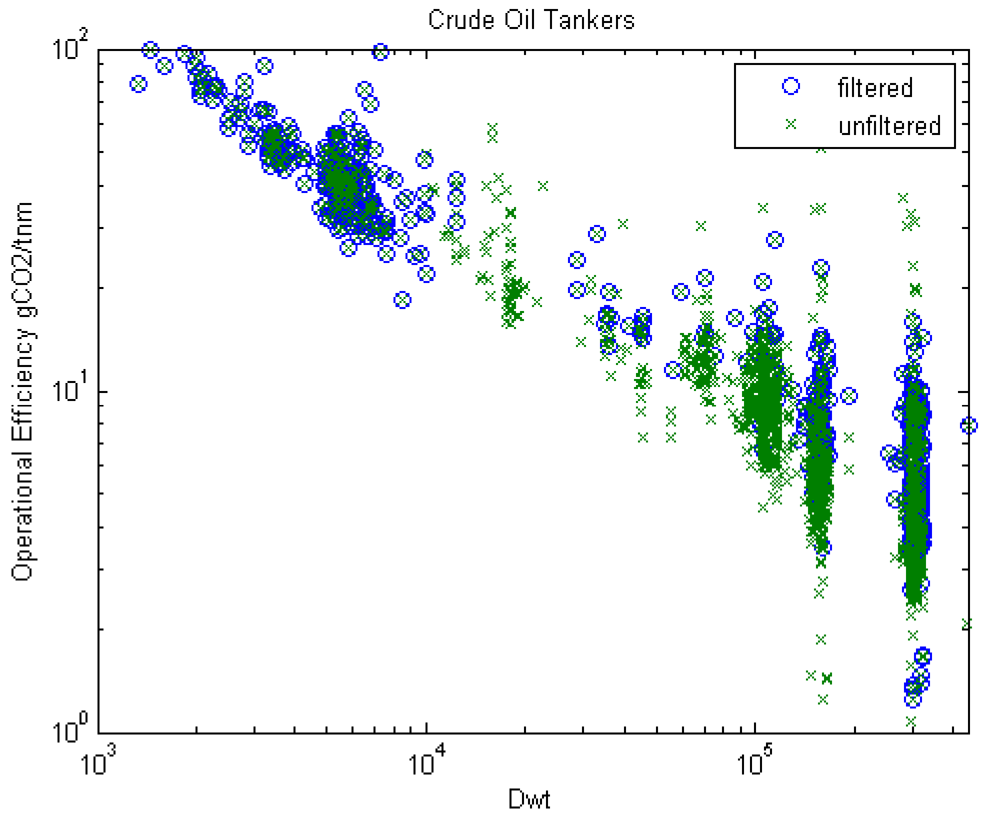
Georgia	Europe
Germany	Europe
Gibraltar	Europe
Greece	Europe
Greenland	Europe
Holy See (Vatican City State)	Europe
Hungary	Europe
Iceland	Europe
Ireland	Europe
Italy	Europe
Latvia	Europe
Lithuania	Europe
Luxembourg	Europe
Malta	Europe
Montenegro	Europe
Netherlands	Europe
Norway	Europe
Poland	Europe
Portugal	Europe
Rep. of Moldova	Europe
Romania	Europe
San Marino	Europe
Serbia	Europe
Serbia and Montenegro	Europe
Slovakia	Europe
Slovenia	Europe
Spain	Europe
Sweden	Europe
Switzerland	Europe
TFYR of Macedonia	Europe
Ukraine	Europe
United Kingdom	Europe
India	India
Bangladesh	Indian Subcontinent (excl. India)
Pakistan	Indian Subcontinent (excl. India)
Sri Lanka	Indian Subcontinent (excl. India)
Japan	Japan
Ryukyu Isd	Japan
Bahrain	Middle East
Iran	Middle East
Iraq	Middle East
Israel	Middle East
Jordan	Middle East

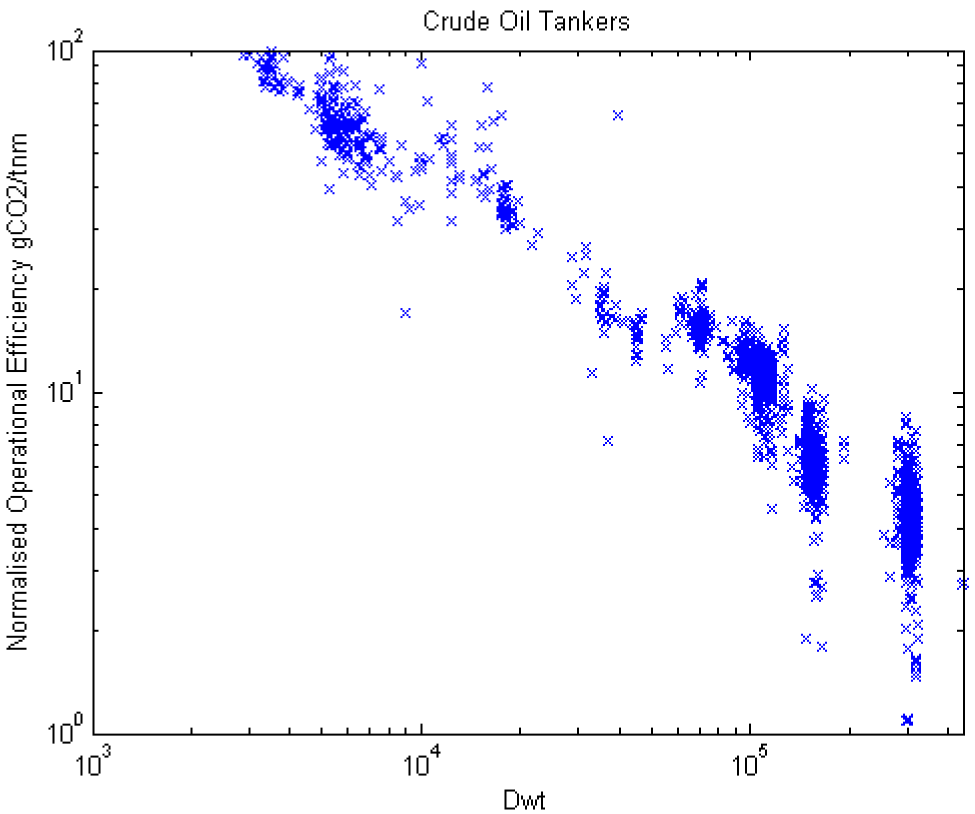
Kuwait	Middle East
Lebanon	Middle East
Occ. Palestinian Terr.	Middle East
Oman	Middle East
Qatar	Middle East
Saudi Arabia	Middle East
Syria	Middle East
Turkey	Middle East
United Arab Emirates	Middle East
Yemen	Middle East
Afghanistan	North East Asia
Azerbaijan	North East Asia
Kazakhstan	North East Asia
Kyrgyzstan	North East Asia
Mongolia	North East Asia
Tajikistan	North East Asia
Turkmenistan	North East Asia
Uzbekistan	North East Asia
Russian Federation	Russia
Anguilla	South America
Antarctica	South America
Argentina	South America
Bolivia	South America
Bouvet Island	South America
Br. Antarctic Terr.	South America
Br. Indian Ocean Terr.	South America
Br. Virgin Isds	South America
Chile	South America
Colombia	South America
Costa Rica	South America
Ecuador	South America
El Salvador	South America
Falkland Isds (Malvinas)	South America
French Guiana	South America
French Polynesia	South America
Guyana	South America
Paraguay	South America
Peru	South America
Suriname	South America
Uruguay	South America
Venezuela	South America
Bhutan	South East Asia
Brunei Darussalam	South East Asia
Cambodia	South East Asia
Dem. People's Rep. of Korea	South East Asia

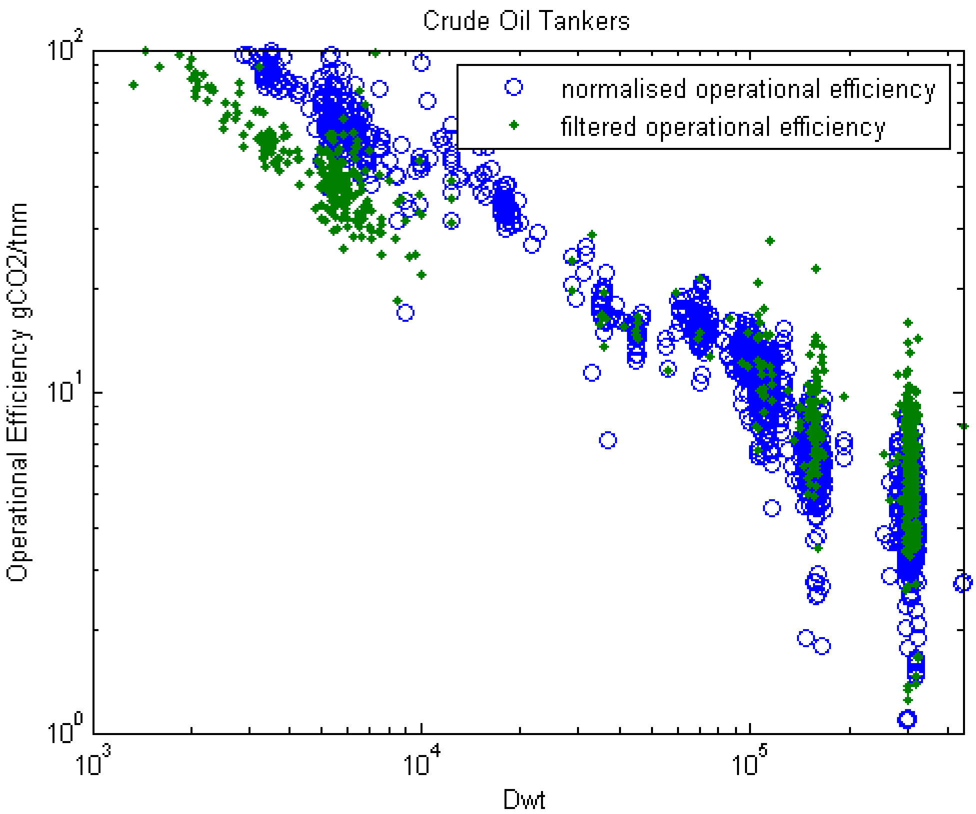
Indonesia	South East Asia
Lao People's Dem. Rep.	South East Asia
Malaysia	South East Asia
Myanmar	South East Asia
Nepal	South East Asia
Palau	South East Asia
Papua New Guinea	South East Asia
Peninsula Malaysia	South East Asia
Philippines	South East Asia
Rep. of Korea	South East Asia
Sabah	South East Asia
Sarawak	South East Asia
Sikkim	South East Asia
Singapore	South East Asia
Thailand	South East Asia
Timor-Leste	South East Asia
Viet Nam	South East Asia
United States Minor Outlying Islands	USA
US Misc. Pacific Isds	USA
US Virgin Isds	USA
USA	USA

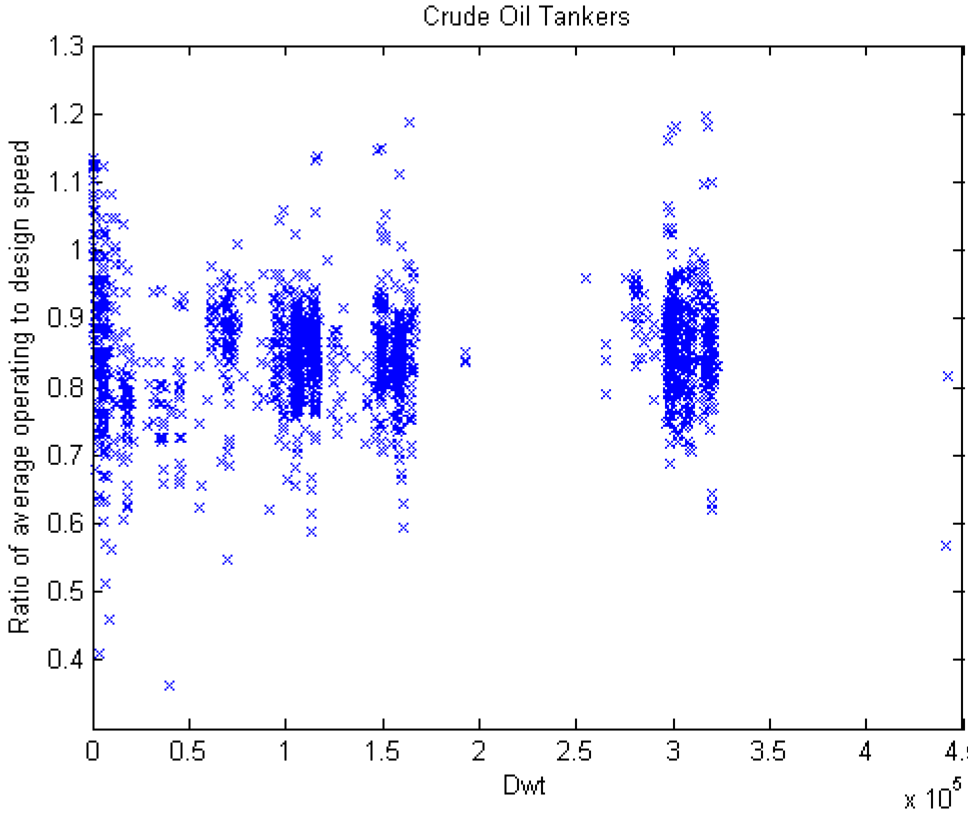
ANNEX 4 – RESULTS BY SHIP TYPE



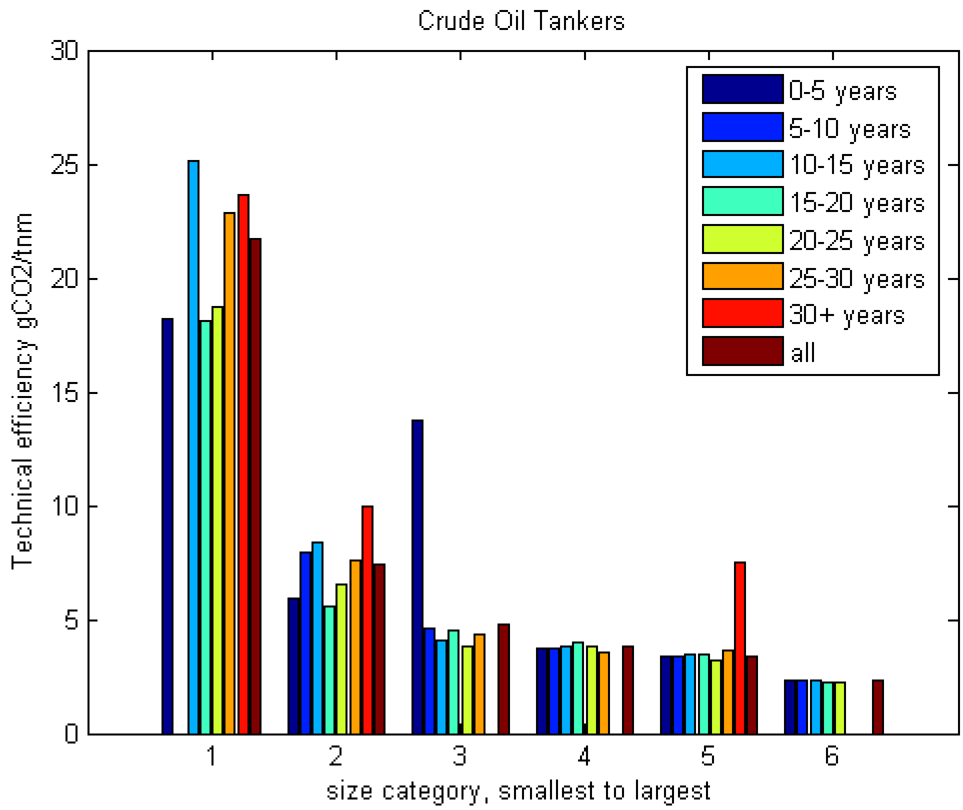



Crude Oil Tankers
Normalised Operational Efficiency gCO2/tnm
Dwt
10^2
10^1
10^0
10^3
10^4
10^5

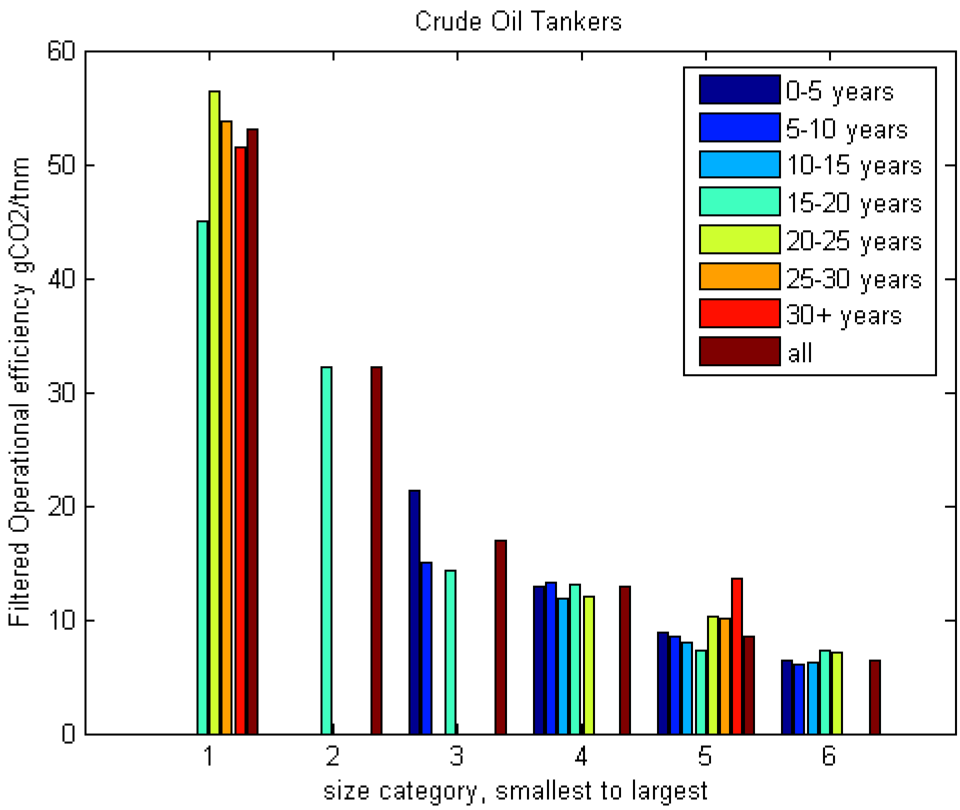

Crude Oil Tankers
Operational Efficiency gCO2/tnm
Dwt
normalised operational efficiency
filtered operational efficiency
10^2
10^1
10^0
10^3
10^4
10^5

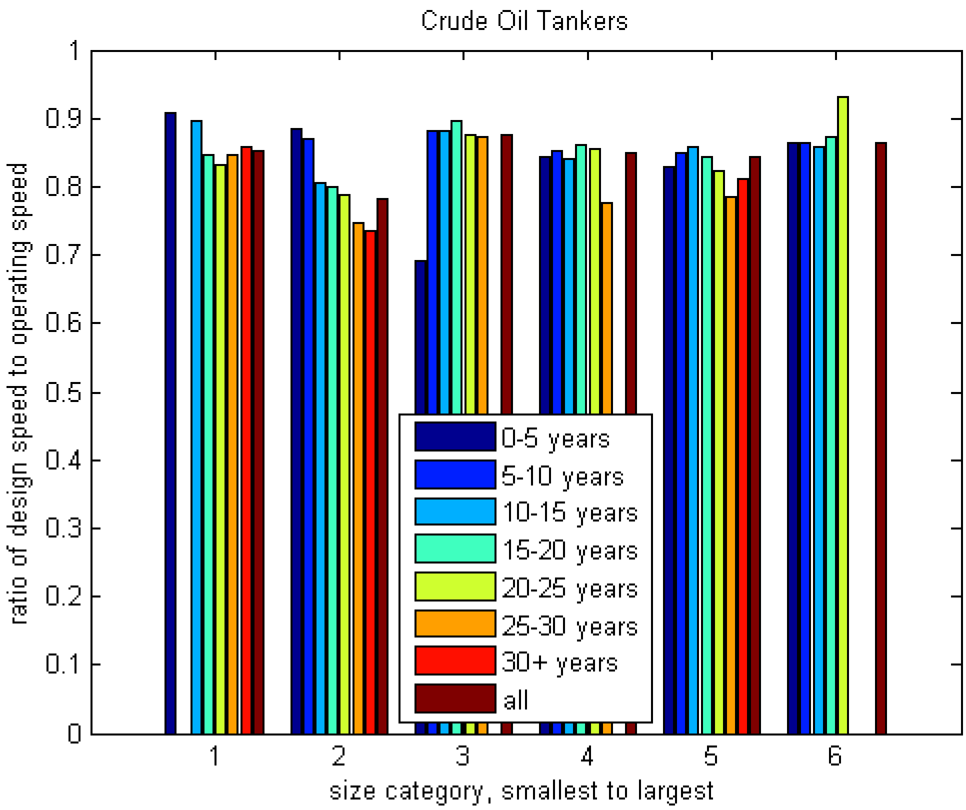


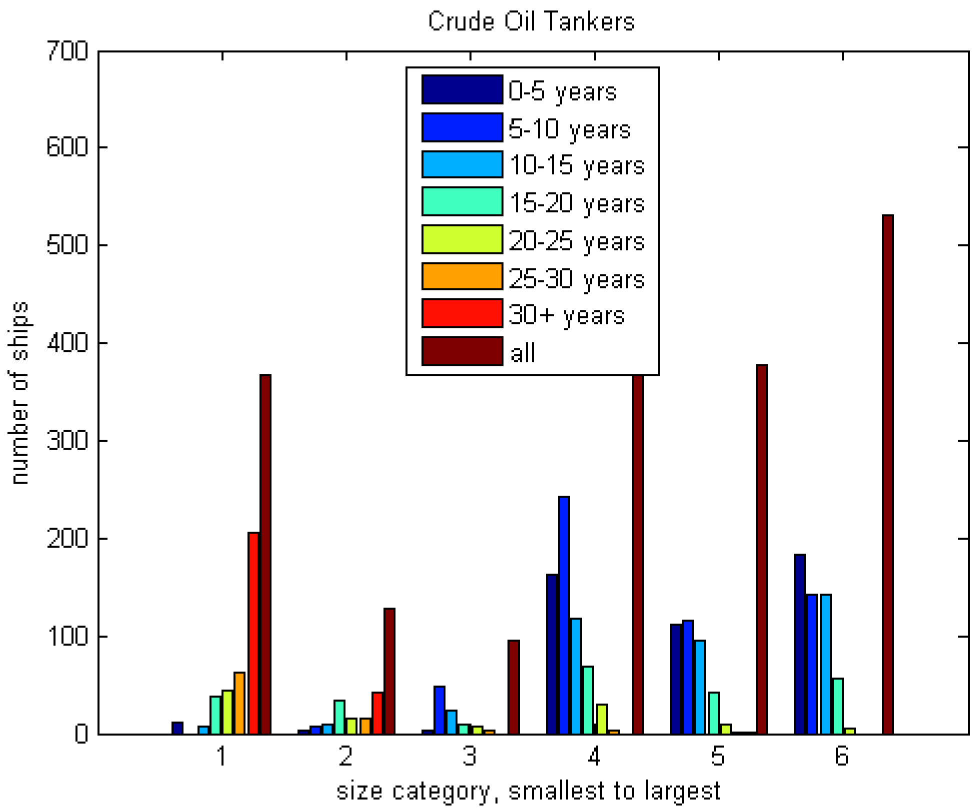
Crude Oil Tankers
Ratio of average operating to design speed
Dwt
x 10^5
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5



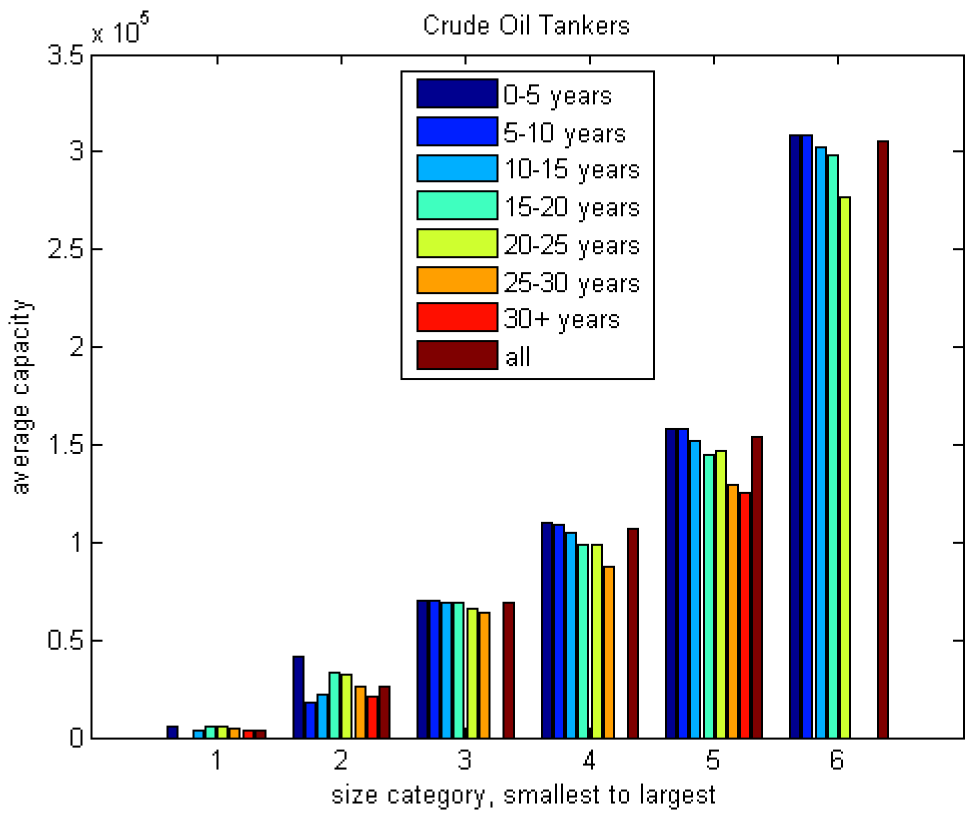
Crude Oil Tankers
Technical efficiency gCO2/tnm
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all
30
25
20
15
10
5
0
1
2
3
4
5
6


Crude Oil Tankers
Filtered Operational efficiency gCO2/tnm
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all

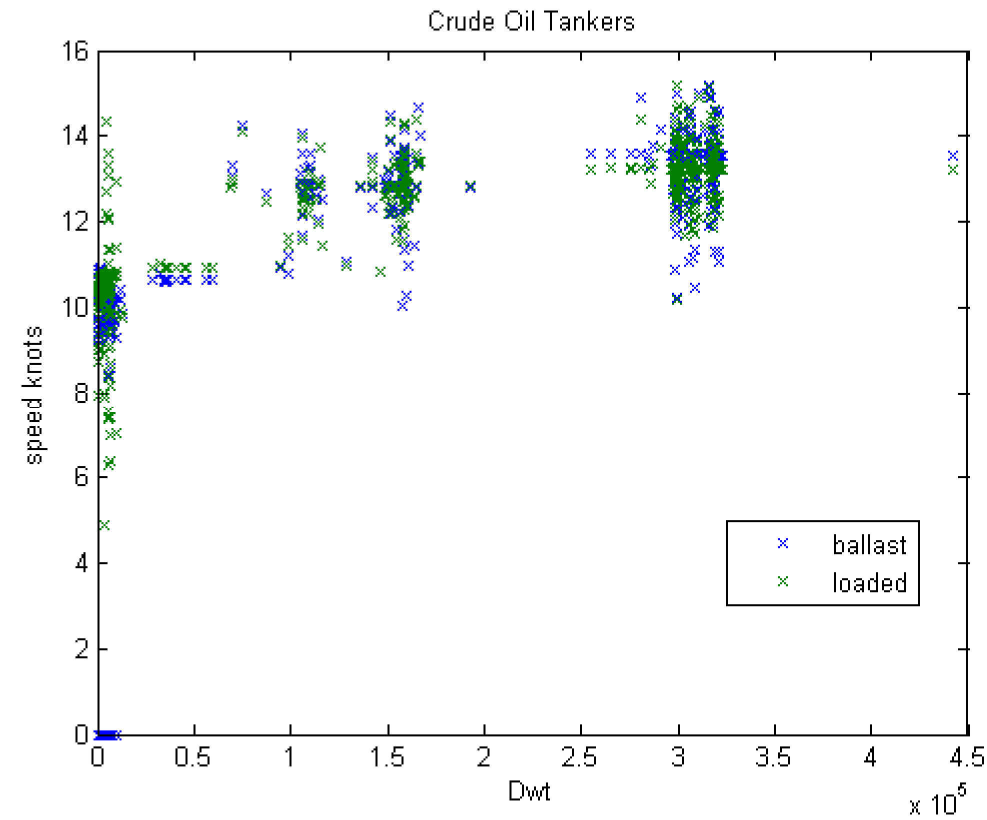

Crude Oil Tankers
ratio of design speed to operating speed
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all

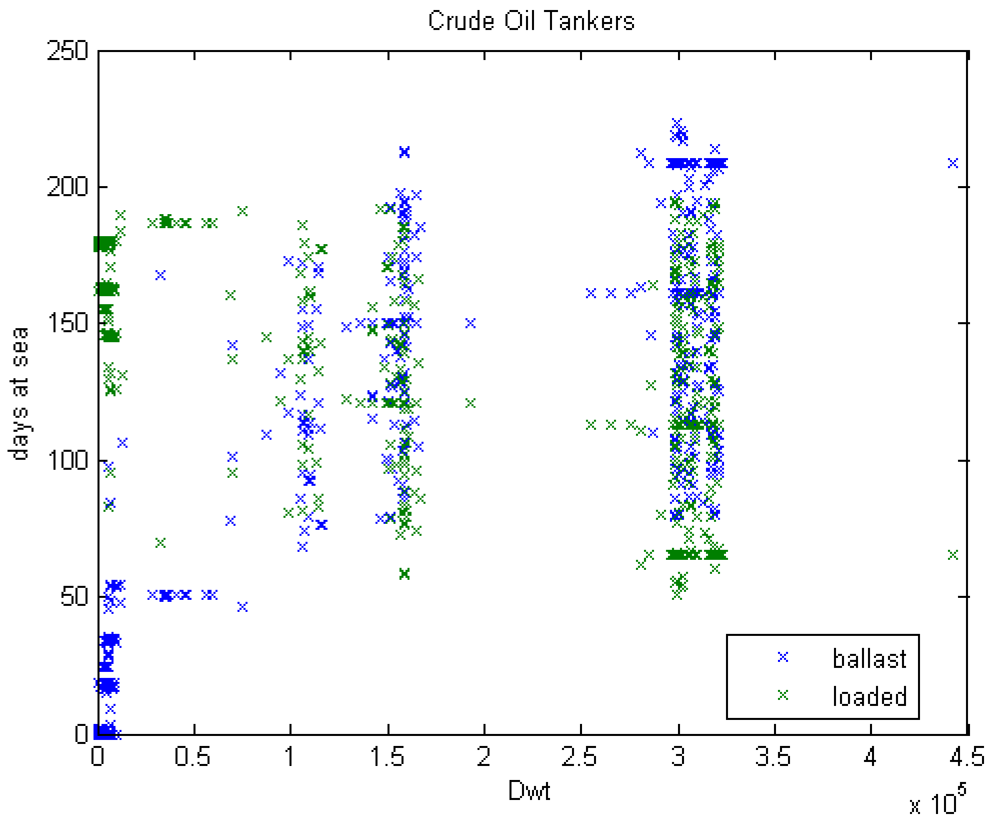


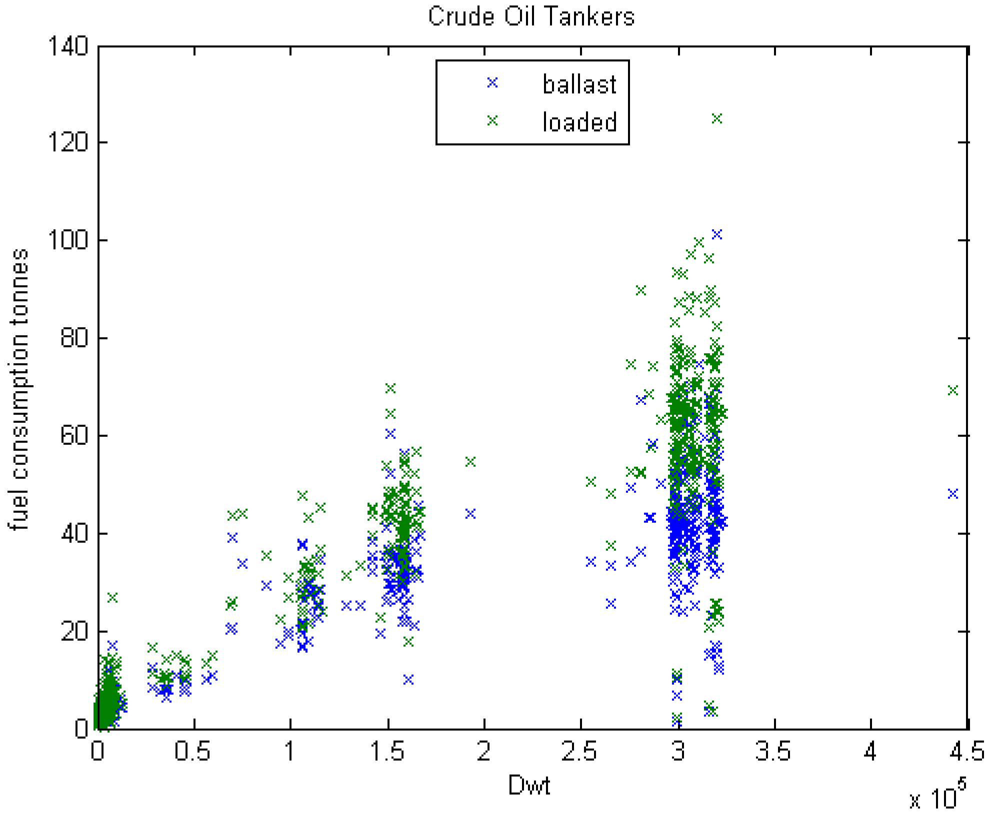
Crude Oil Tankers
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all
number of ships
0
100
200
300
400
500
600
700
1
2
3
4
5
6
size category, smallest to largest

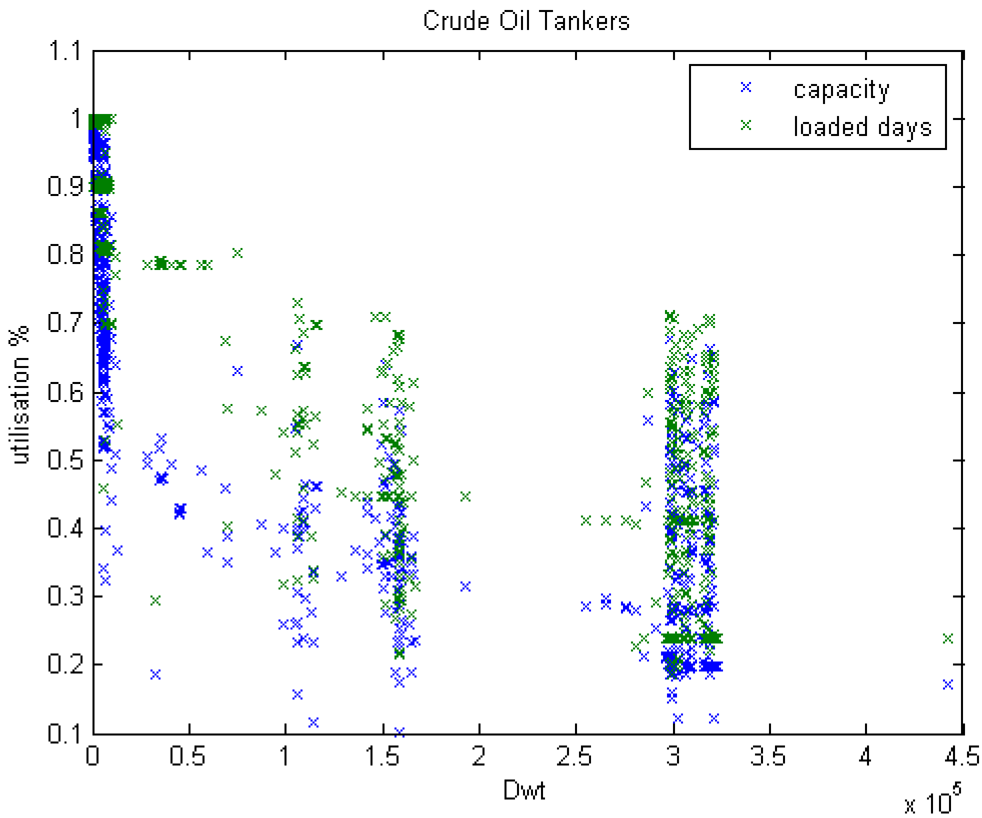


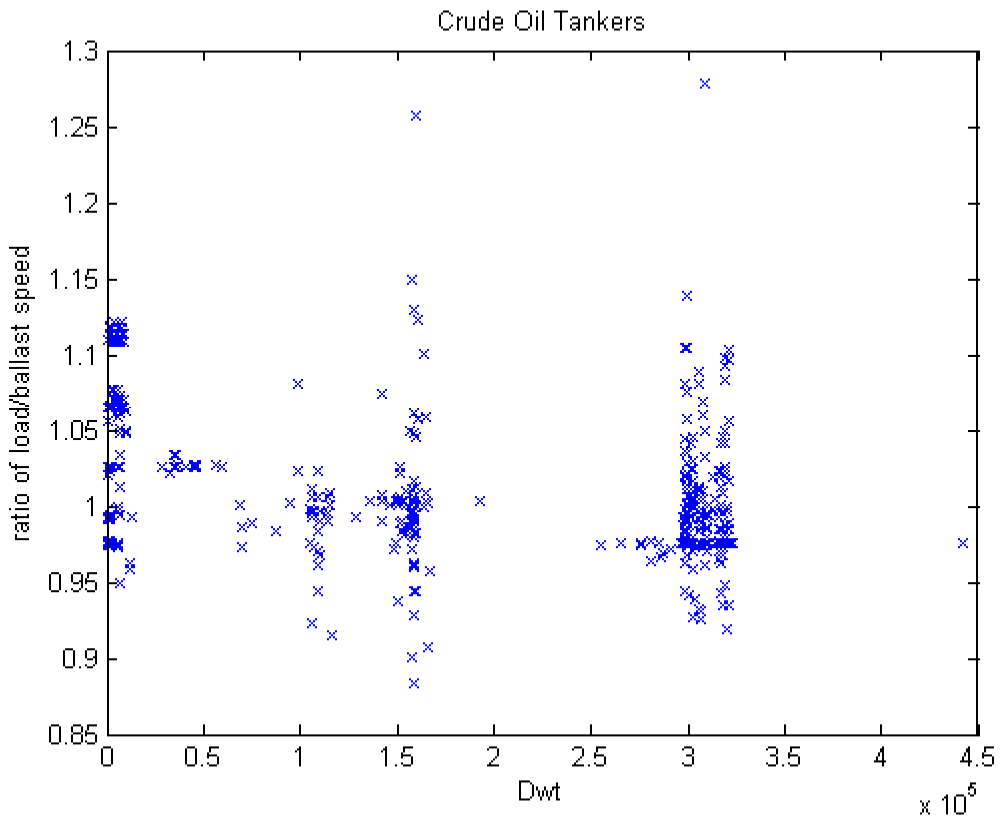
Crude Oil Tankers
x 10^5
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all
average capacity
0
0.5
1
1.5
2
2.5
3
3.5
1
2
3
4
5
6
size category, smallest to largest

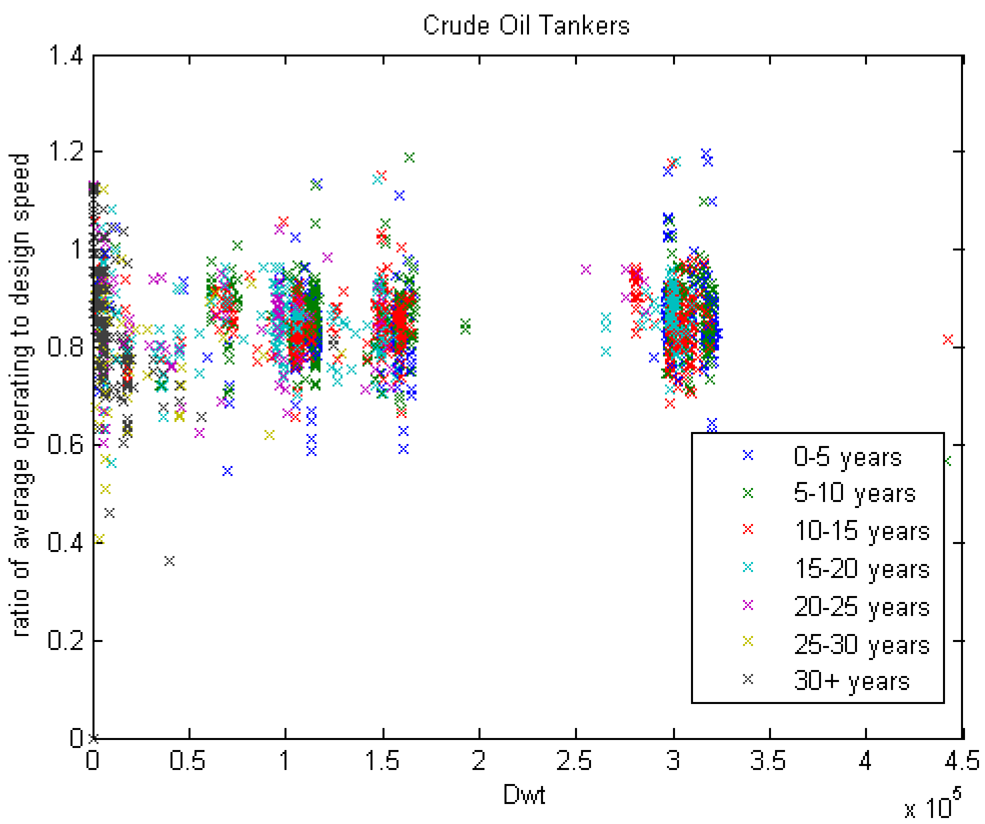

Crude Oil Tankers
speed knots
Dwt
x 10^5
ballast
loaded
0
2
4
6
8
10
12
14
16
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5

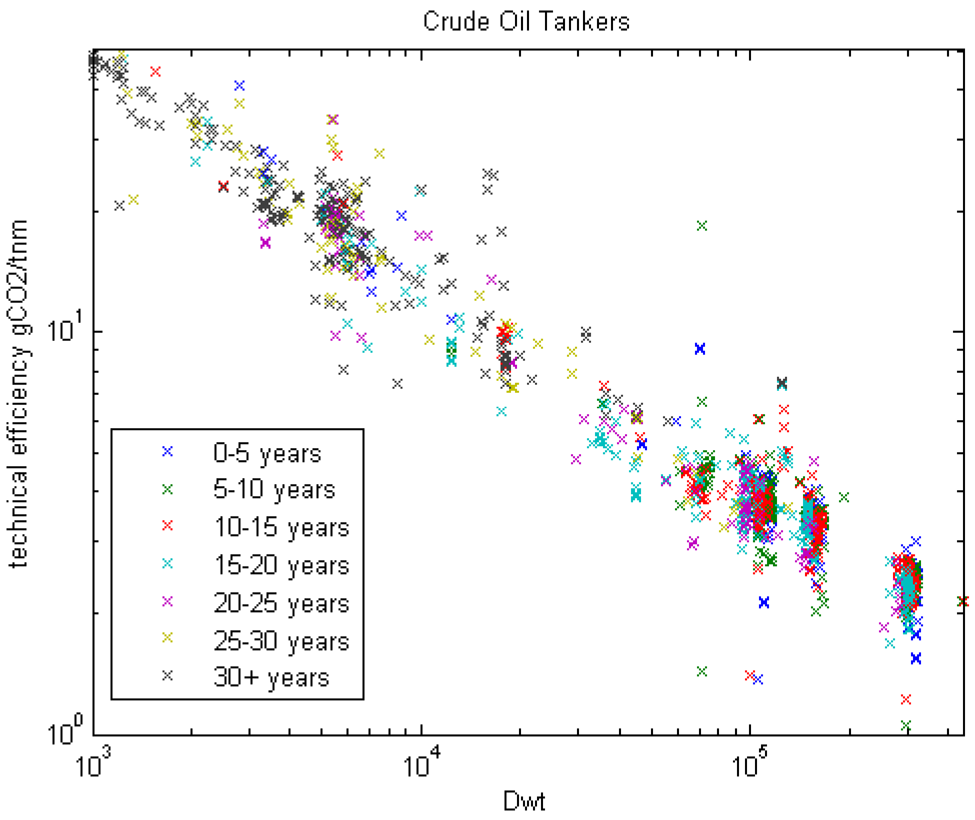

Crude Oil Tankers
days at sea
Dwt
x 10^5
ballast
loaded
0
50
100
150
200
250
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5

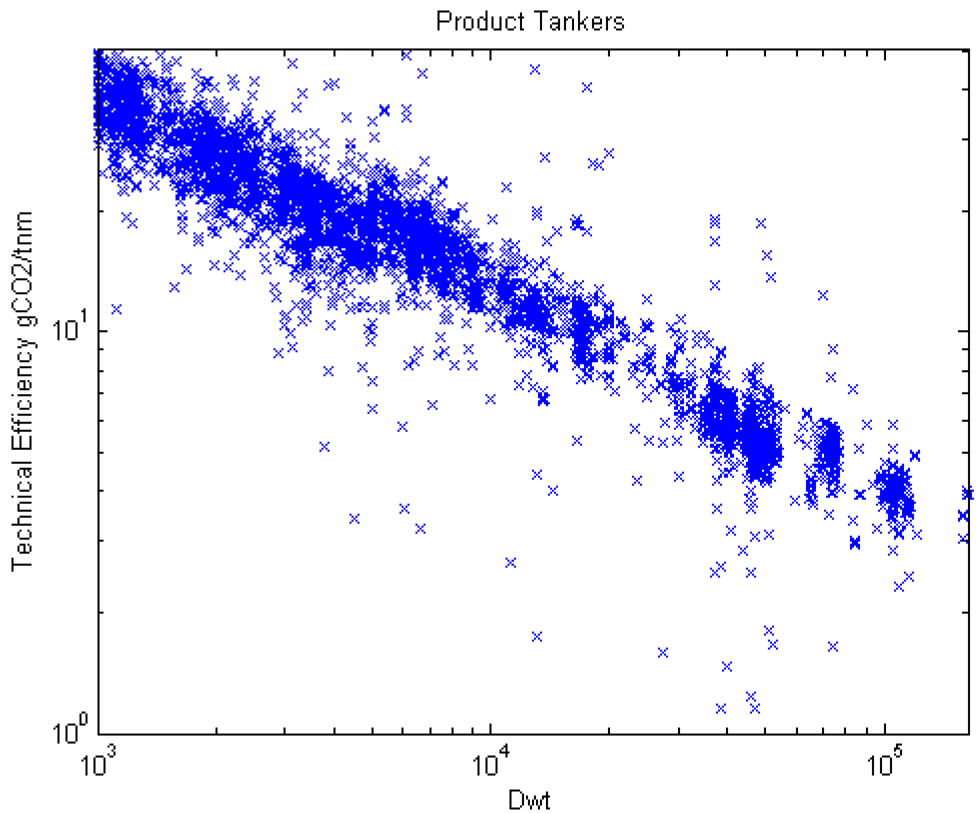

Crude Oil Tankers
ballast
loaded
fuel consumption tonnes
Dwt
x 10^5
0
20
40
60
80
100
120
140
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5

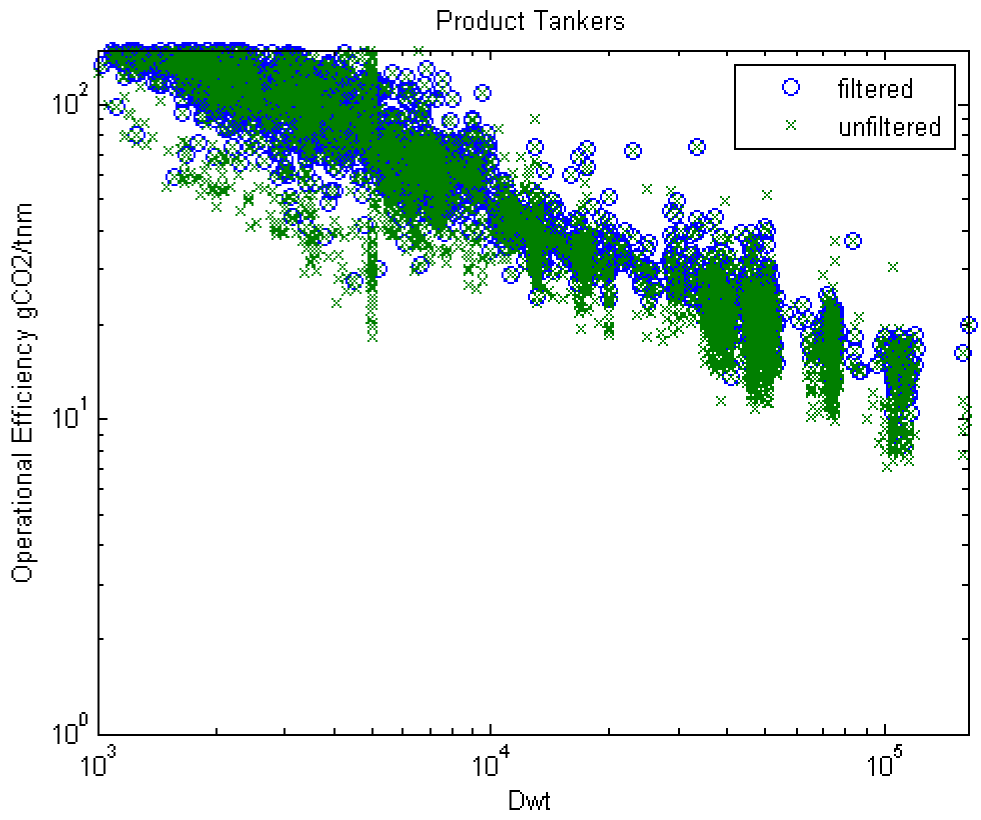

Crude Oil Tankers
capacity
loaded days
utilisation %
Dwt
x 10^5
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5

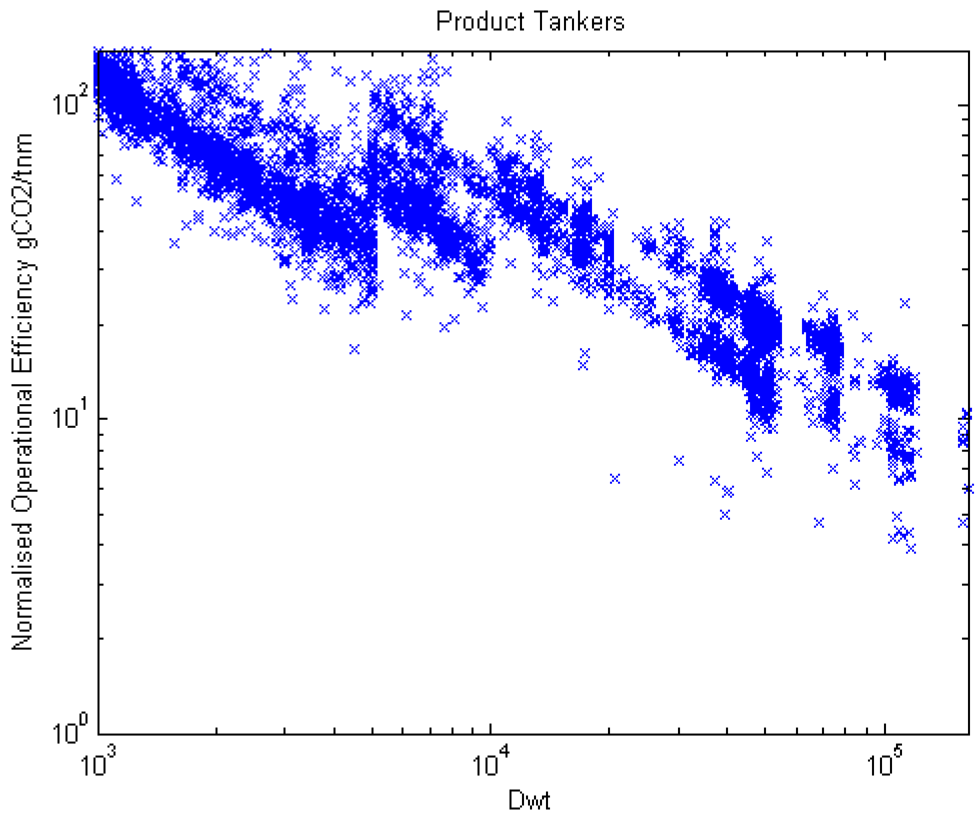

Crude Oil Tankers
ratio of load/ballast speed
Dwt
x 10^5
1.3
1.25
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5

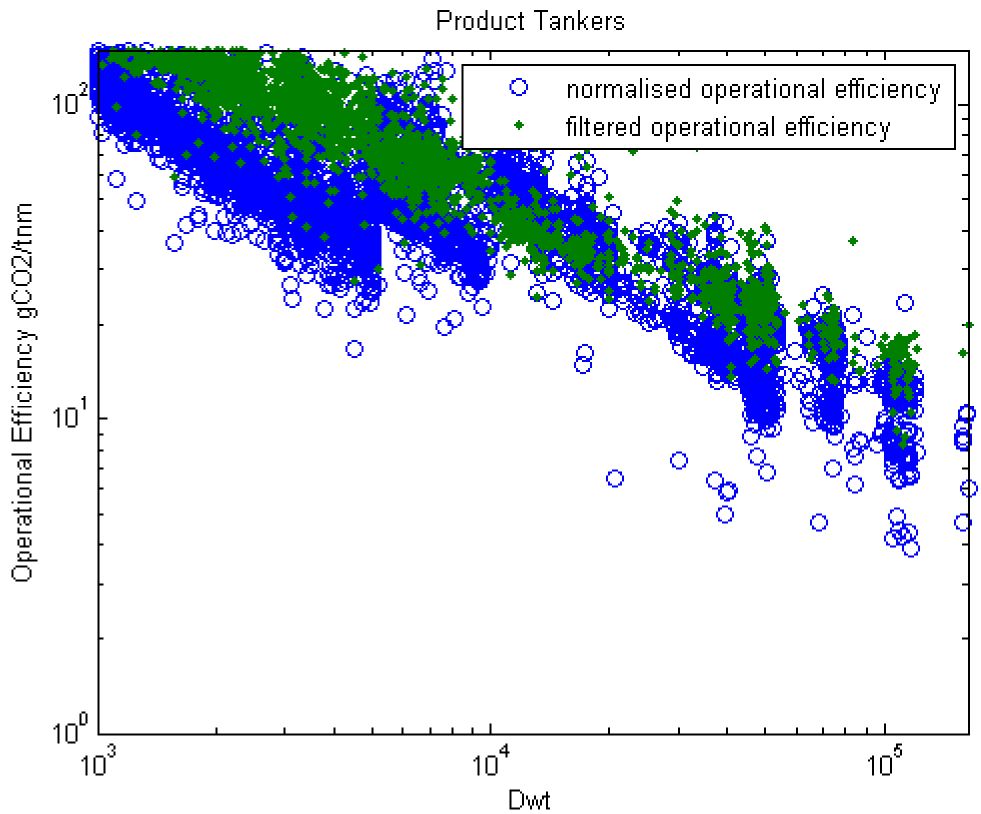

Crude Oil Tankers
ratio of average operating to design speed
Dwt
x 10^5
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years

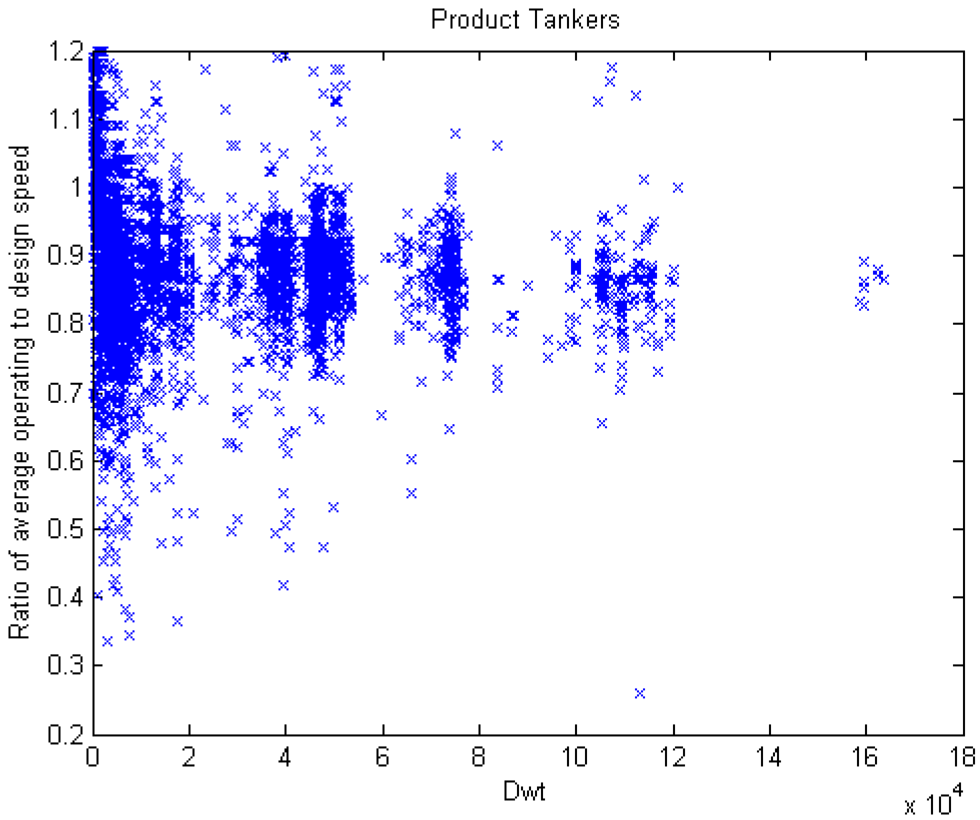

Crude Oil Tankers
technical efficiency gCO2/tnm
Dwt
10^0
10^1
10^3
10^4
10^5
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years


Product Tankers
Technical Efficiency gCO2/tnm
Dwt
10^0
10^1
10^3
10^4
10^5

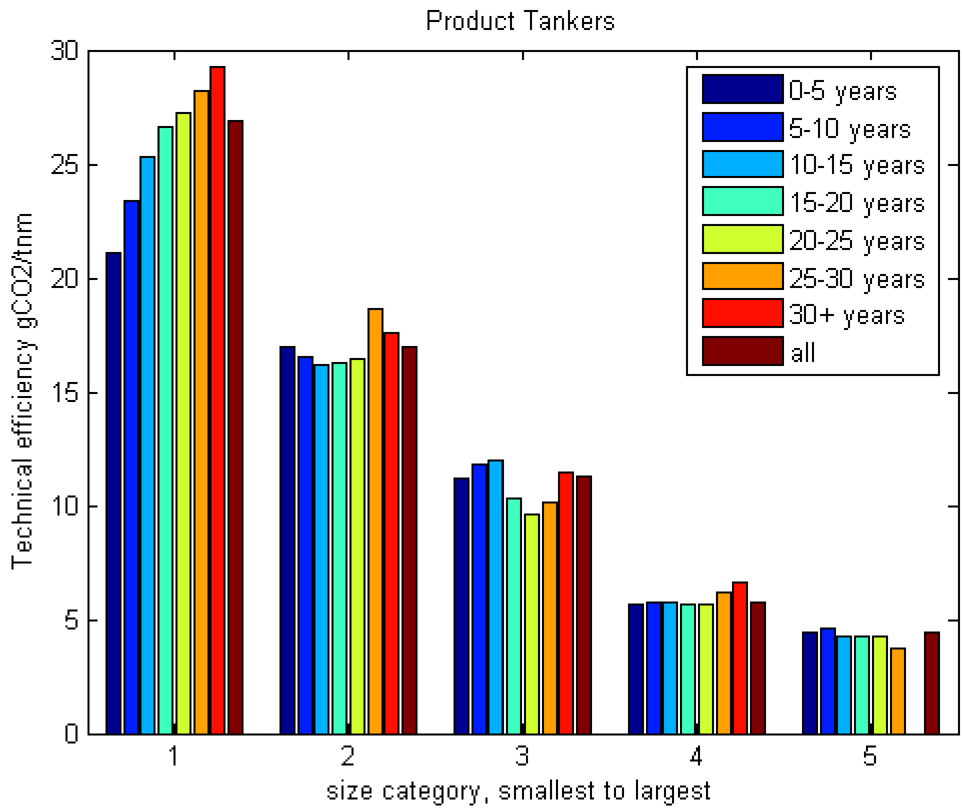

Product Tankers
Operational Efficiency gCO2/tnm
Dwt
filtered
unfiltered
10^0
10^1
10^2
10^3
10^4
10^5


Product Tankers
Normalised Operational Efficiency gCO2/tnm
Dwt
10^2
10^1
10^0
10^3
10^4
10^5

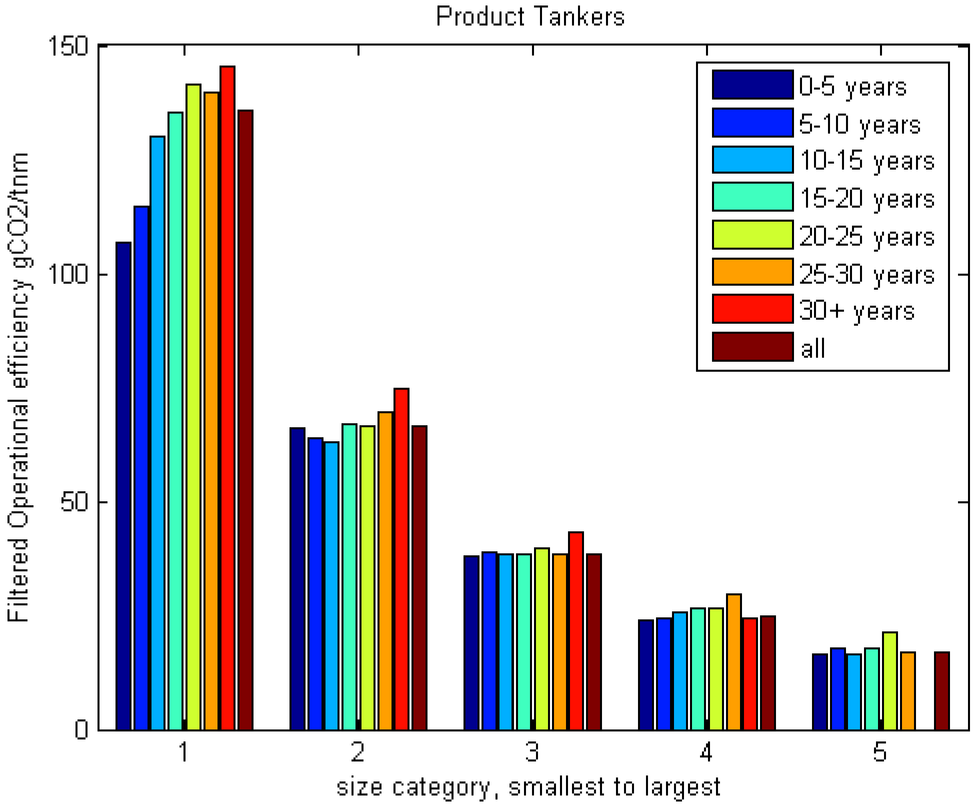

Product Tankers
Operational Efficiency gCO2/tnm
Dwt
normalised operational efficiency
filtered operational efficiency
10^2
10^1
10^0
10^3
10^4
10^5

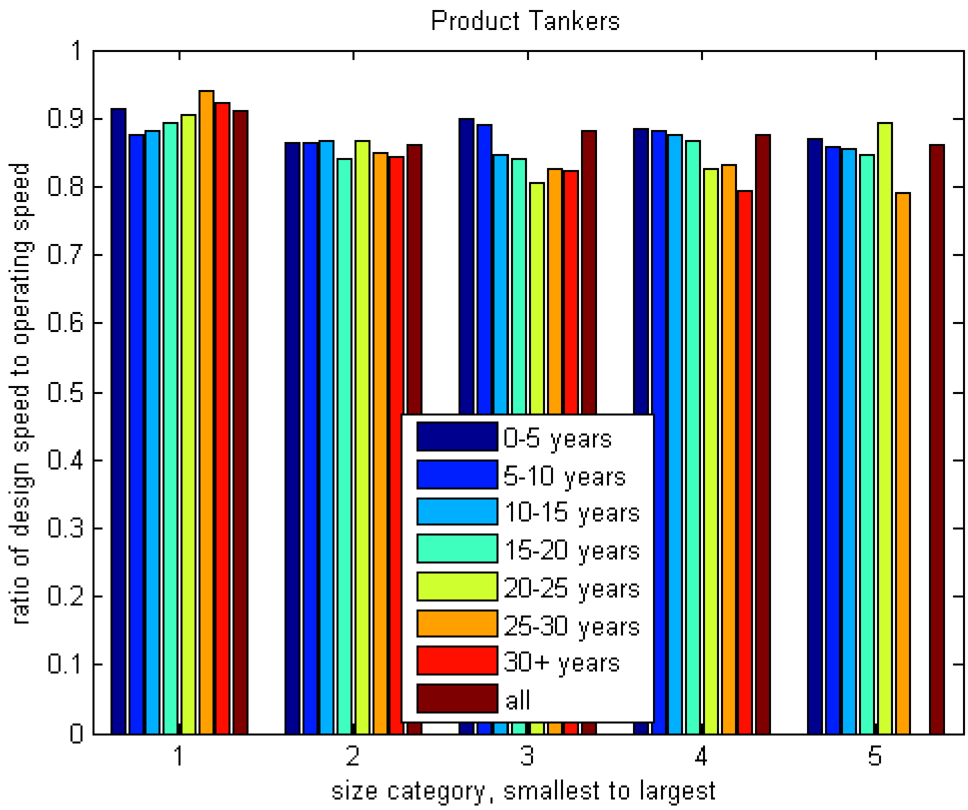


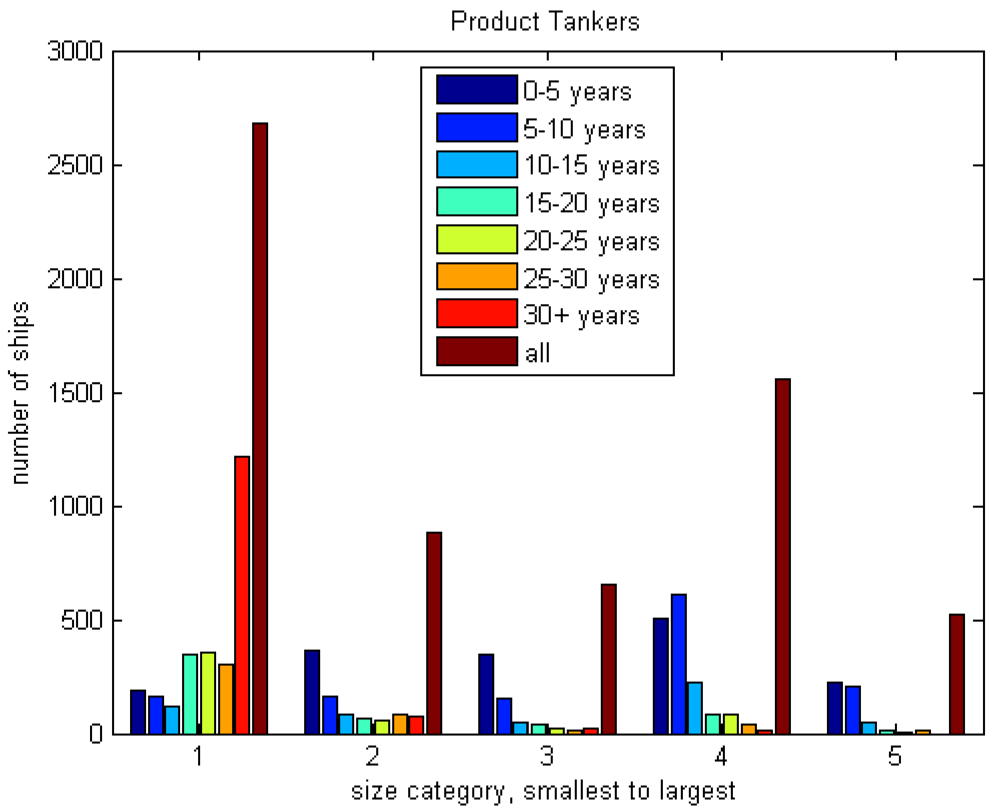
Product Tankers
Ratio of average operating to design speed
Dwt
x 10^4



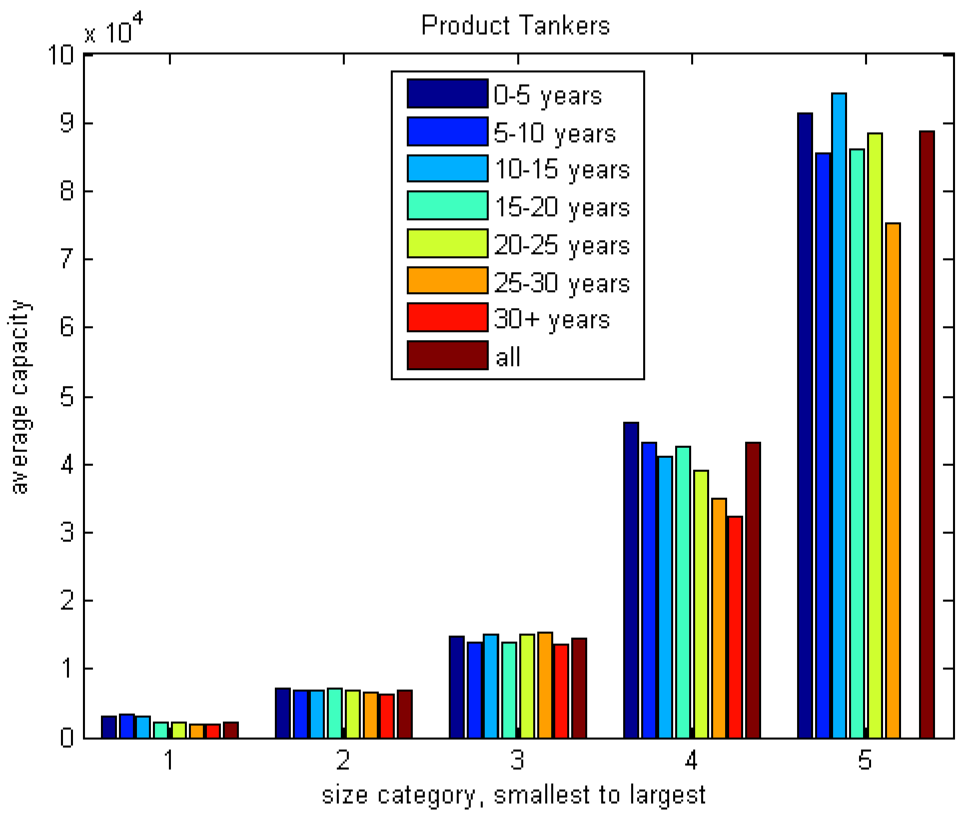
Product Tankers
Technical efficiency gCO2/tnm
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all


Product Tankers
150
100
50
0
Filtered Operational efficiency gCO2/tnm
1
2
3
4
5
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all

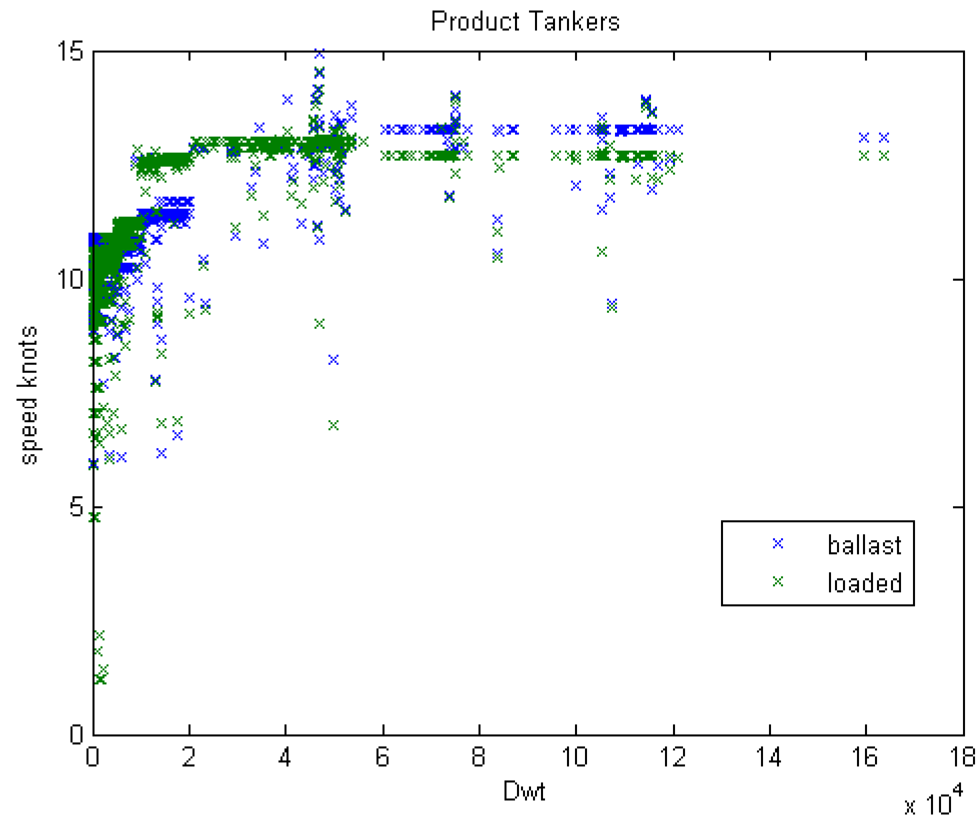

Product Tankers
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
ratio of design speed to operating speed
1
2
3
4
5
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all

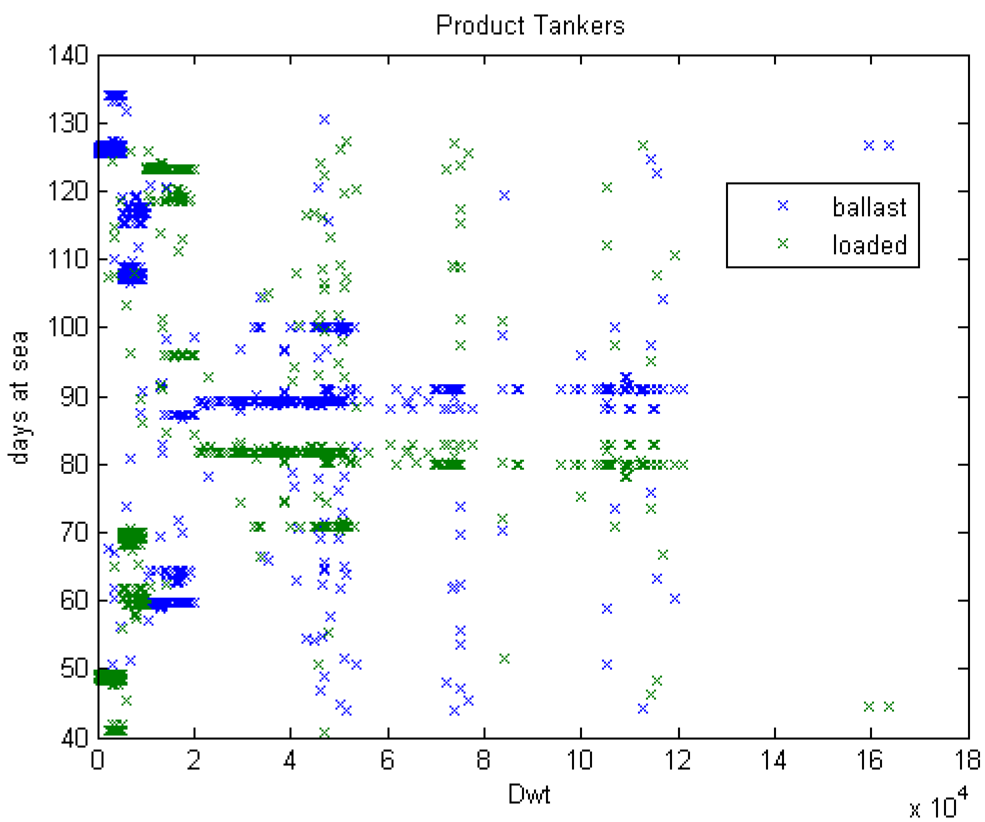


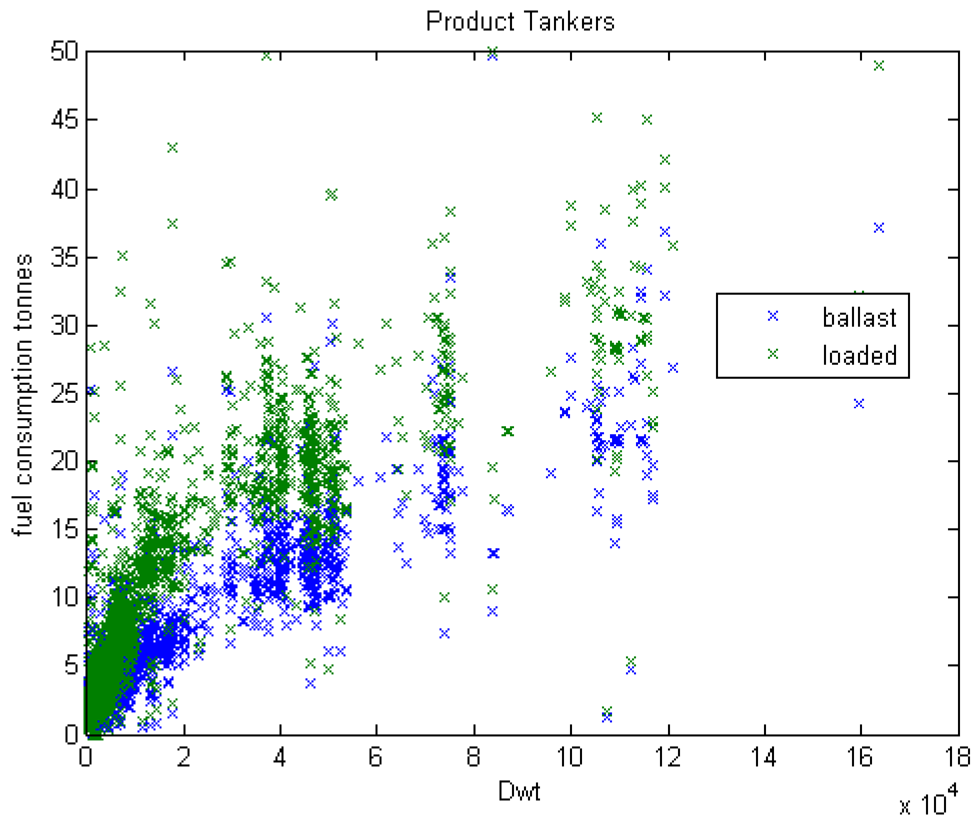
Product Tankers
number of ships
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all
size category, smallest to largest

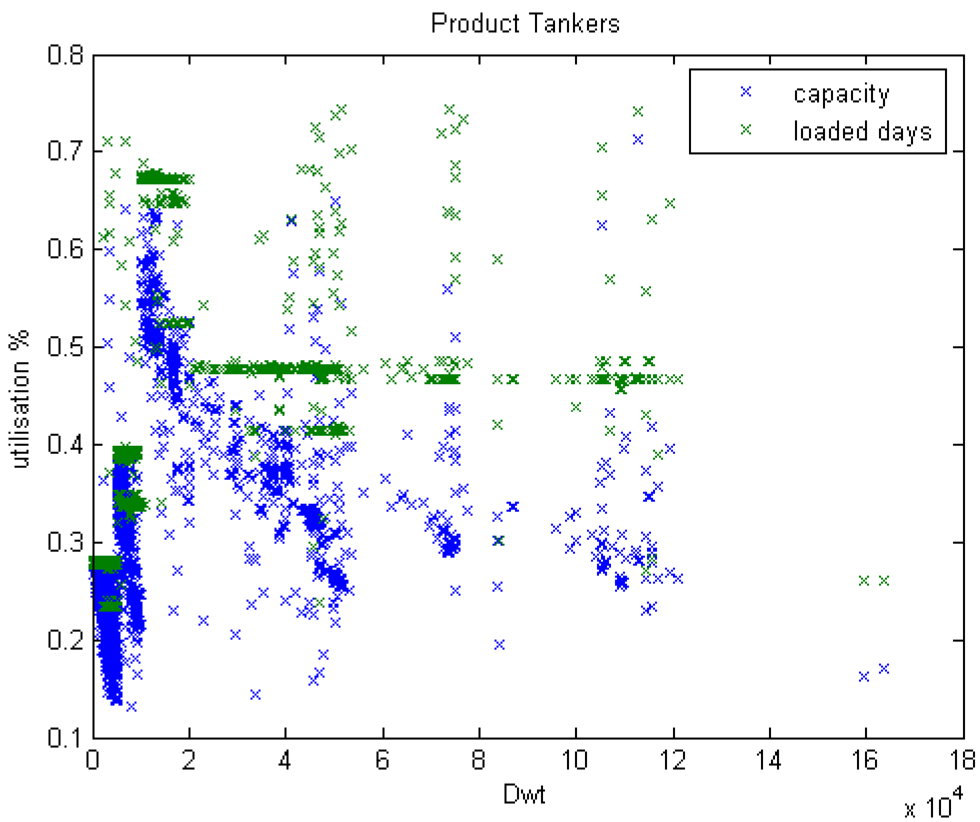


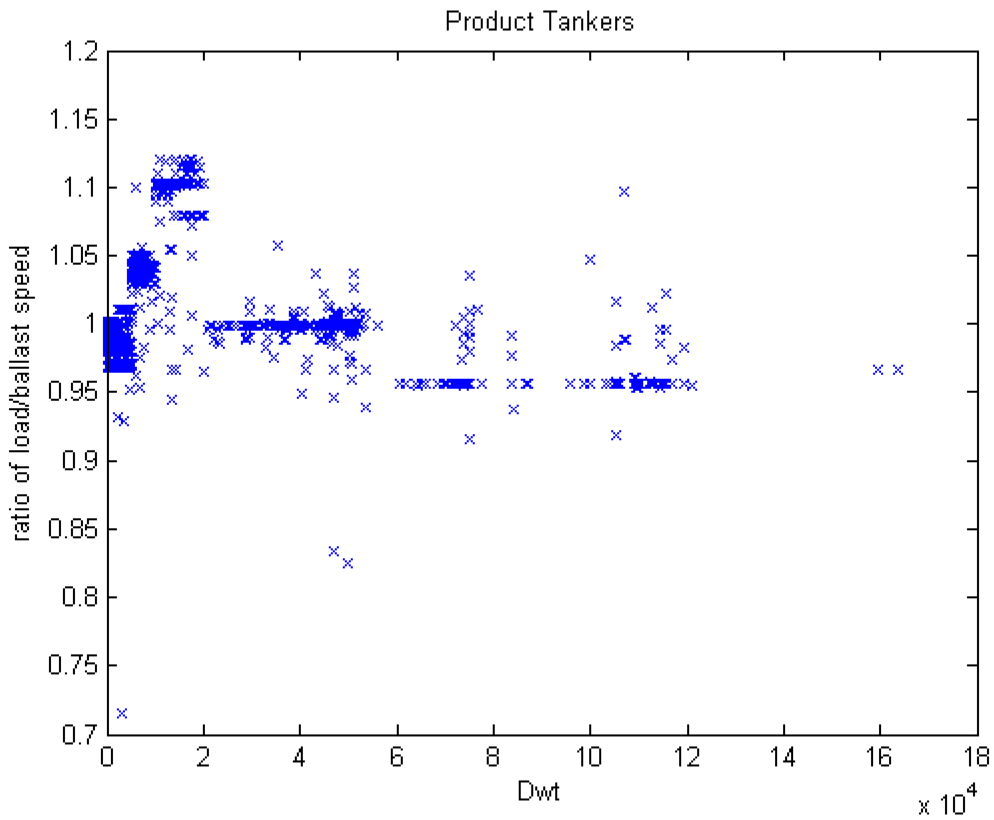
Product Tankers
x 10^4
average capacity
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all
size category, smallest to largest

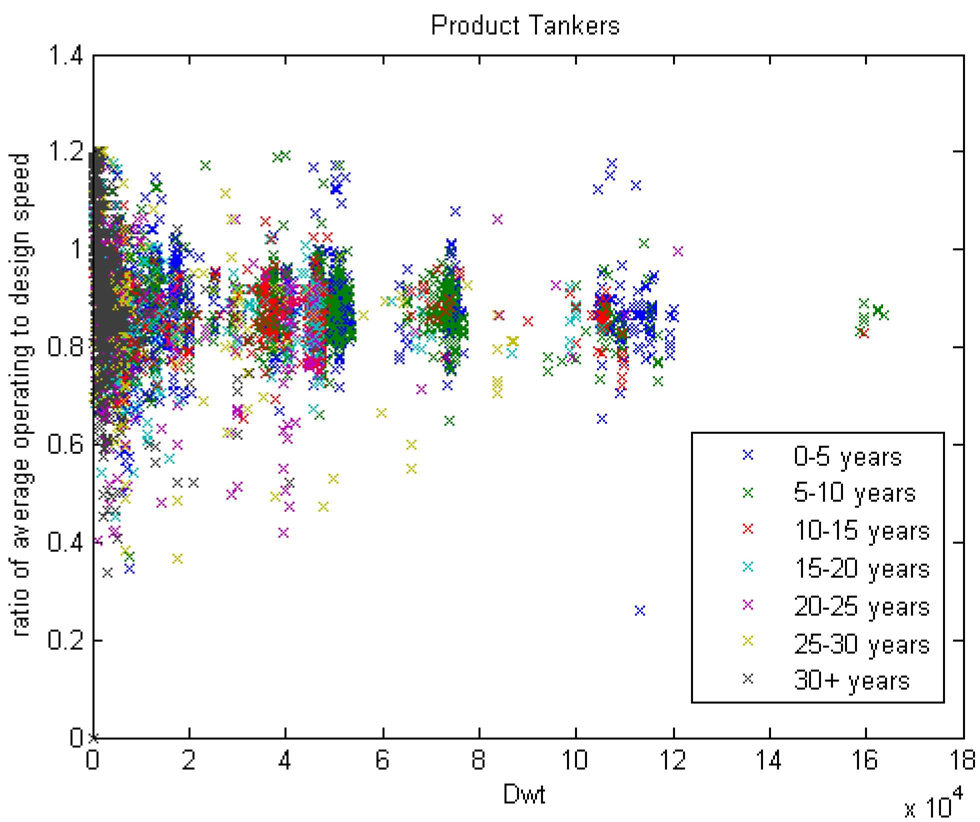

Product Tankers
speed knots
Dwt
x 10^4
ballast
loaded
0
5
10
15
0
2
4
6
8
10
12
14
16
18

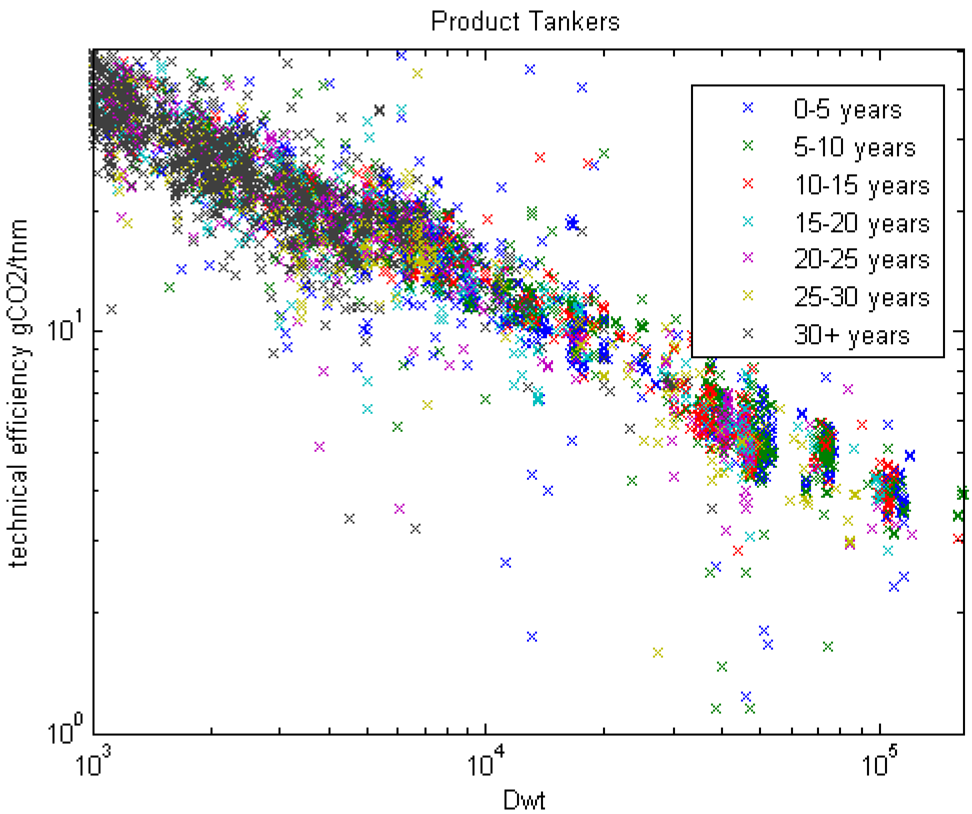

Product Tankers
days at sea
Dwt
x 10^4
ballast
loaded
40
50
60
70
80
90
100
110
120
130
140
0
2
4
6
8
10
12
14
16
18

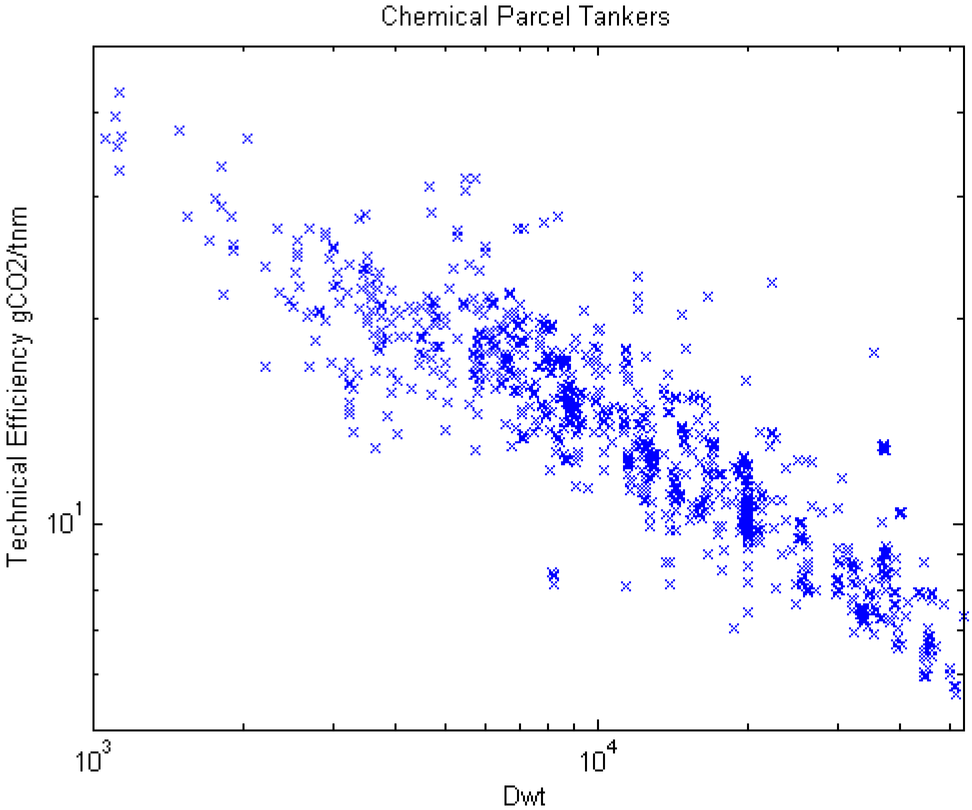

Product Tankers
fuel consumption tonnes
Dwt
x 10^4
ballast
loaded
0
5
10
15
20
25
30
35
40
45
50
0
2
4
6
8
10
12
14
16
18

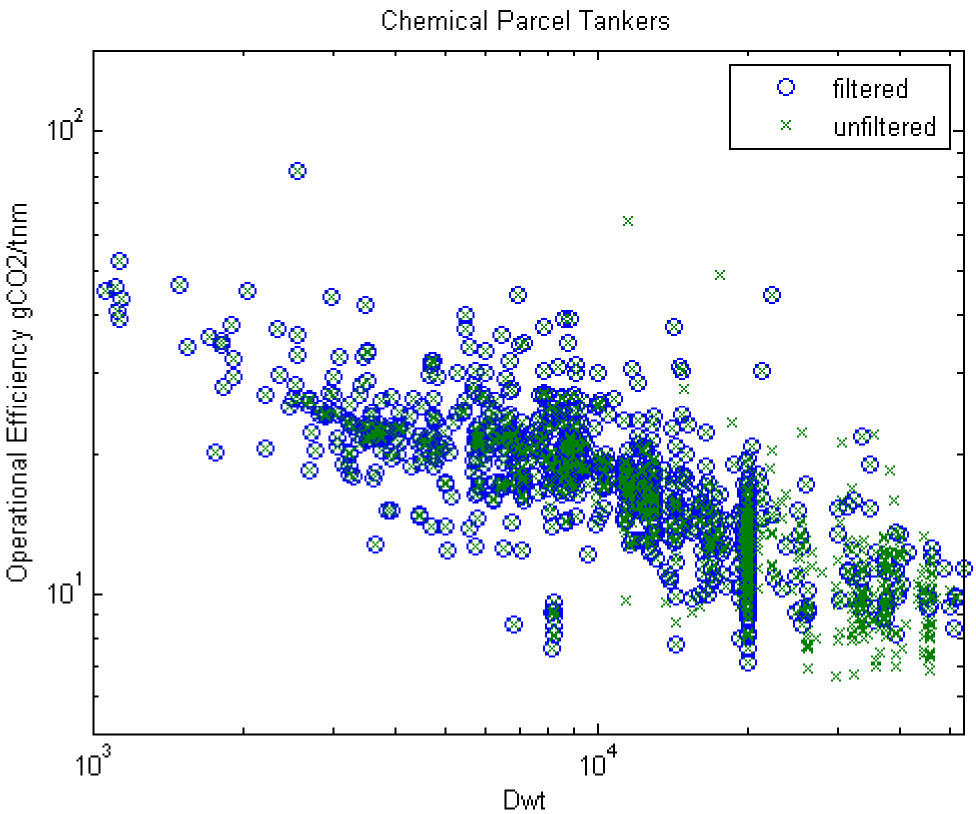

Product Tankers
utilisation %
Dwt
x 10^4
capacity
loaded days
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
2
4
6
8
10
12
14
16
18

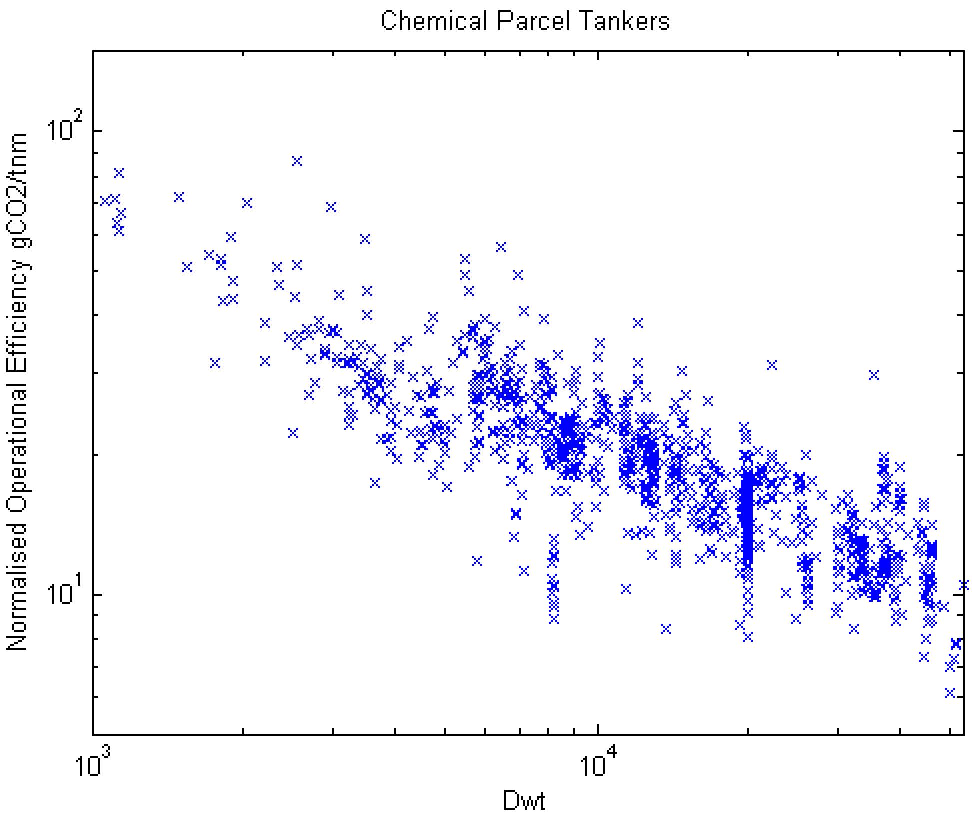

Product Tankers
ratio of load/ballast speed
Dwt
x 10^4
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
0.75
0.7
0
2
4
6
8
10
12
14
16
18

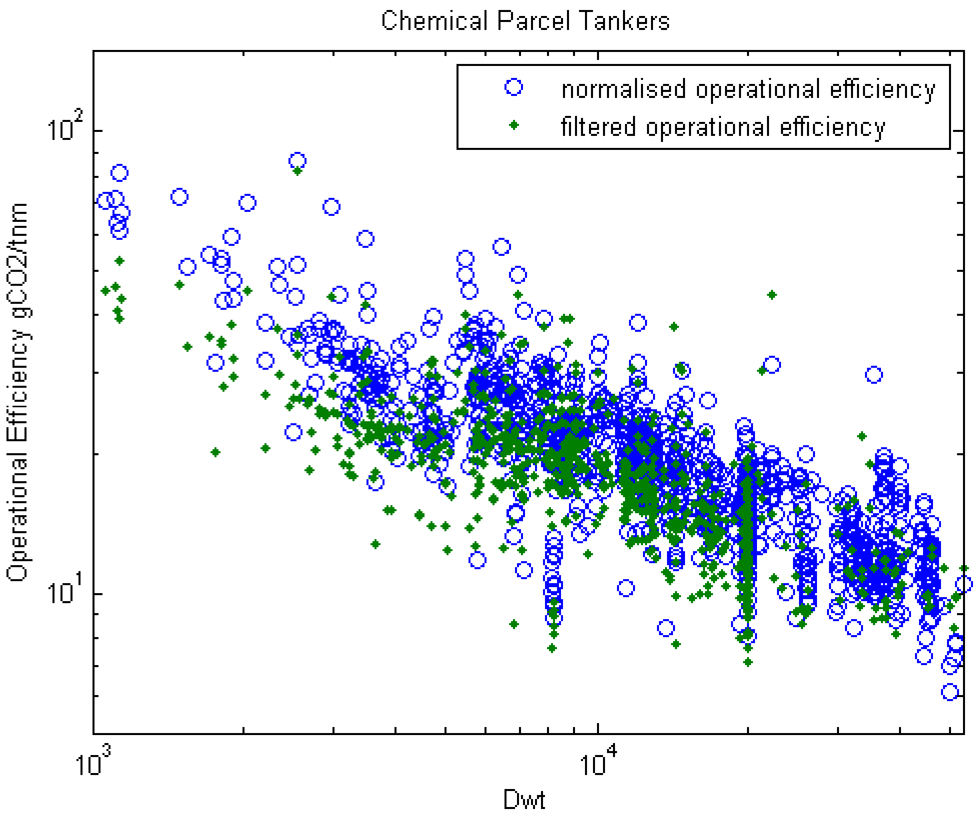

Product Tankers
ratio of average operating to design speed
Dwt
x 10^4
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
12
14
16
18
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years

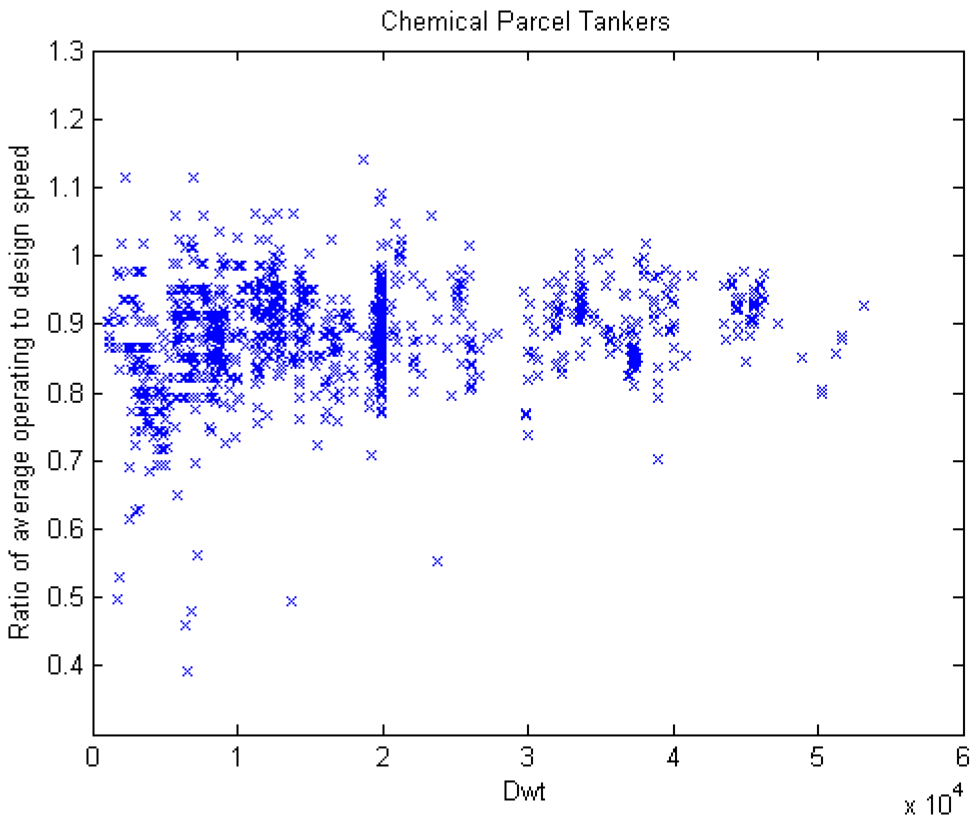

Product Tankers
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
technical efficiency gCO2/tnm
10^1
10^0
10^3
10^4
10^5
Dwt

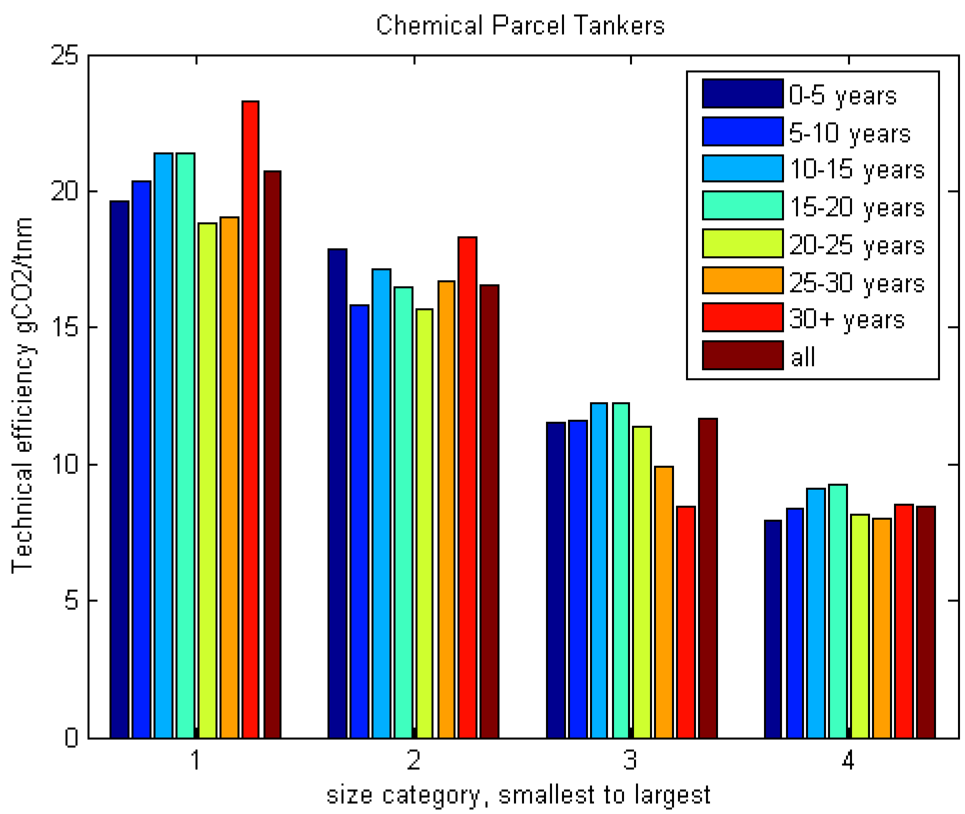

Chemical Parcel Tankers
Technical Efficiency gCO2/tnm
10^1
10^3
10^4
Dwt

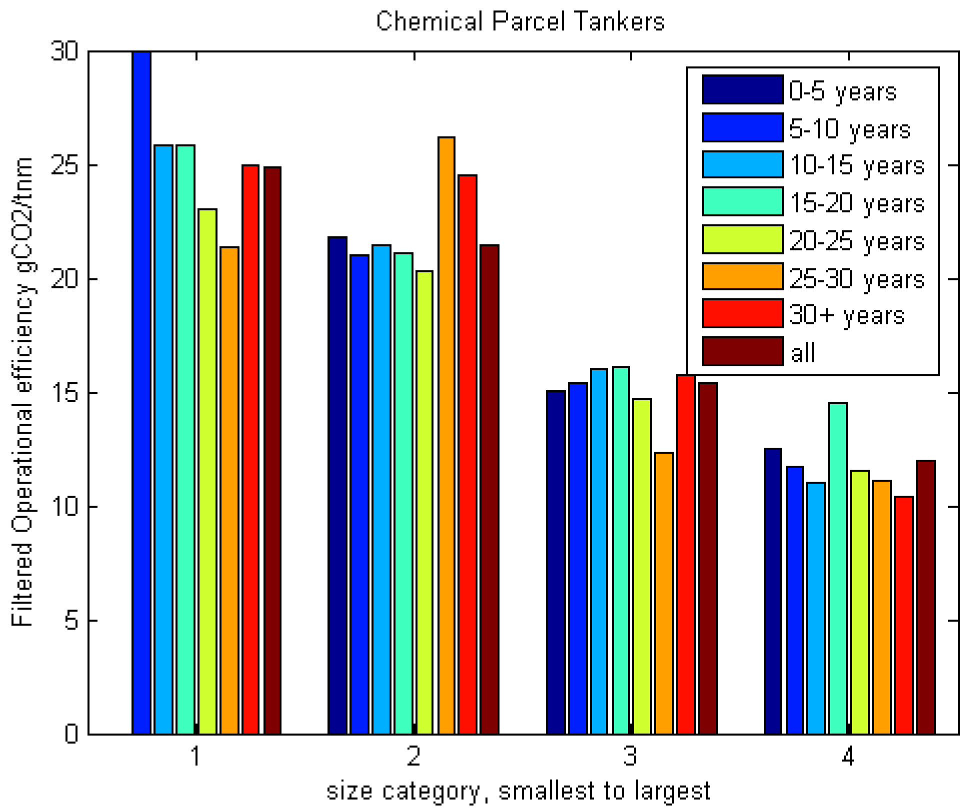

Chemical Parcel Tankers
Operational Efficiency gCO2/tnm
filtered
unfiltered
10^2
10^1
10^3
10^4
Dwt

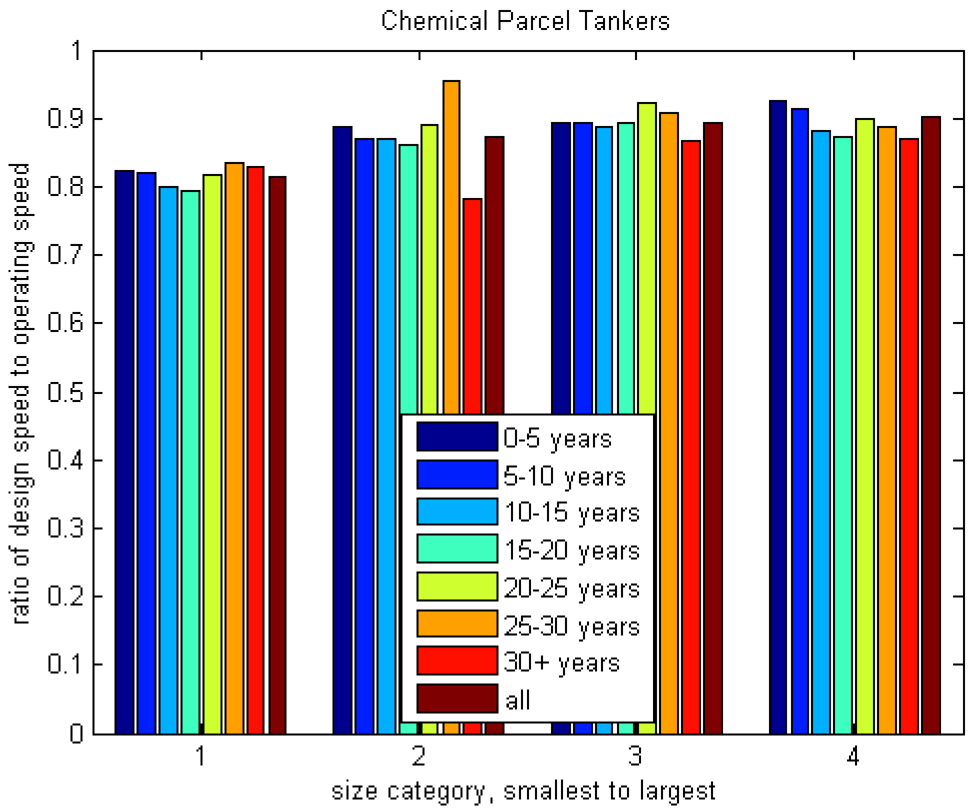

Chemical Parcel Tankers
Normalised Operational Efficiency gCO2/tnm
10^2
10^1
10^3
10^4
Dwt

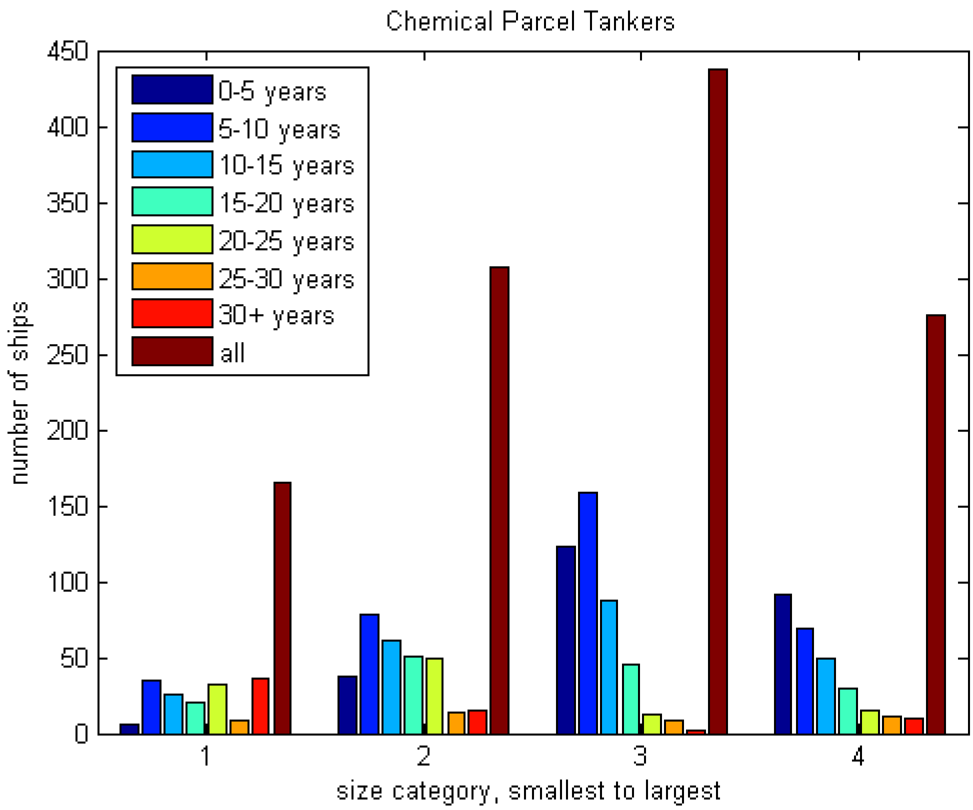

Chemical Parcel Tankers
normalised operational efficiency
filtered operational efficiency
Operational Efficiency gCO2/tnm
10^2
10^1
10^3
10^4
Dwt

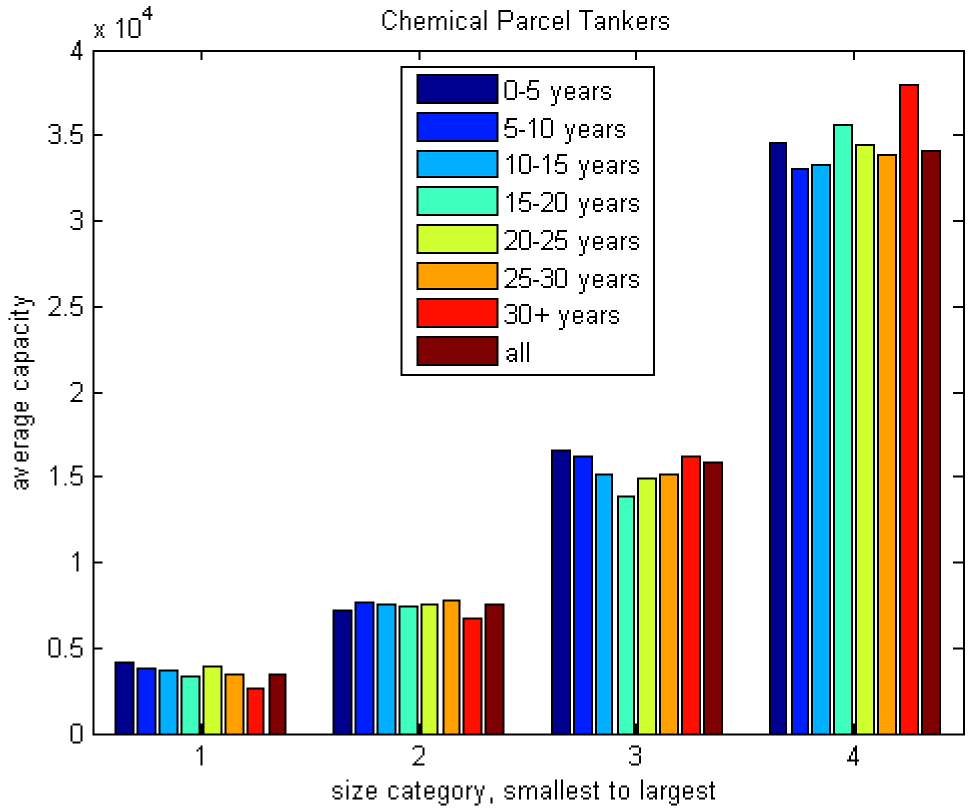

Chemical Parcel Tankers
Ratio of average operating to design speed
Dwt
x 10^4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0
1
2
3
4
5
6

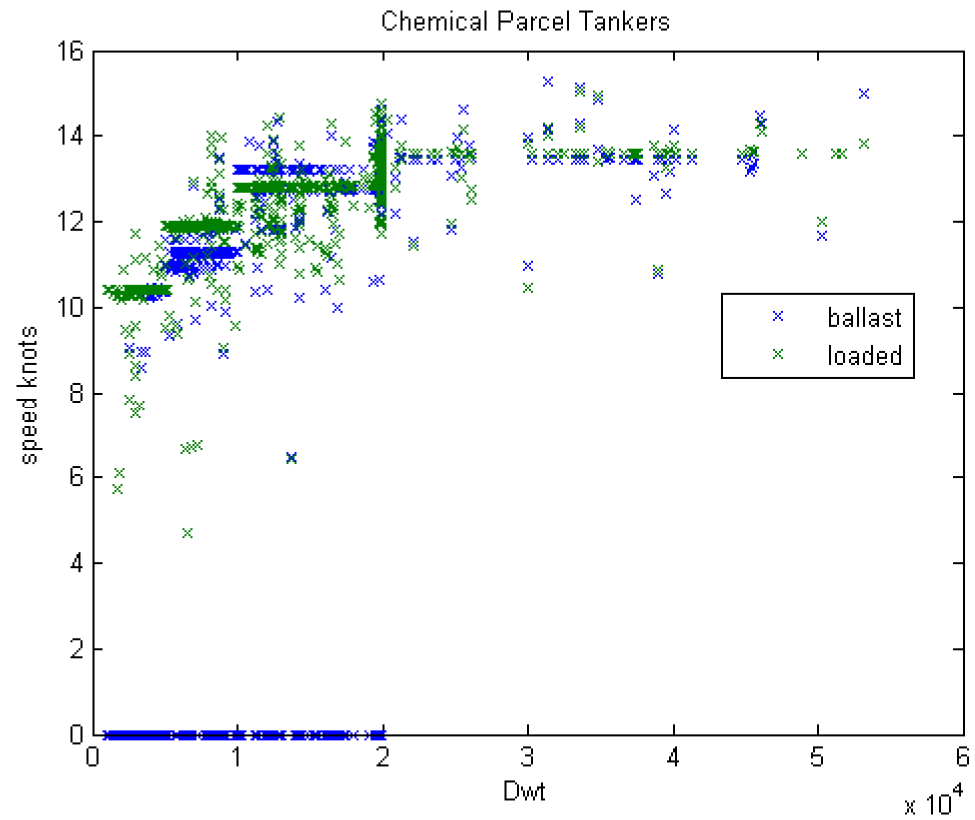

Chemical Parcel Tankers
Technical efficiency gCO2/tnm
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all
25
20
15
10
5
0
1
2
3
4

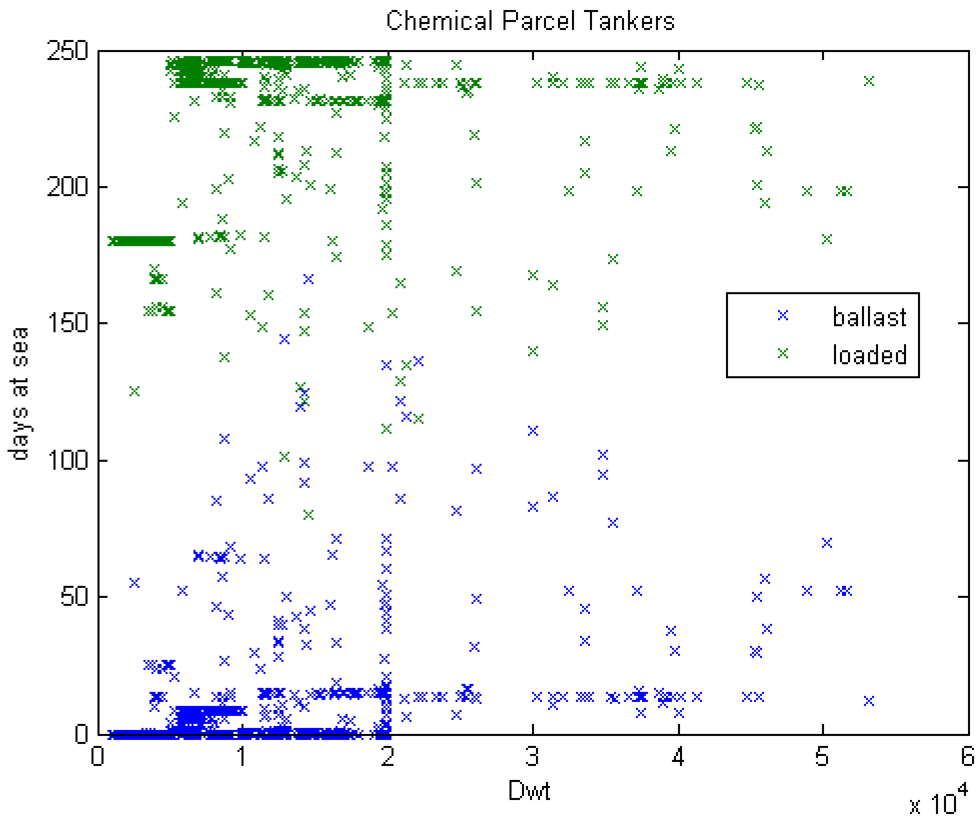

Chemical Parcel Tankers
Filtered Operational efficiency gCO2/tnm
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all

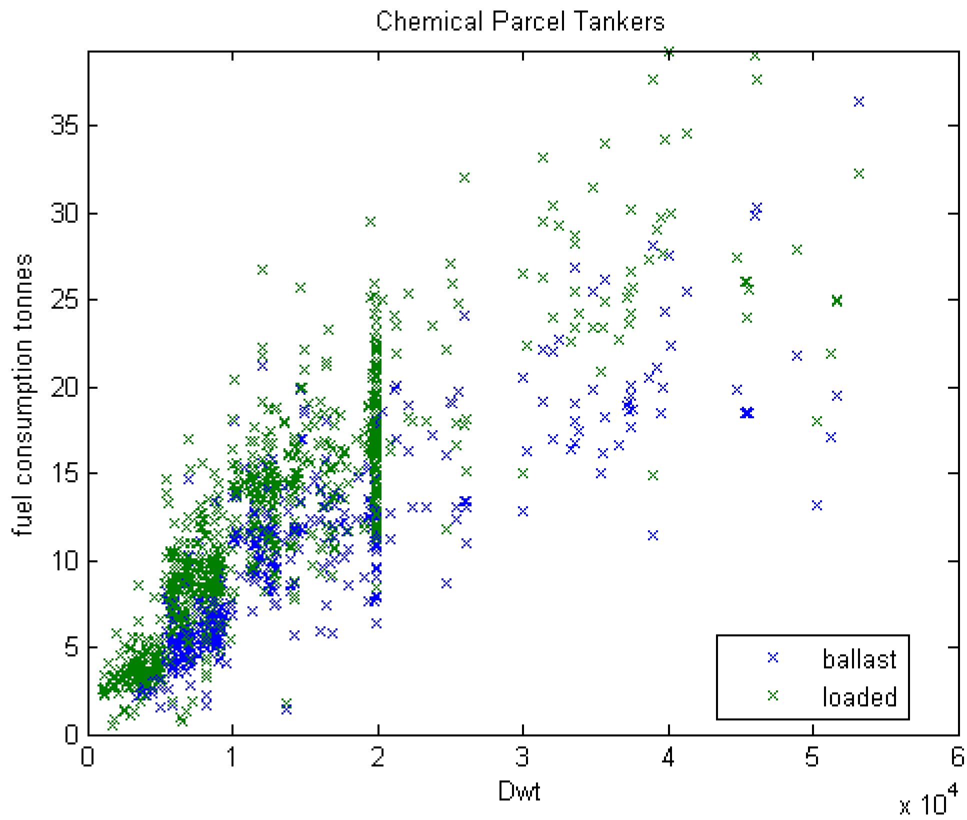

Chemical Parcel Tankers
ratio of design speed to operating speed
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all

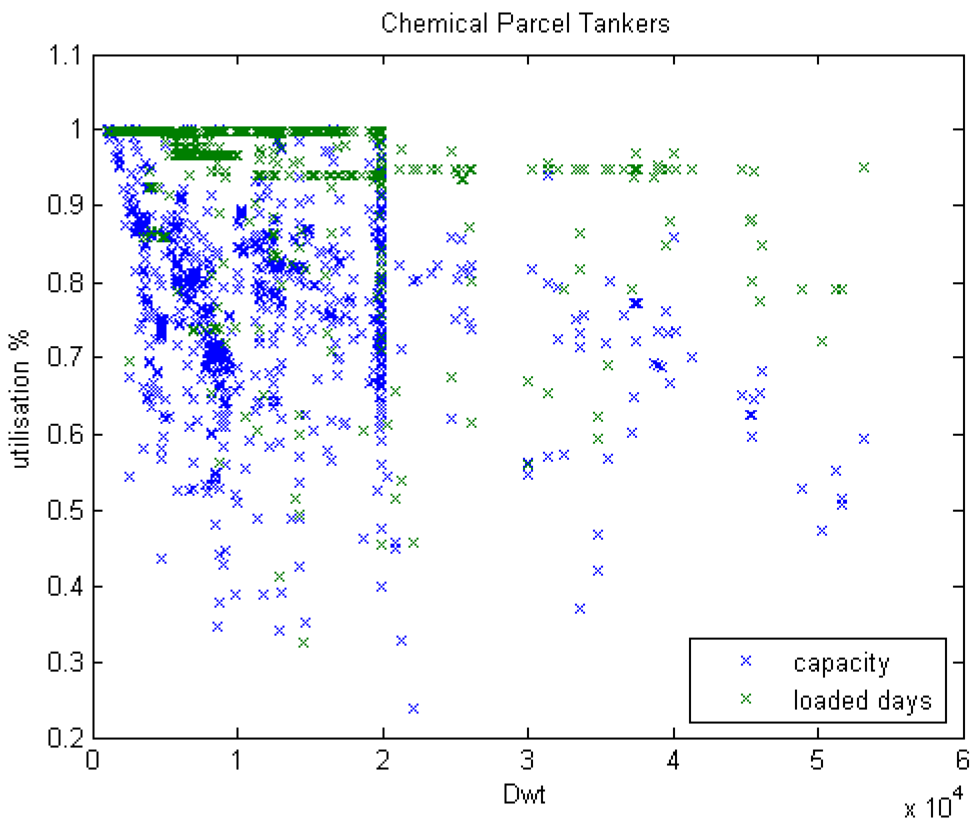

Chemical Parcel Tankers
number of ships
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all
size category, smallest to largest

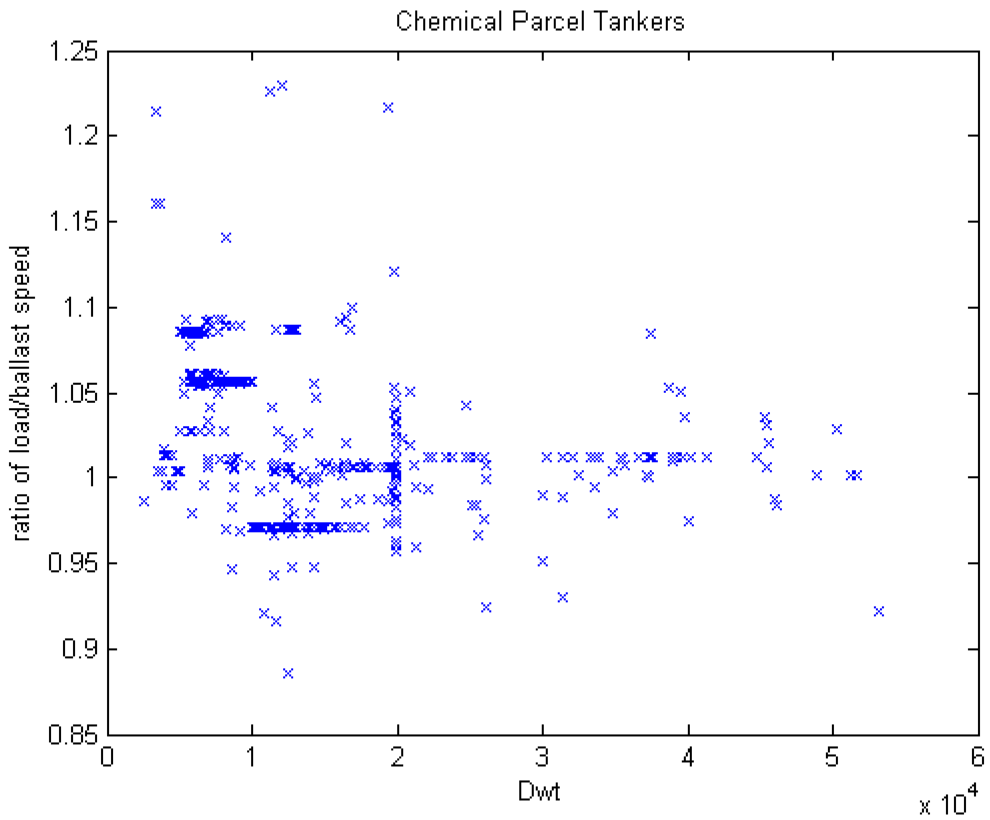

Chemical Parcel Tankers
x 10^4
average capacity
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all
size category, smallest to largest

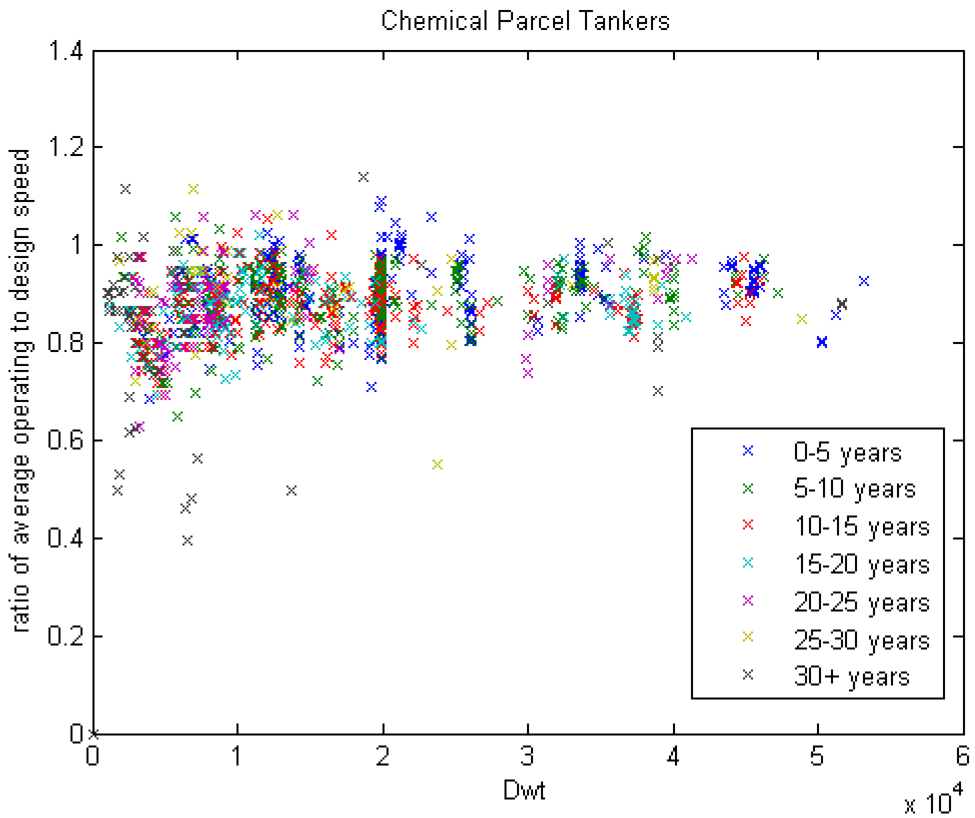

Chemical Parcel Tankers
speed knots
Dwt
x 10^4
ballast
loaded

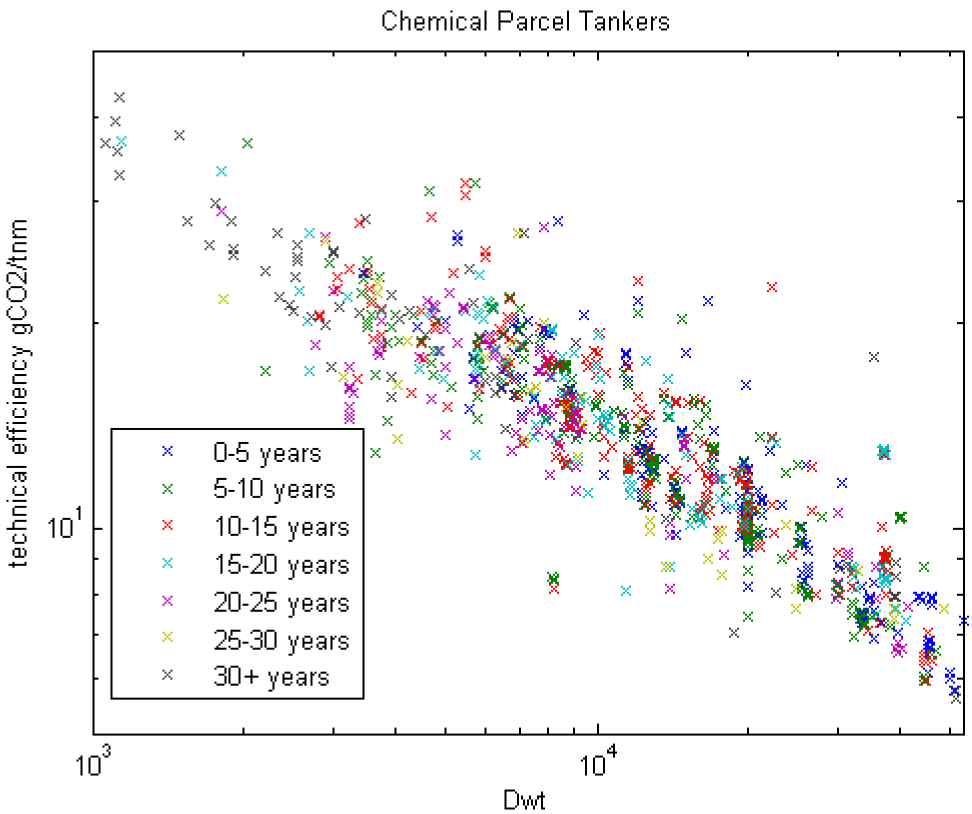

Chemical Parcel Tankers
days at sea
Dwt
x 10^4
ballast
loaded

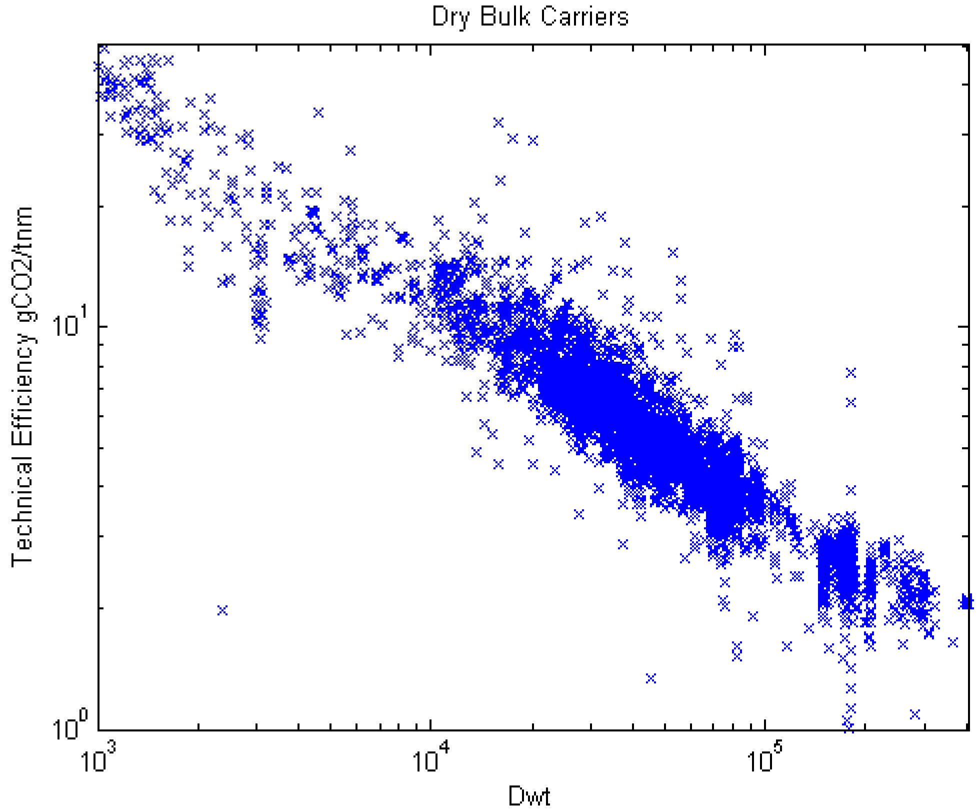

Chemical Parcel Tankers
fuel consumption tonnes
Dwt
x 10^4
ballast
loaded
0
5
10
15
20
25
30
35
1
2
3
4
6


Chemical Parcel Tankers
utilisation %
Dwt
x 10^4
capacity
loaded days
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
0
1
2
3
4
5
6

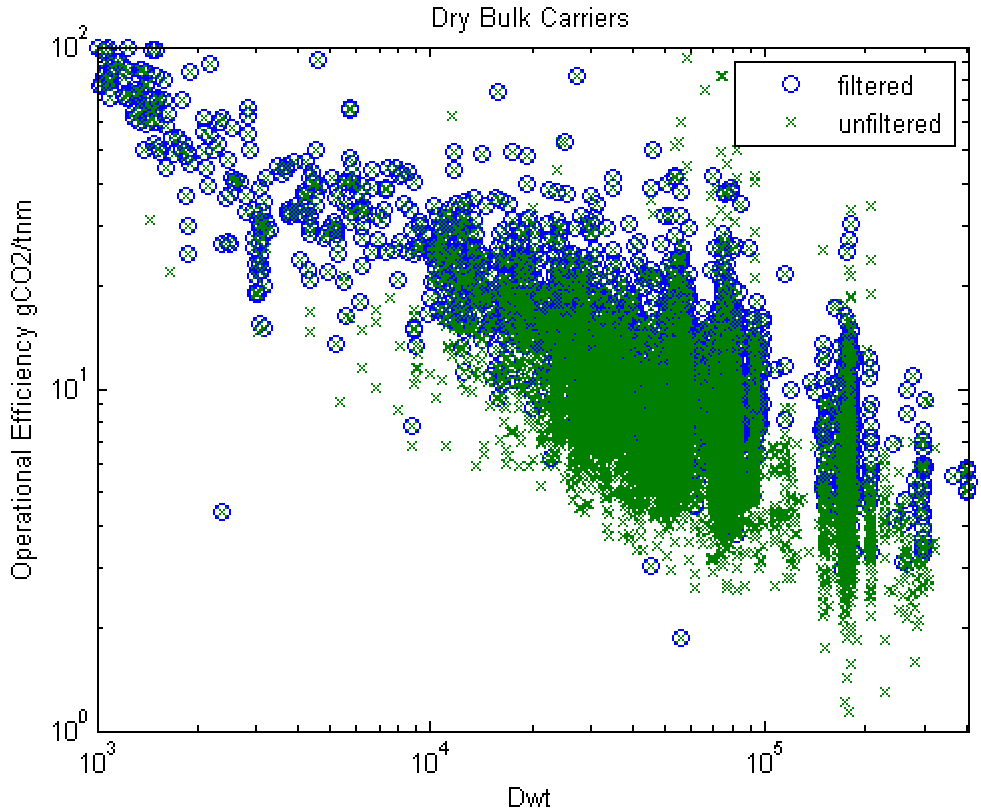

Chemical Parcel Tankers
ratio of load/ballast speed
1.25
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0
1
2
3
4
5
6
Dwt
x 10^4


Chemical Parcel Tankers
ratio of average operating to design speed
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
Dwt
x 10^4
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years

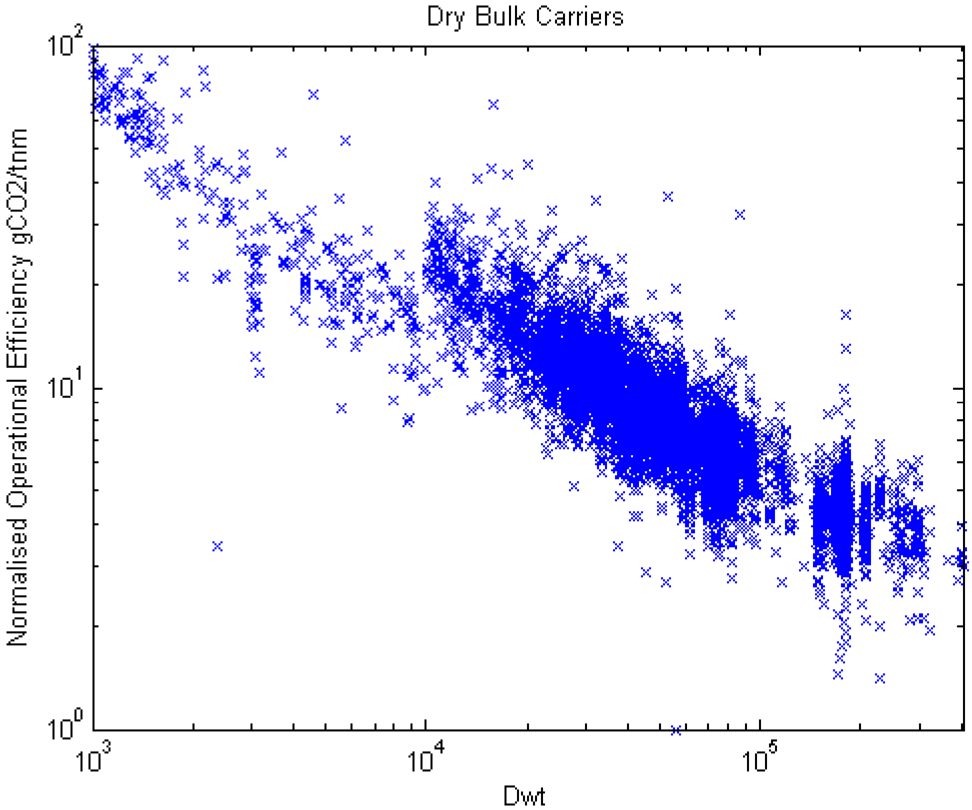

Chemical Parcel Tankers
technical efficiency gCO2/tnm
10^1
10^3
10^4
Dwt
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years

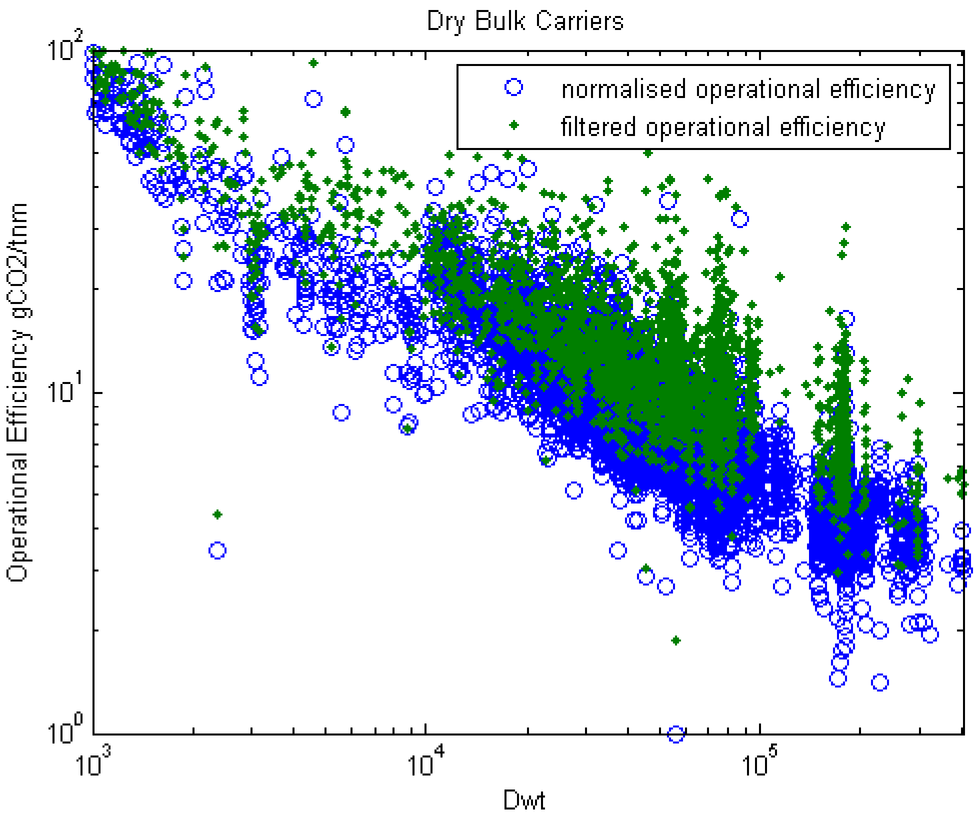


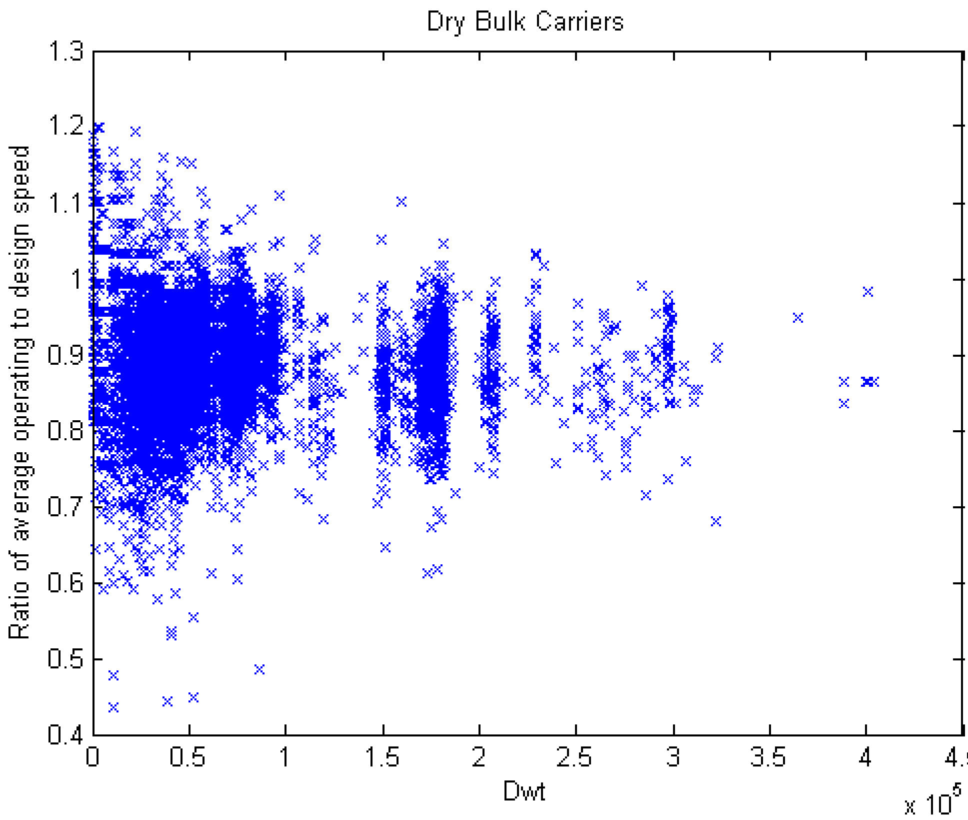
Dry Bulk Carriers
Technical Efficiency gCO2/tnm
Dwt

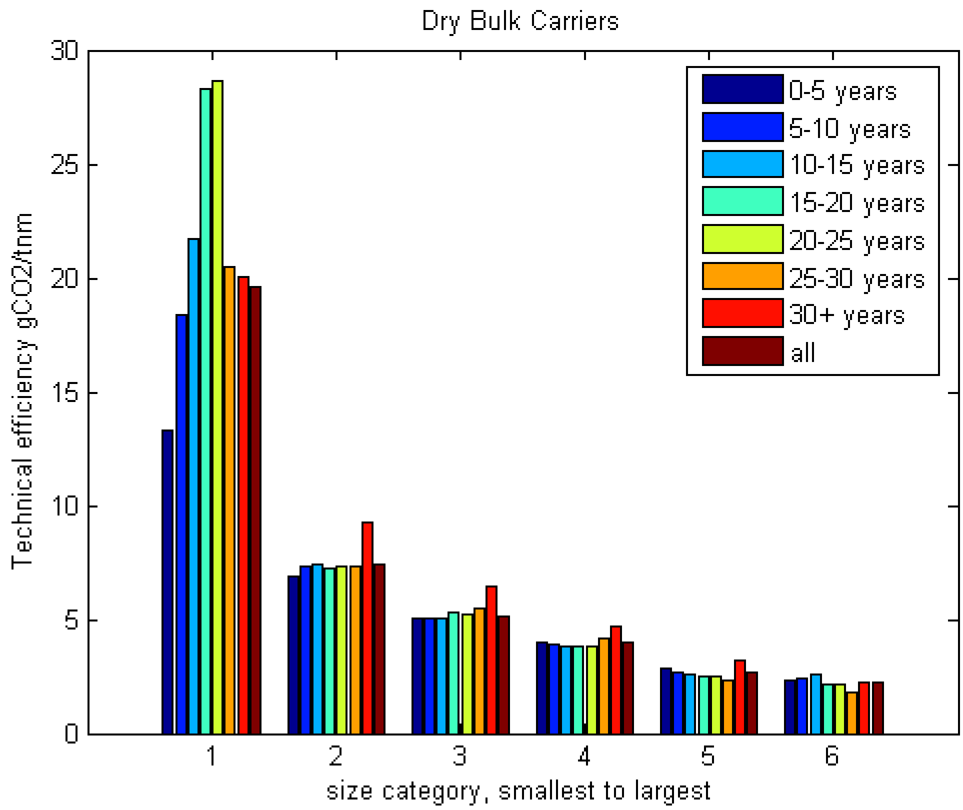


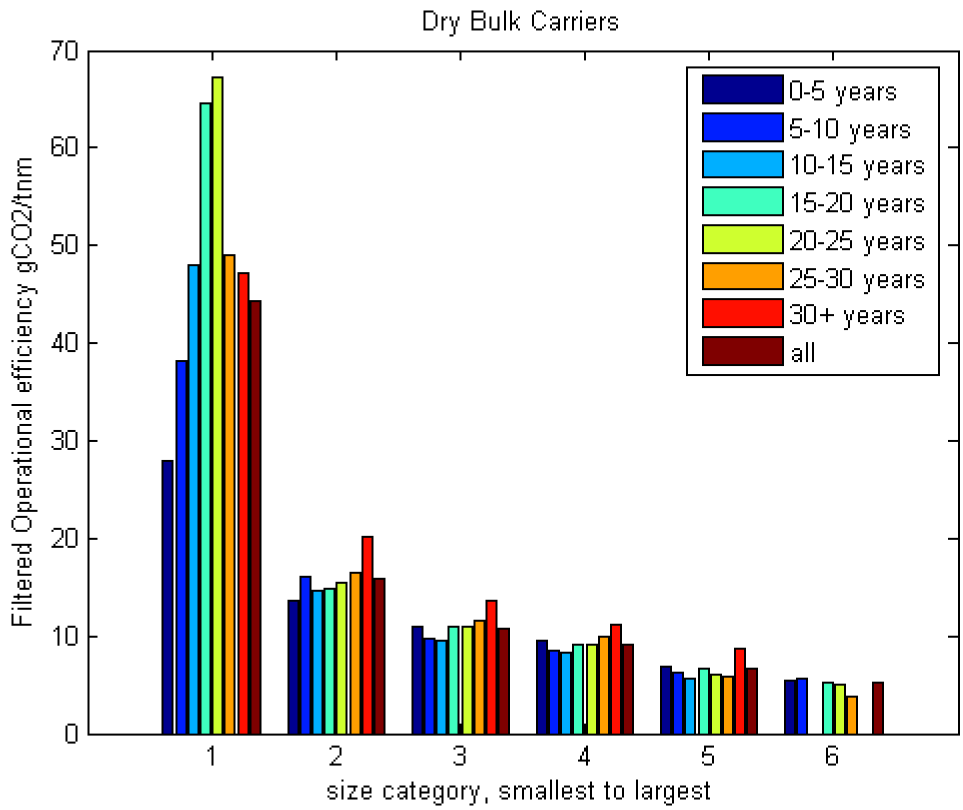
Dry Bulk Carriers
Operational Efficiency gCO2/tnm
Dwt
filtered
unfiltered

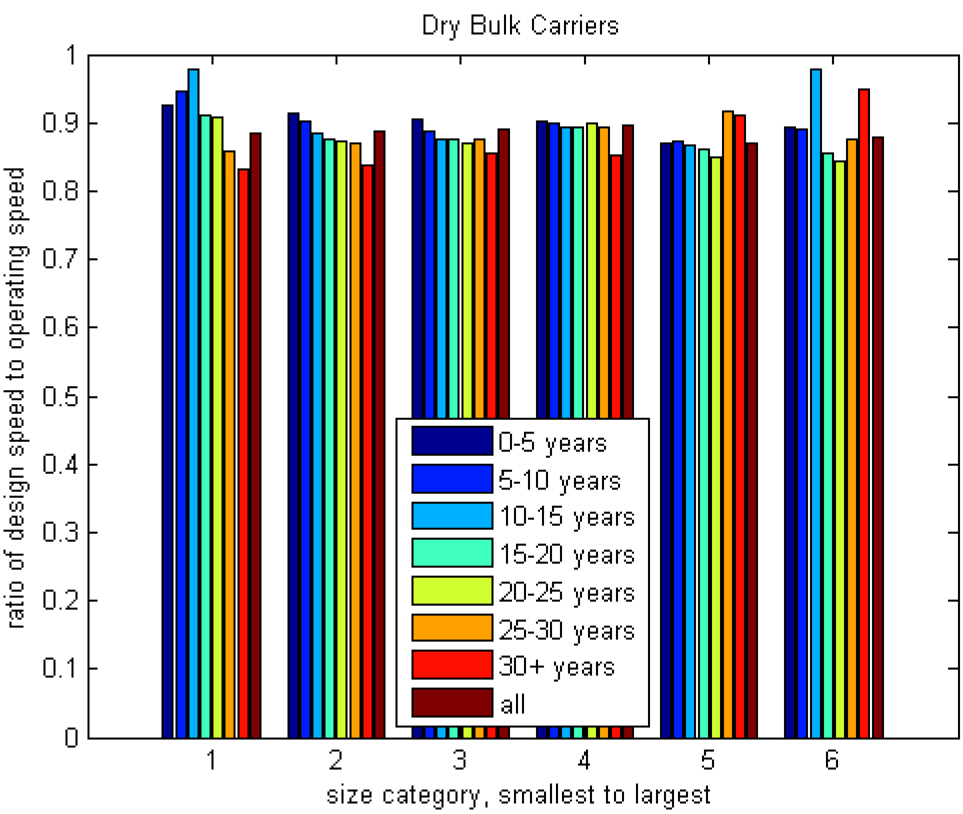

Dry Bulk Carriers
Normalised Operational Efficiency gCO2/tnm
Dwt
10^2
10^1
10^0
10^3
10^4
10^5

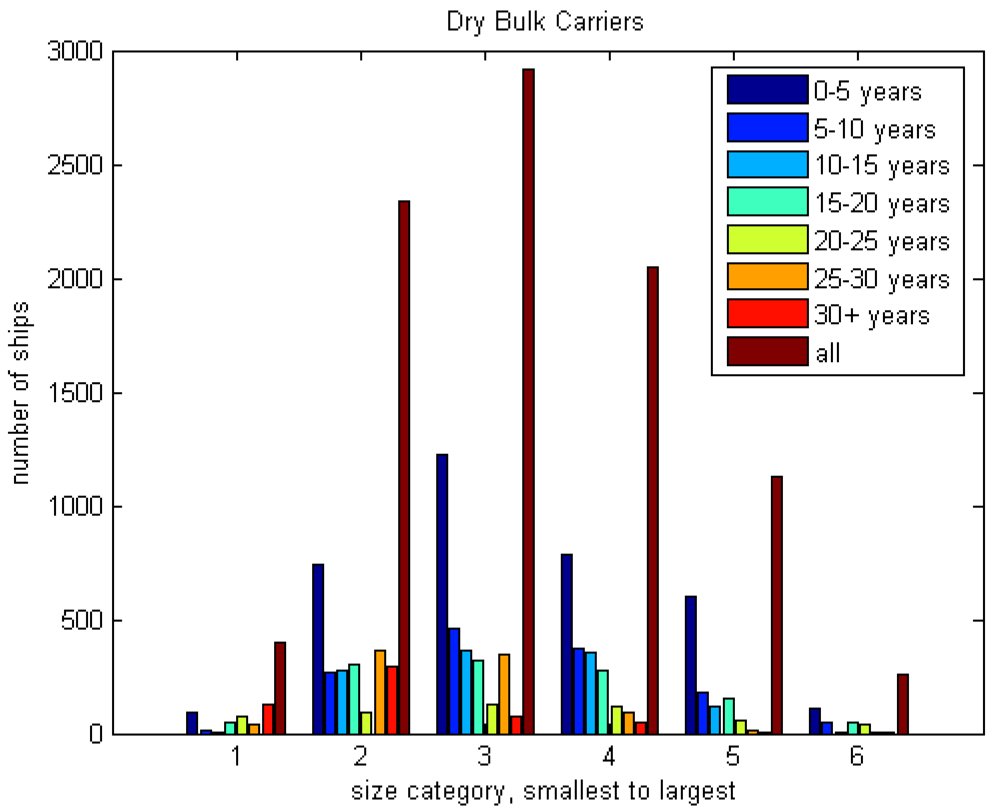

Dry Bulk Carriers
normalised operational efficiency
filtered operational efficiency
Operational Efficiency gCO2/tnm
Dwt
10^2
10^1
10^0
10^3
10^4
10^5

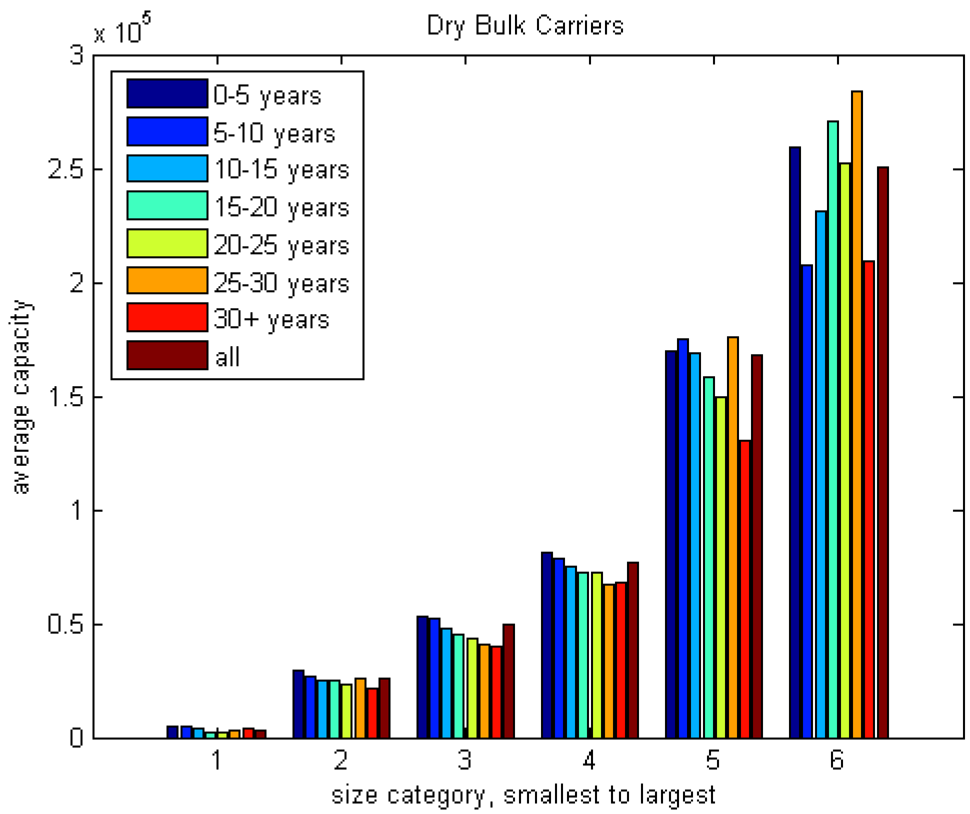

Dry Bulk Carriers
Ratio of average operating to design speed
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Dwt
$x\ 10^5$

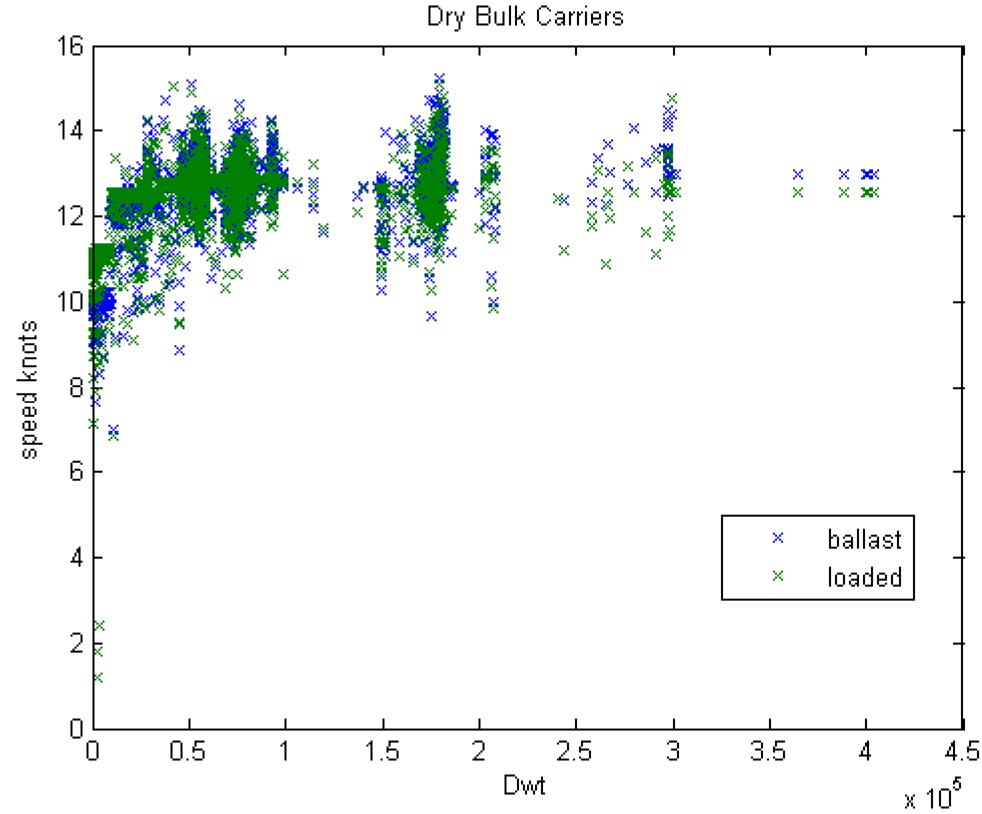

Dry Bulk Carriers
Technical efficiency gCO2/tnm
30
25
20
15
10
5
0
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all
1
2
3
4
5
6
size category, smallest to largest

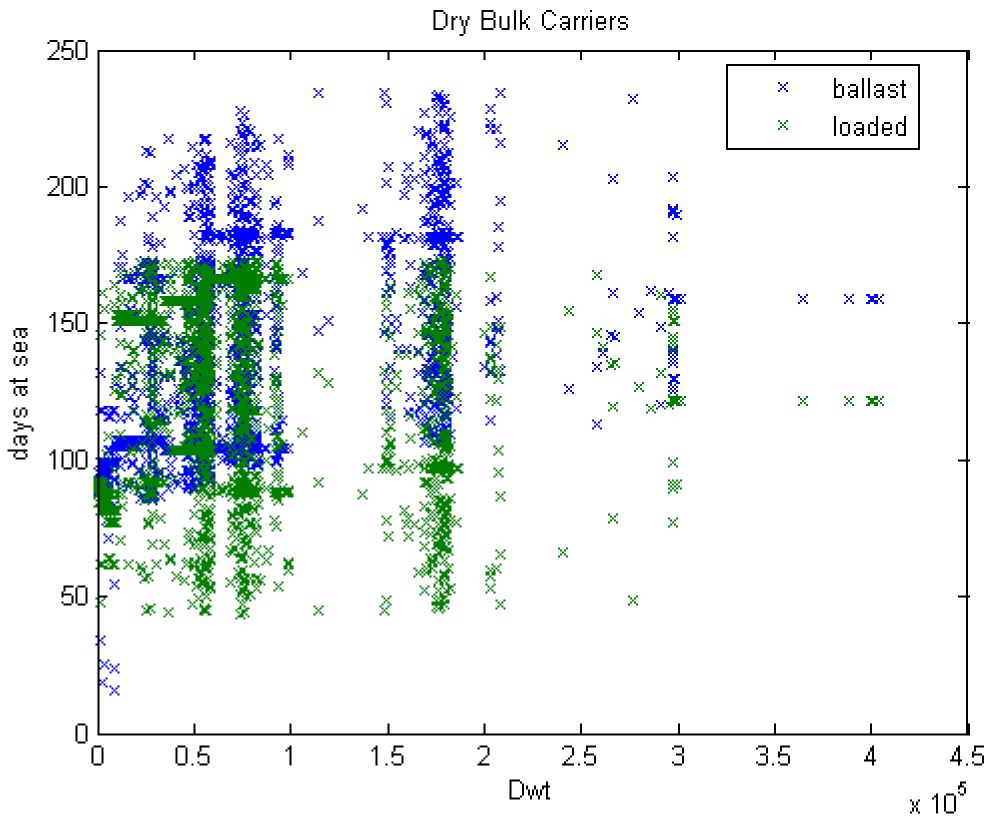

Dry Bulk Carriers
Filtered Operational efficiency gCO2/tnm
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all

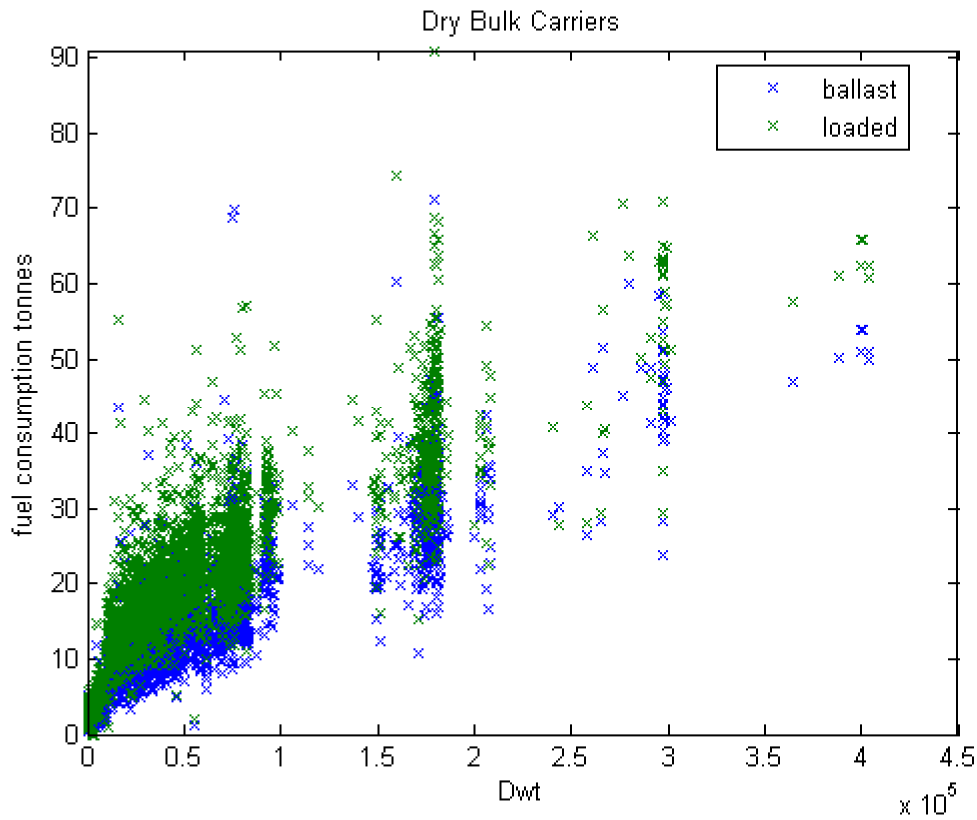

Dry Bulk Carriers
ratio of design speed to operating speed
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all

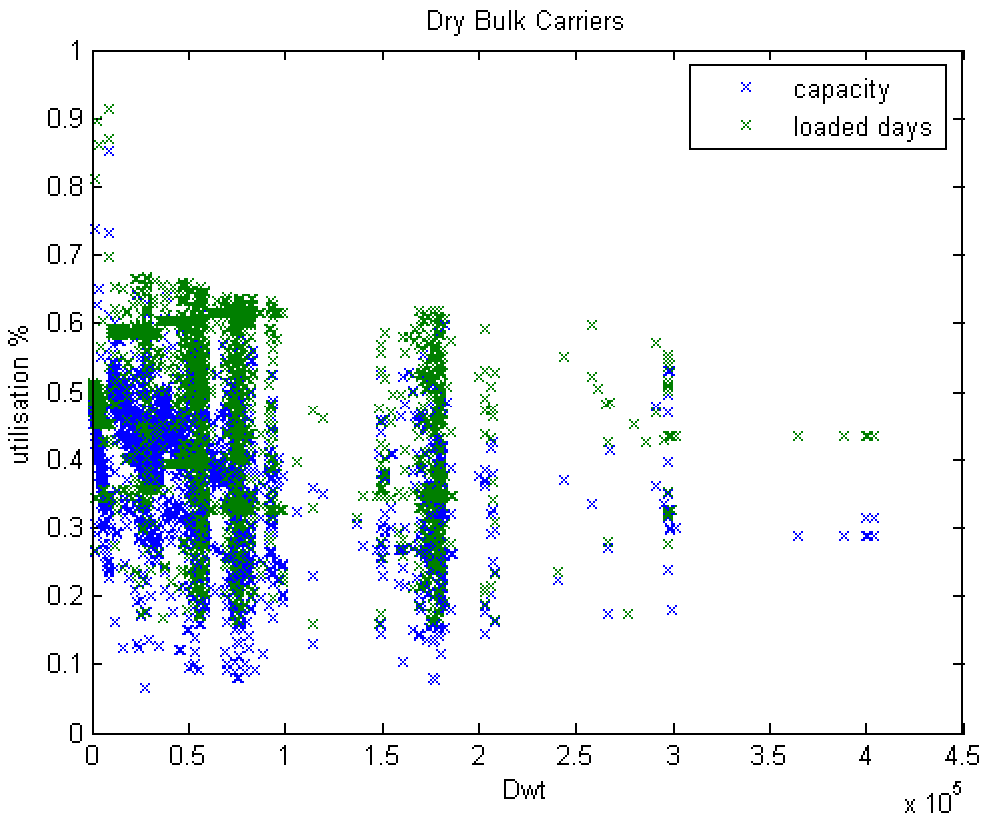

Dry Bulk Carriers
number of ships
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all

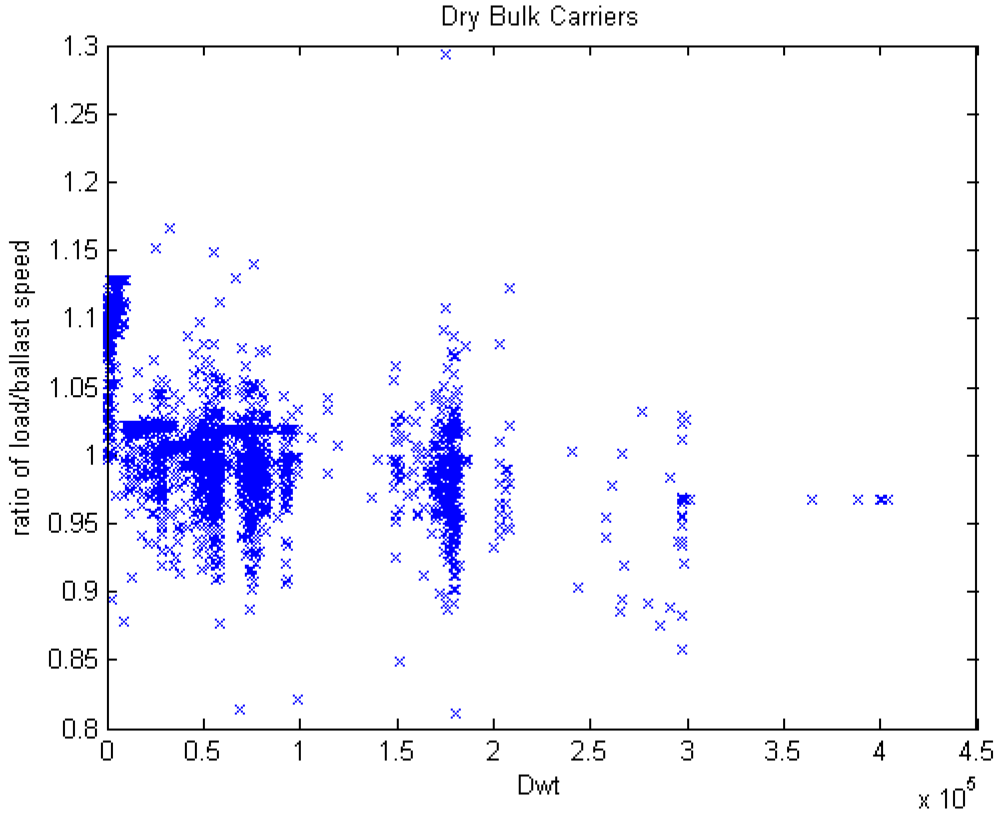

Dry Bulk Carriers
x 10^5
average capacity
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all

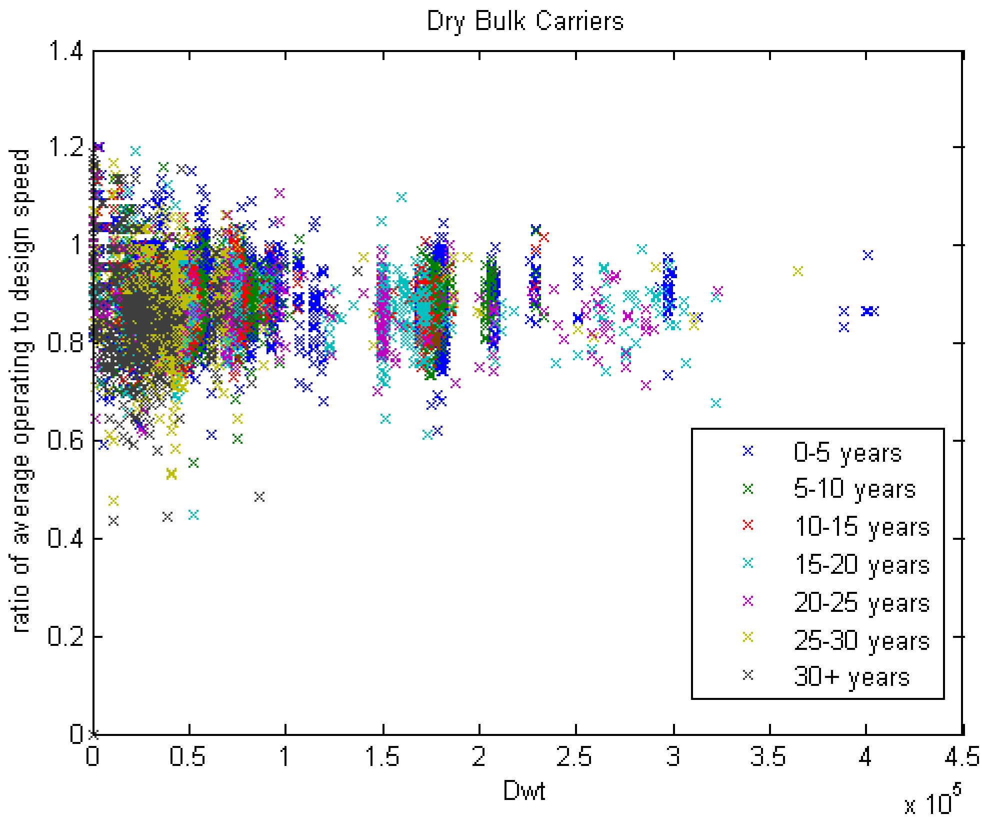

Dry Bulk Carriers
speed knots
Dwt
x 10^5
ballast
loaded
16
14
12
10
8
6
4
2
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5

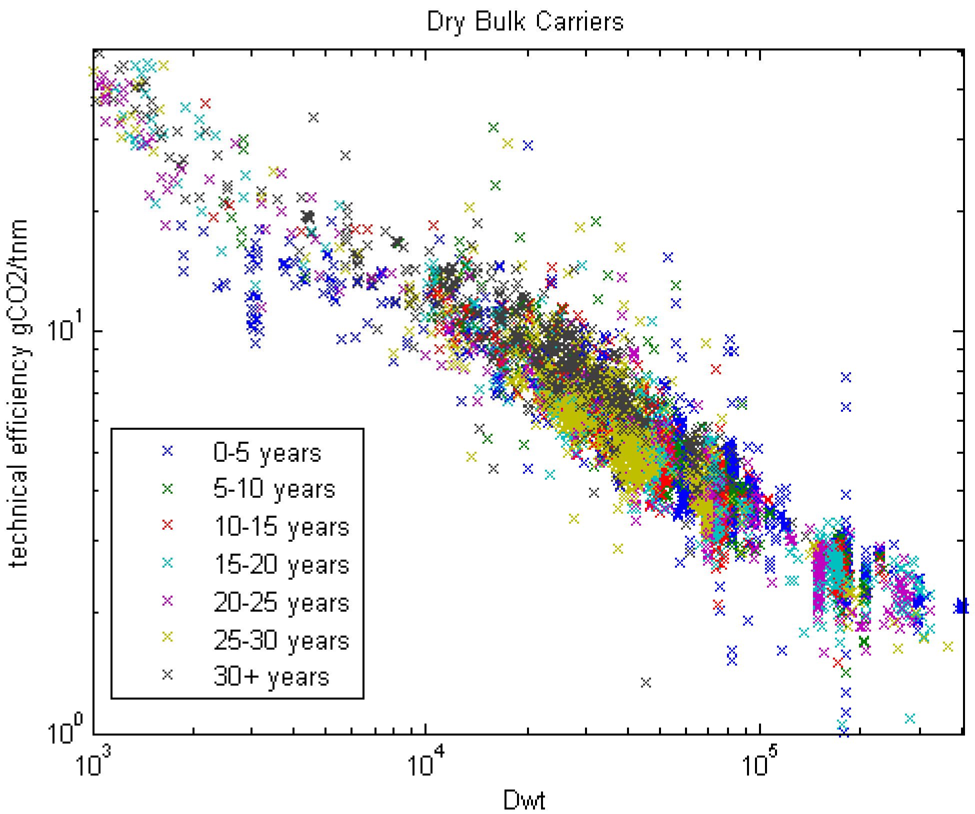

Dry Bulk Carriers
days at sea
Dwt
x 10^5
ballast
loaded
250
200
150
100
50
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5


Dry Bulk Carriers
ballast
loaded
fuel consumption tonnes
Dwt
x 10^5
0
10
20
30
40
50
60
70
80
90
0.5
1
1.5
2
2.5
3
3.5
4
4.5

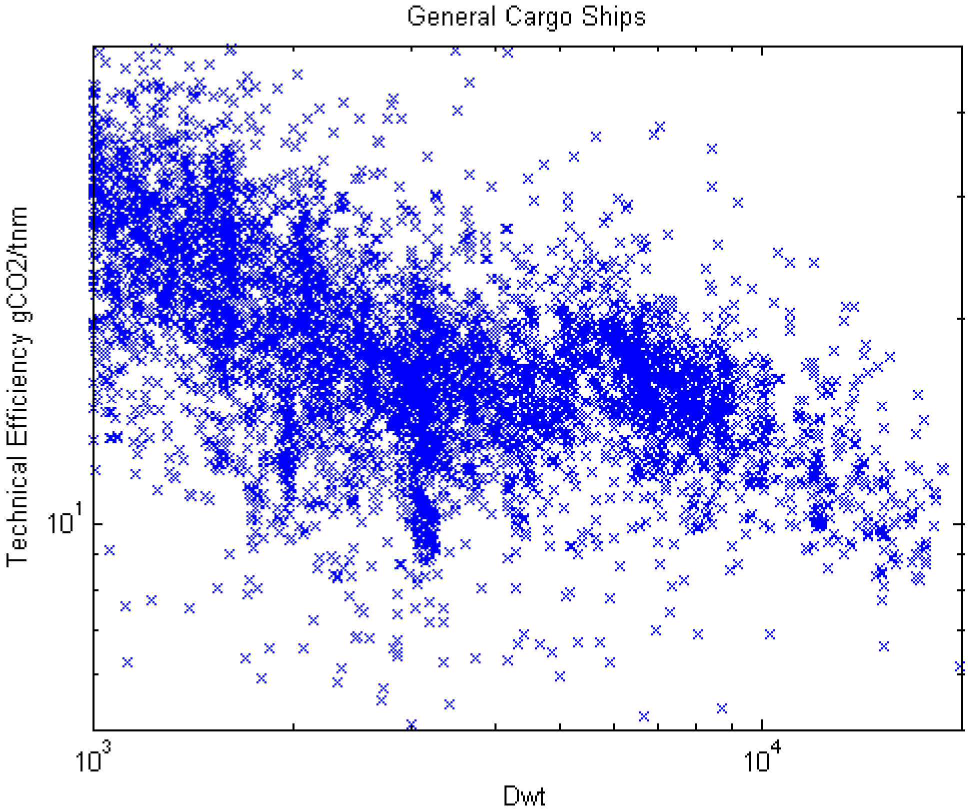

Dry Bulk Carriers
capacity
loaded days
utilisation %
Dwt
x 10^5
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.5
1.5
2
2.5
3
3.5
4
4.5

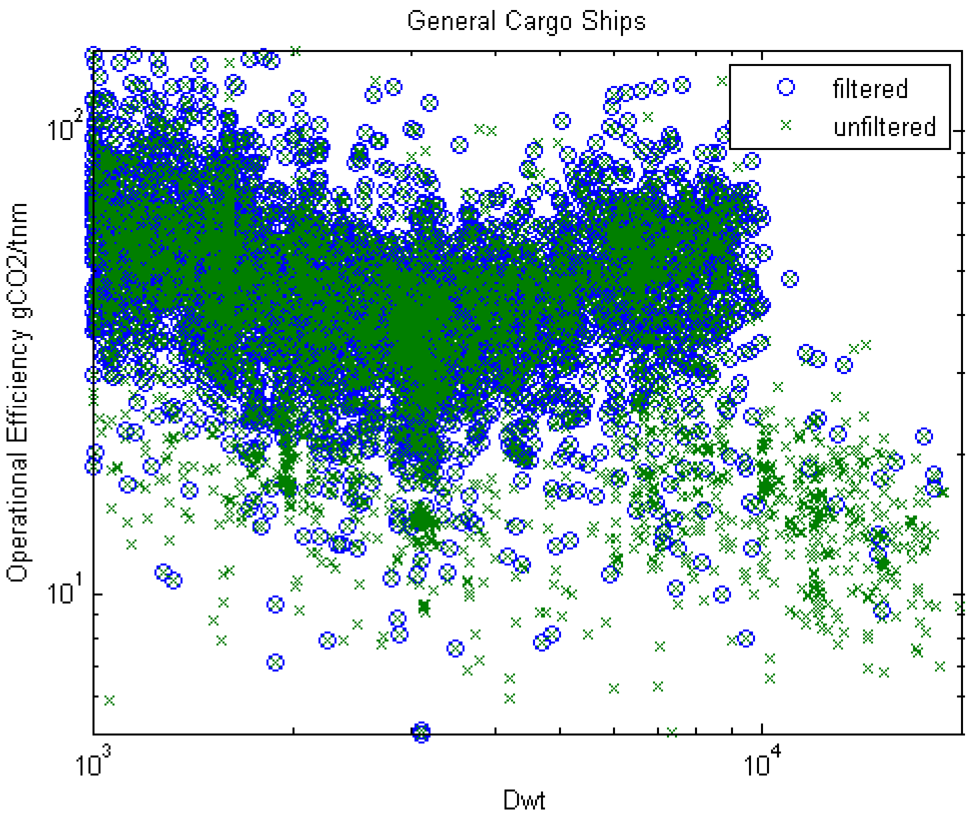

Dry Bulk Carriers
ratio of load/ballast speed
Dwt
x 10^5

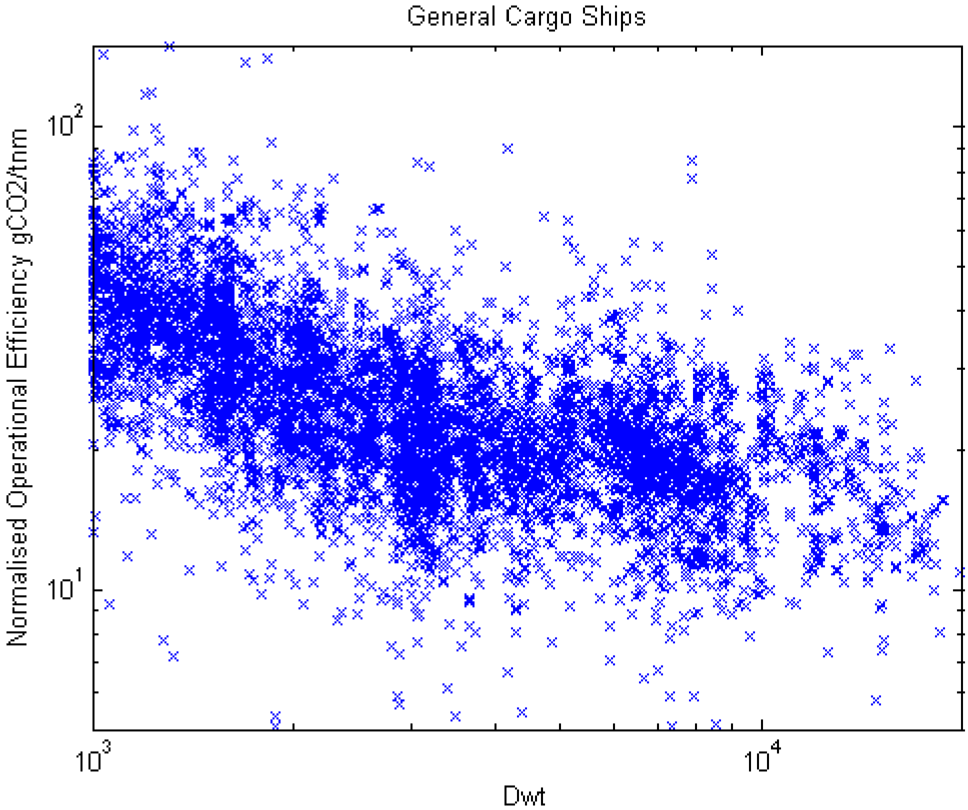

Dry Bulk Carriers
ratio of average operating to design speed
Dwt
x 10^5
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years

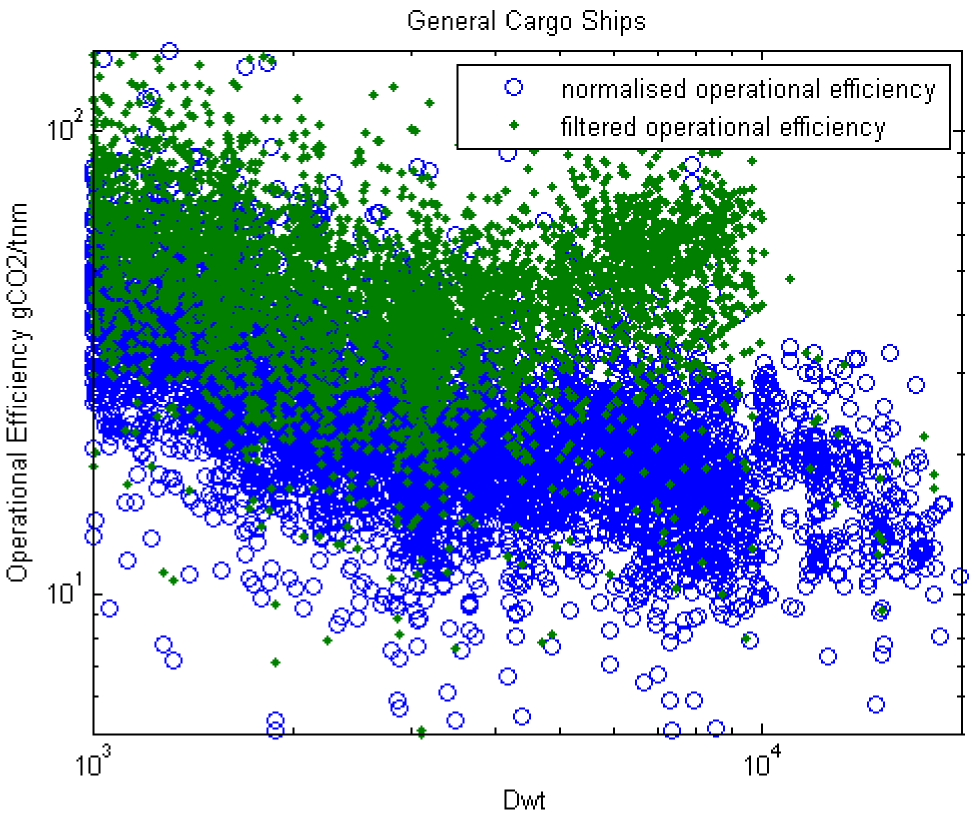


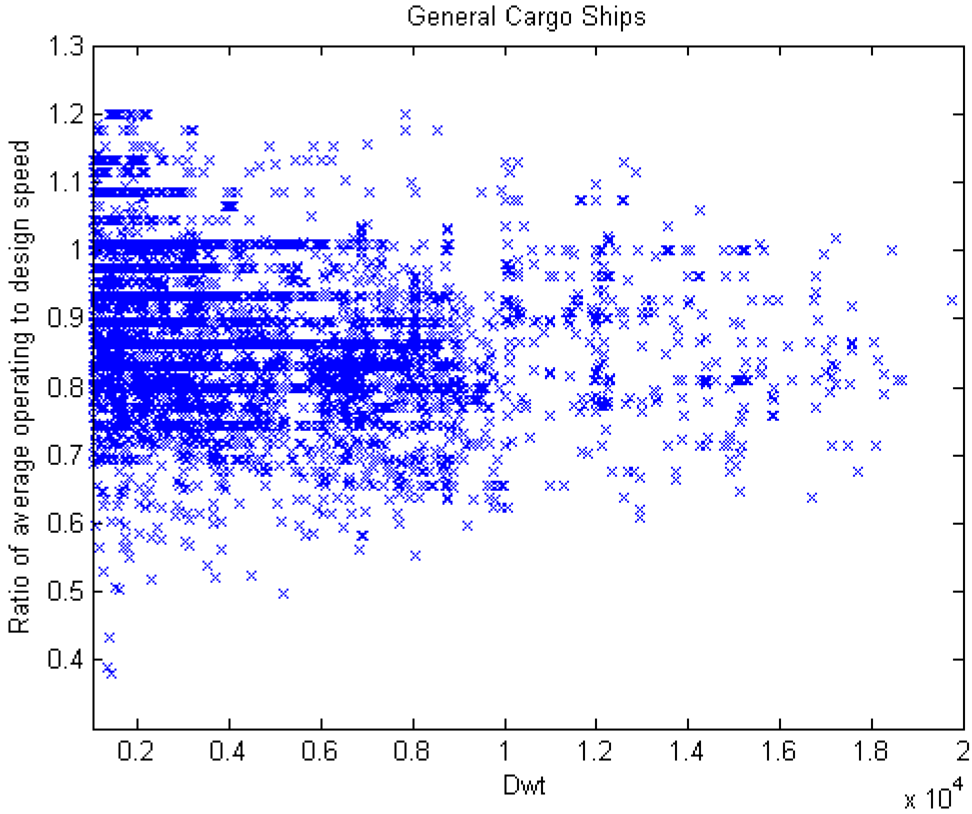
Dry Bulk Carriers
technical efficiency gCO2/tnm
Dwt
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years

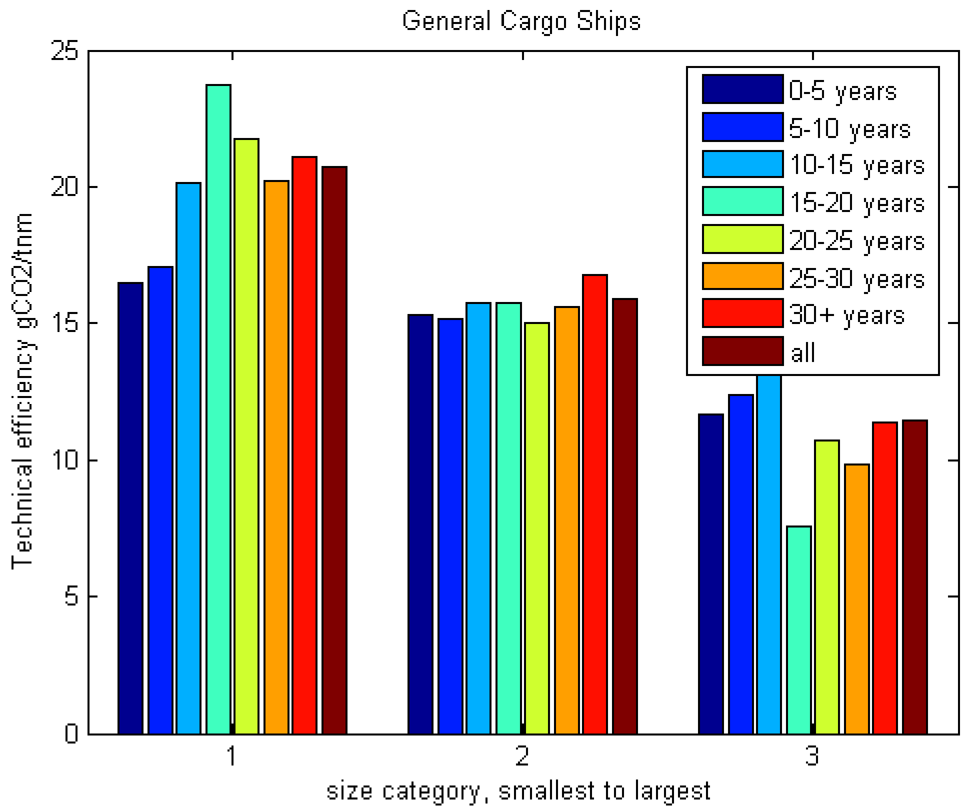

General Cargo Ships
Technical Efficiency gCO2/tnm
10^1
10^3
10^4
Dwt

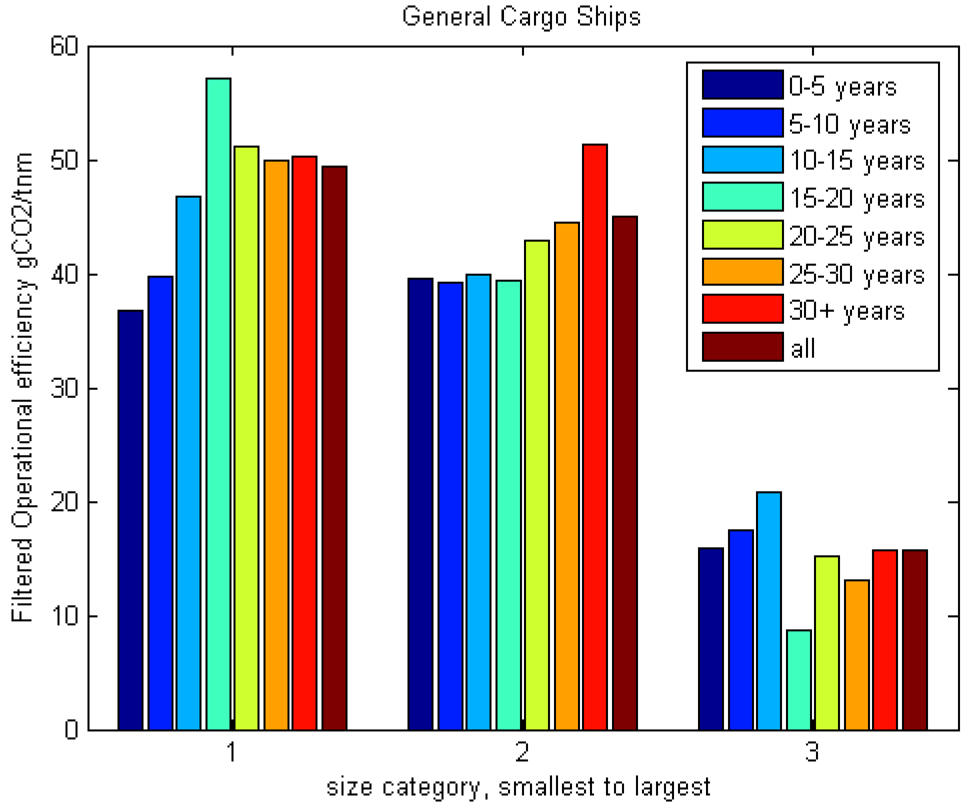

General Cargo Ships
filtered
unfiltered
Operational Efficiency gCO2/tnm
10^2
10^1
10^3
10^4
Dwt


General Cargo Ships
Normalised Operational Efficiency gCO2/tnm
10^2
10^1
10^3
10^4
Dwt

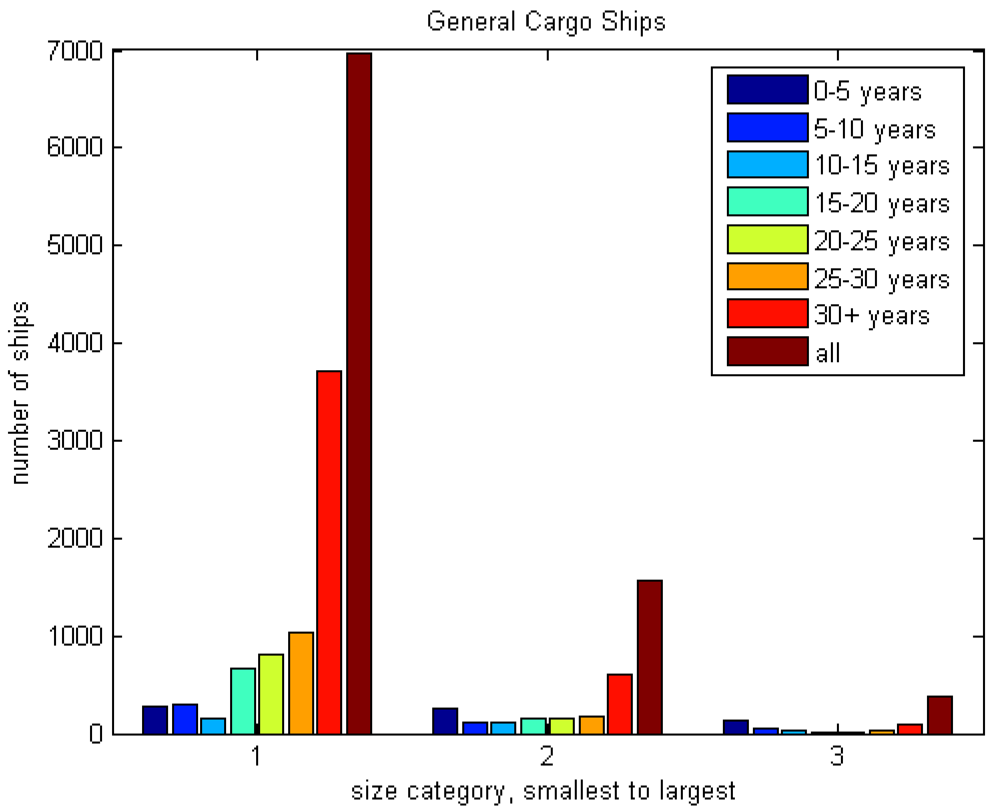

General Cargo Ships
normalised operational efficiency
filtered operational efficiency
Operational Efficiency gCO2/tnm
10^2
10^1
10^3
10^4
Dwt

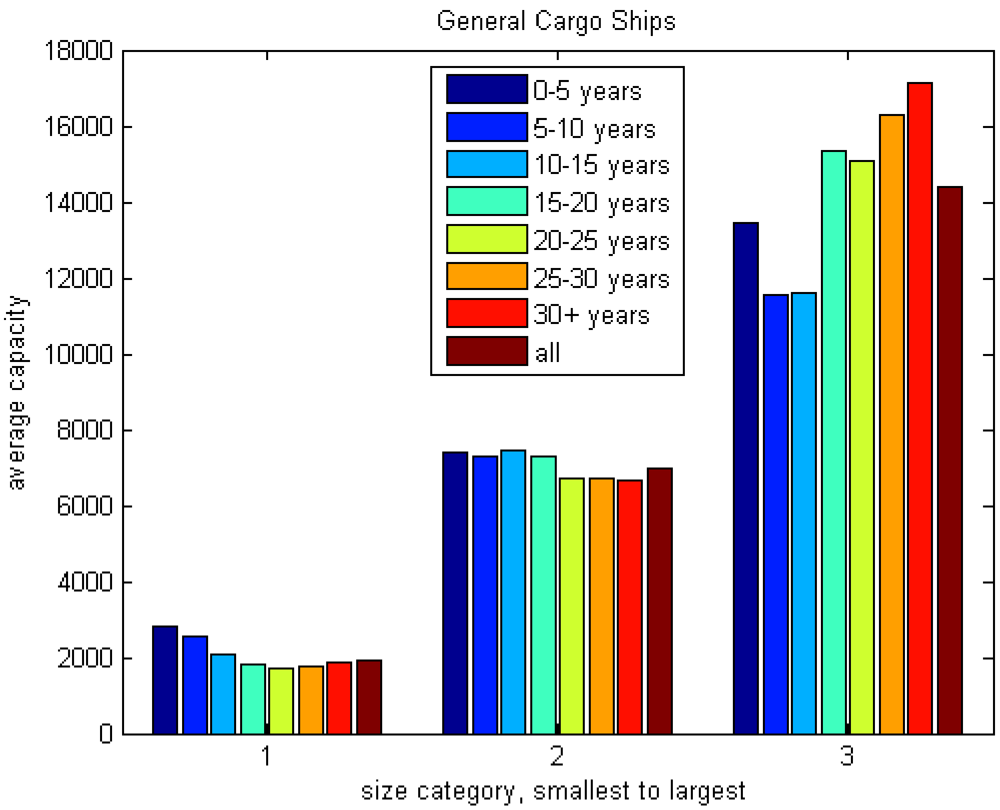

General Cargo Ships
Ratio of average operating to design speed
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Dwt
x 10^4

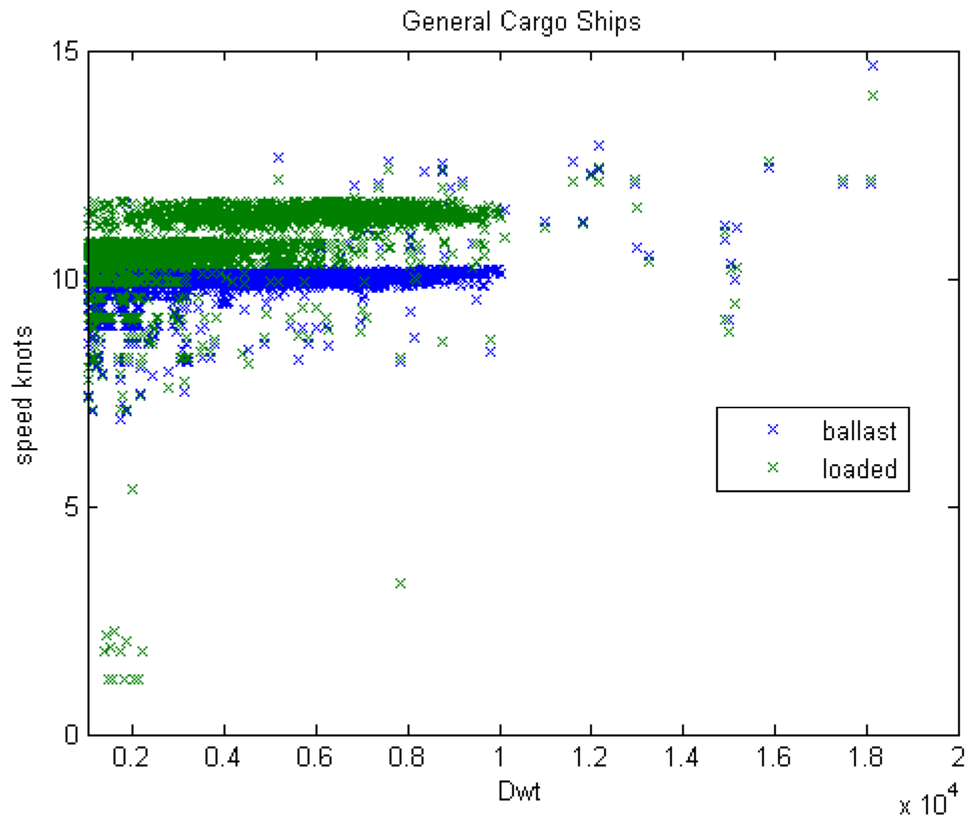

General Cargo Ships
Technical efficiency gCO2/tnm
25
20
15
10
5
0
1
2
3
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all

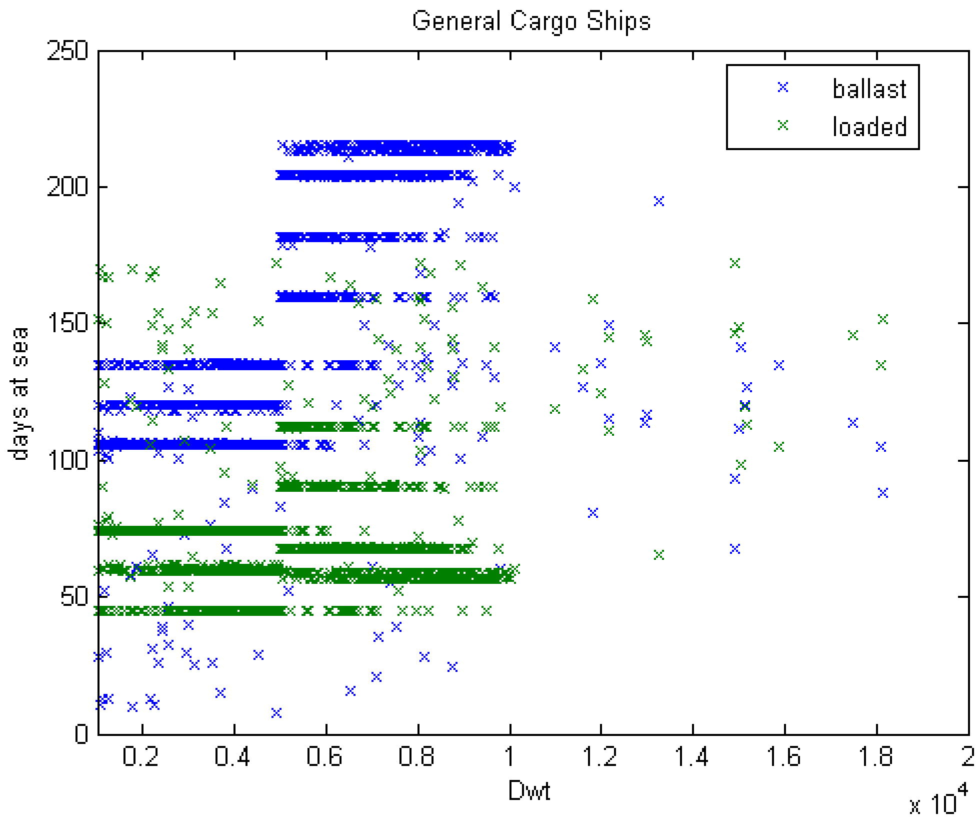

General Cargo Ships
Filtered Operational efficiency gCO2/tnm
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all

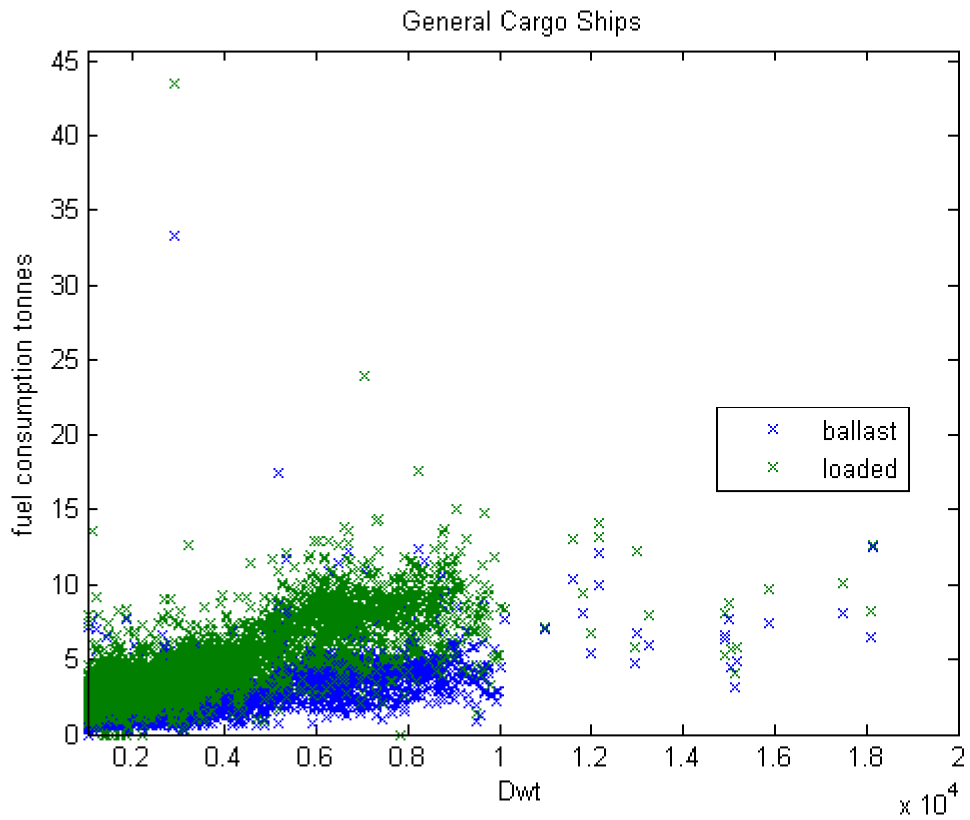

General Cargo Ships
ratio of design speed to operating speed
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all

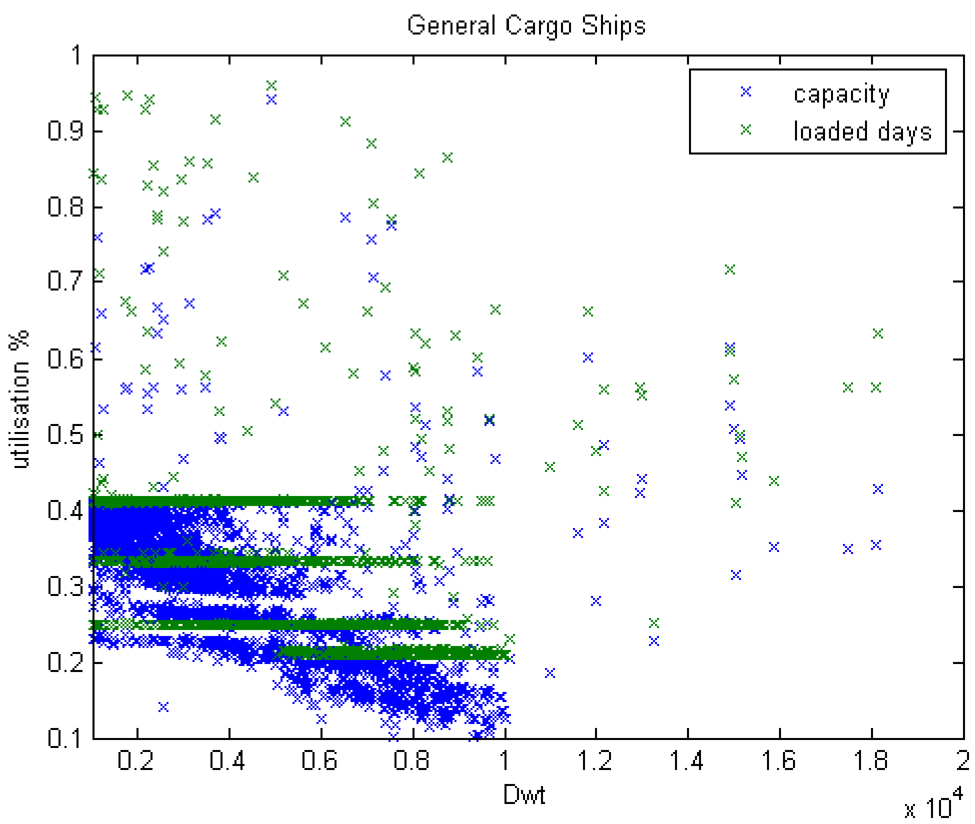

General Cargo Ships
number of ships
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all
0
1000
2000
3000
4000
5000
6000
7000
1
2
3

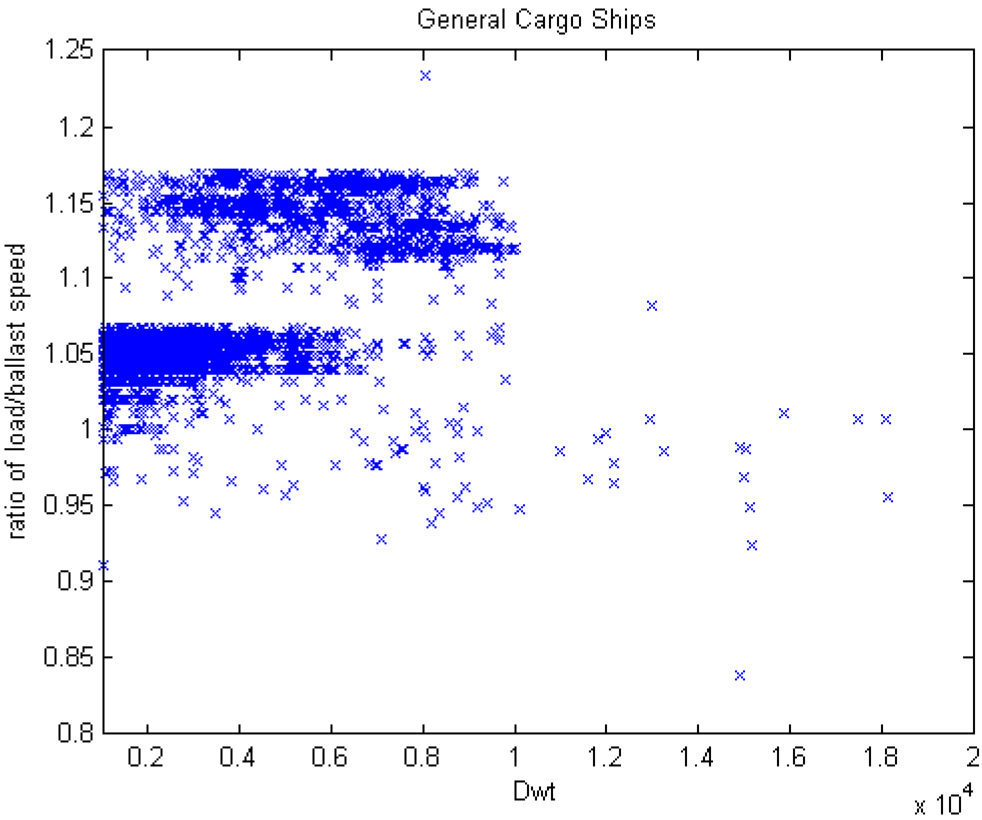

General Cargo Ships
average capacity
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
1
2
3

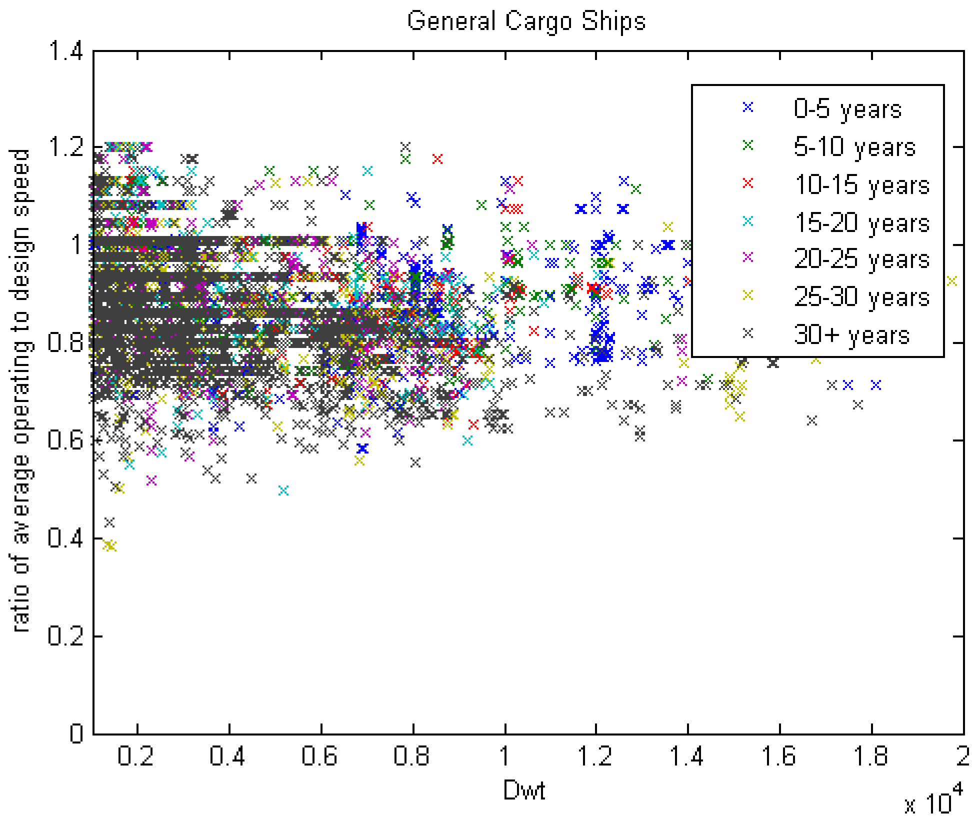

General Cargo Ships
speed knots
Dwt
x 10^4
ballast
loaded
15
10
5
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

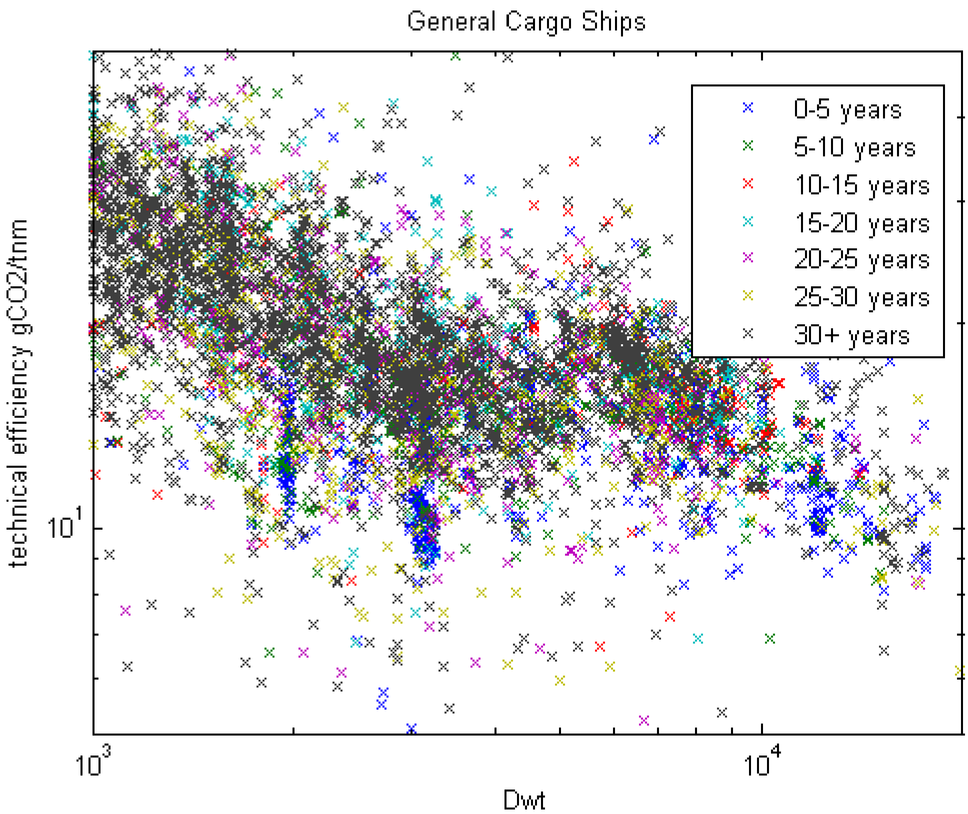

General Cargo Ships
days at sea
Dwt
x 10^4
ballast
loaded
250
200
150
100
50
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2


General Cargo Ships
fuel consumption tonnes
Dwt
x 10^4
ballast
loaded

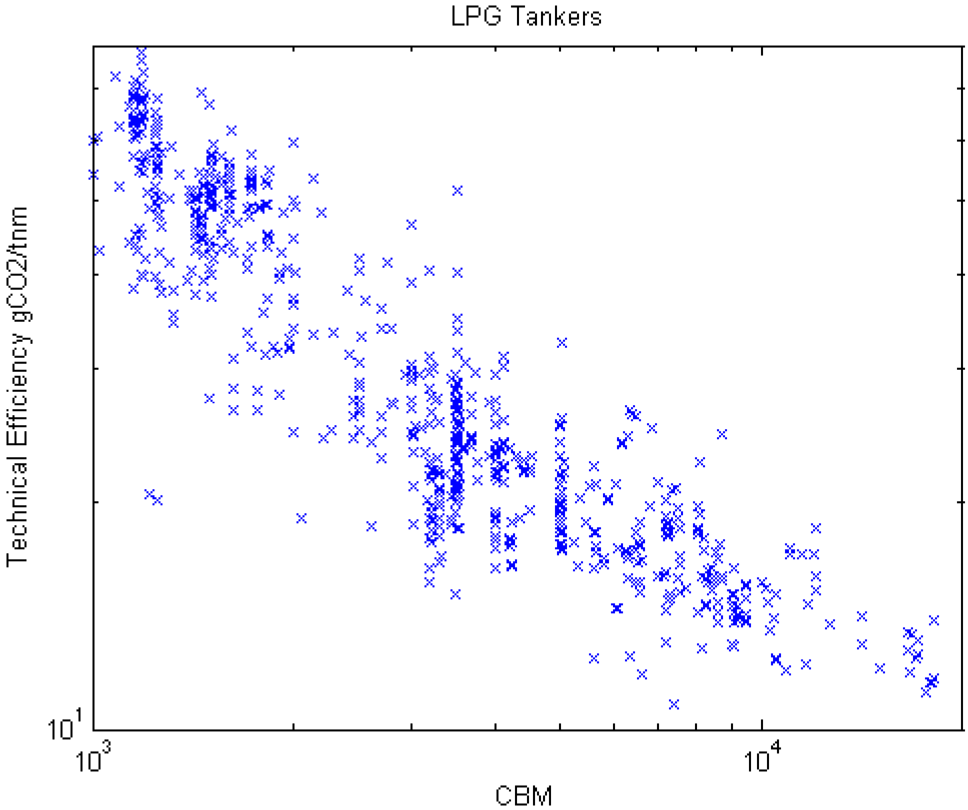

General Cargo Ships
utilisation %
Dwt
x 10^4
capacity
loaded days


General Cargo Ships
ratio of load/ballast speed
Dwt
x 10^4

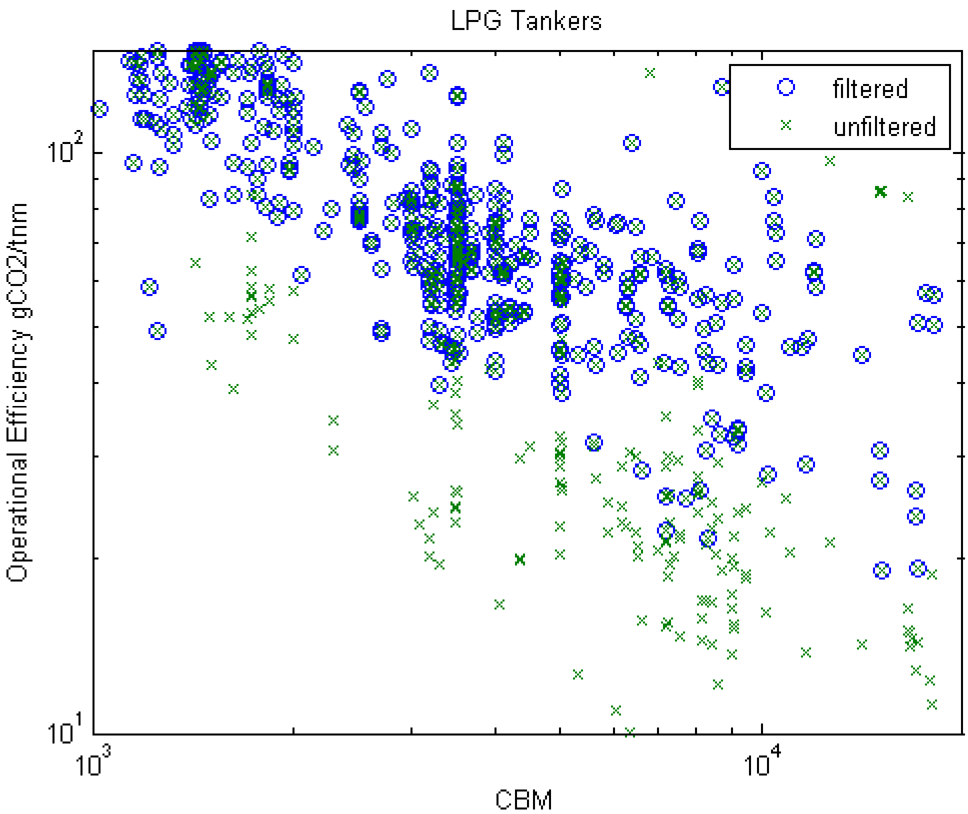

General Cargo Ships
ratio of average operating to design speed
Dwt
x 10^4
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years



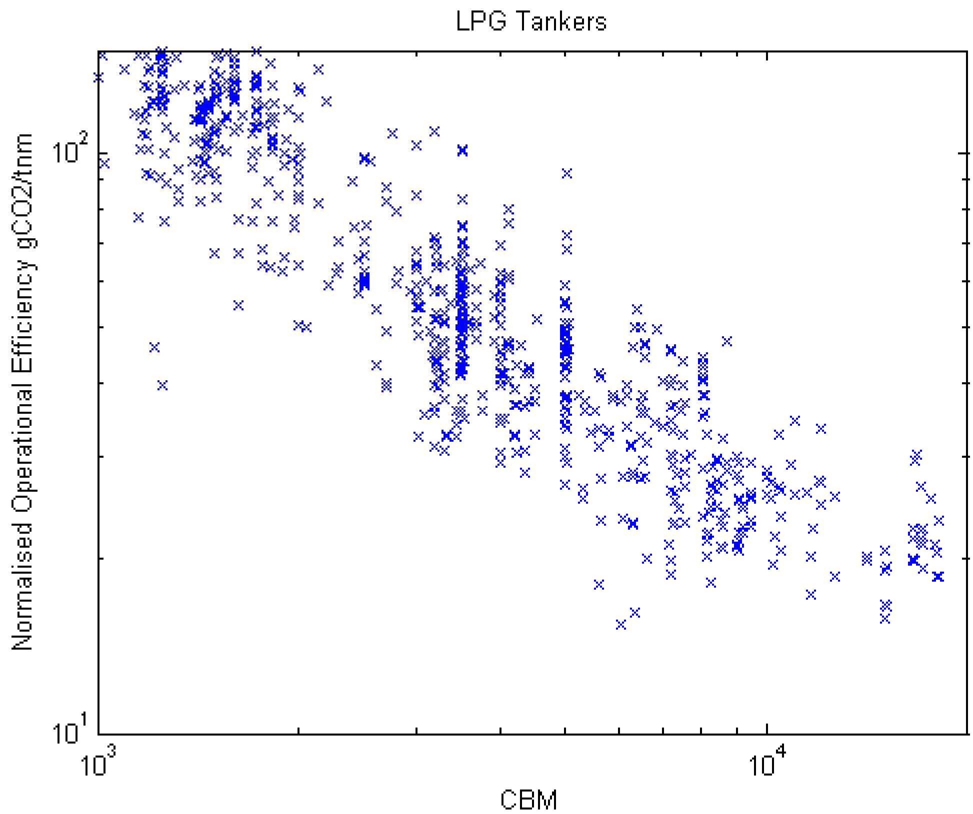
General Cargo Ships
technical efficiency gCO2/tnm
Dwt
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years

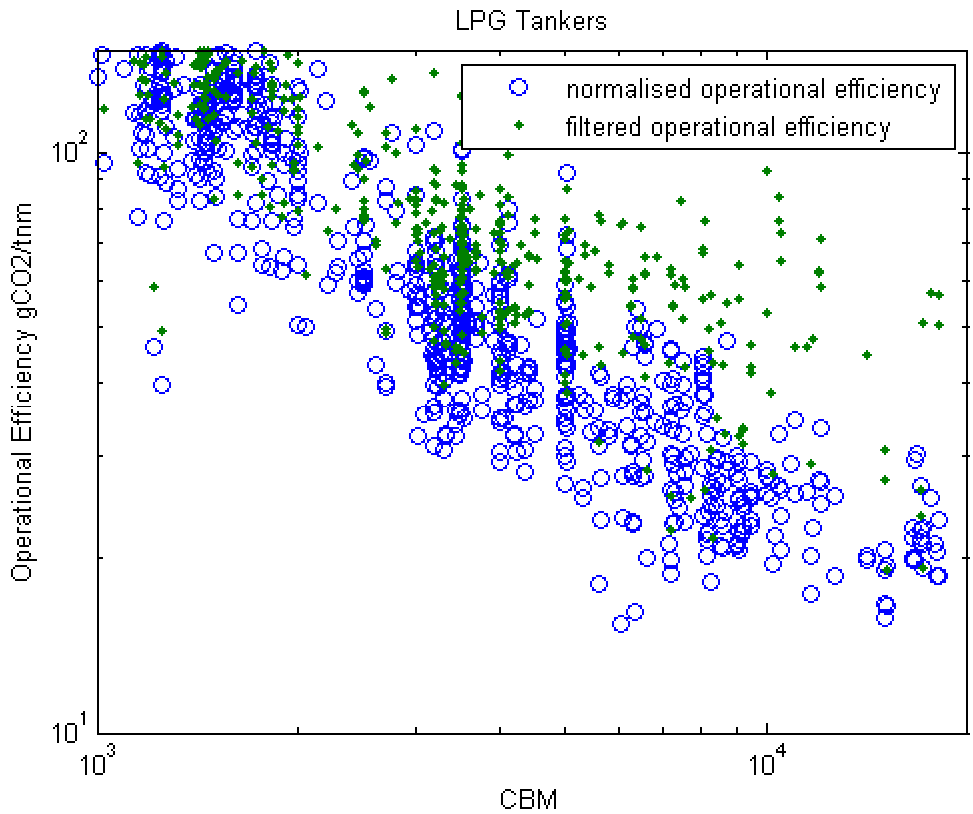


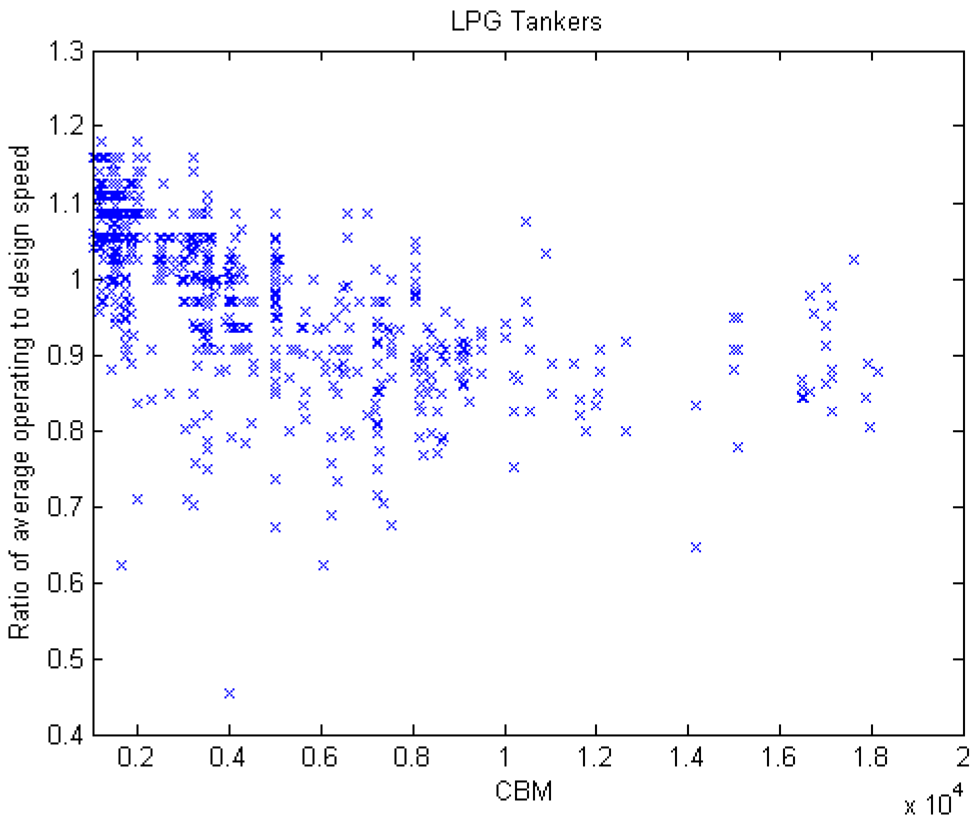
LPG Tankers
Technical Efficiency gCO2/tnm
CBM
10^1
10^3
10^4

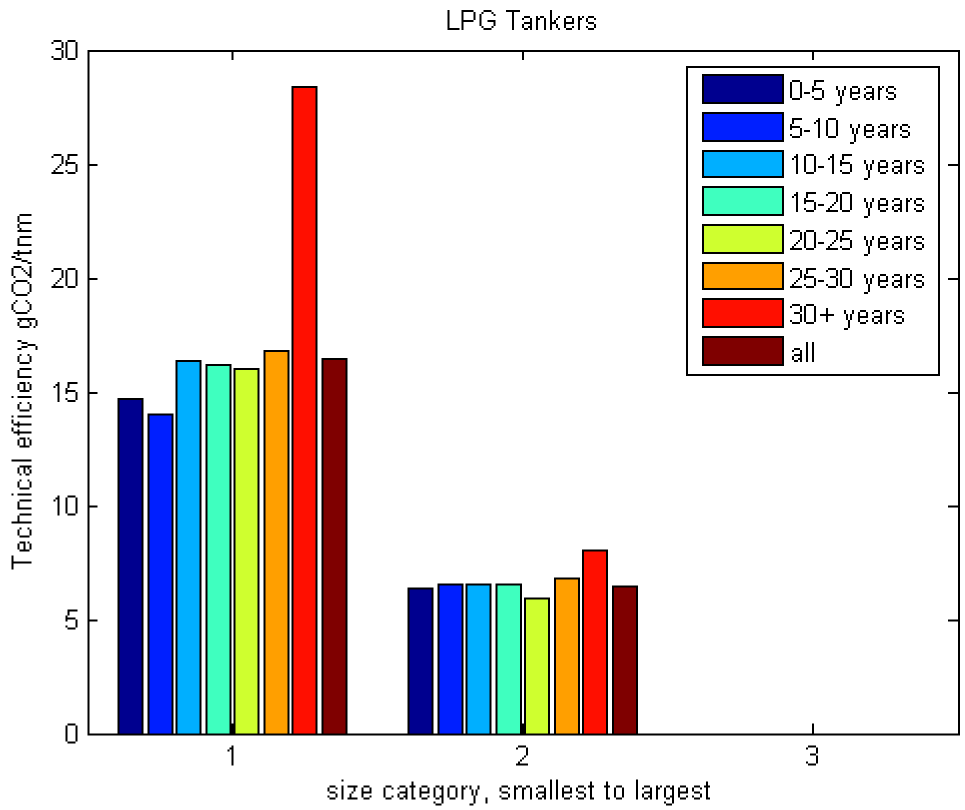


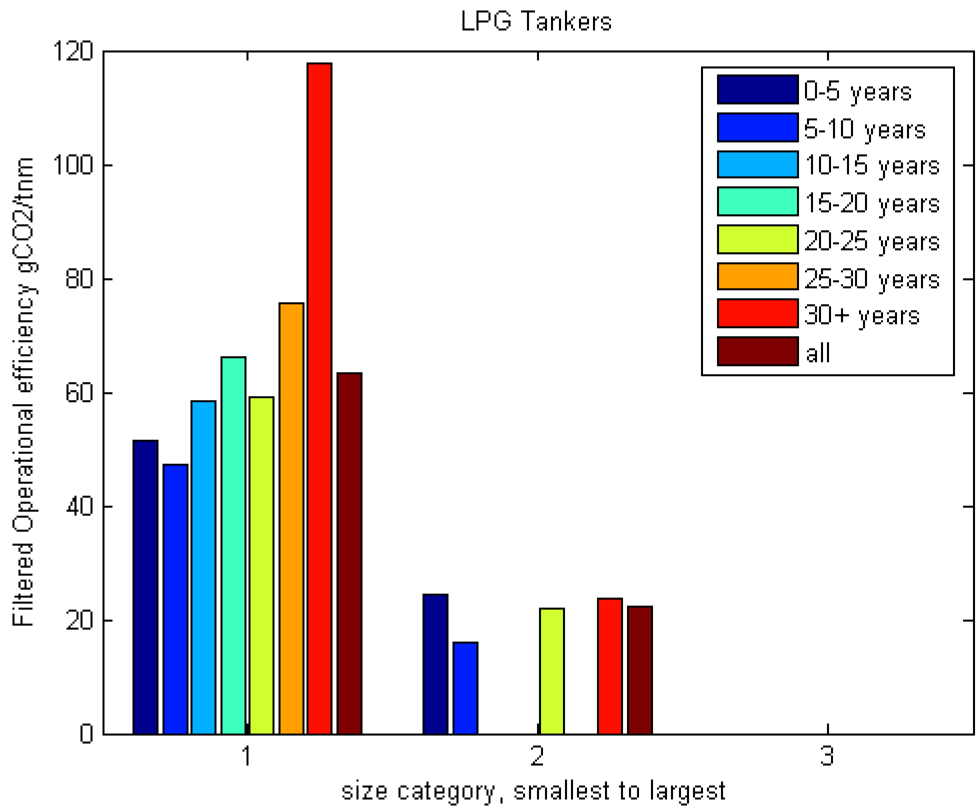
LPG Tankers
Operational Efficiency gCO2/tnm
CBM
filtered
unfiltered
10^2
10^1
10^3
10^4

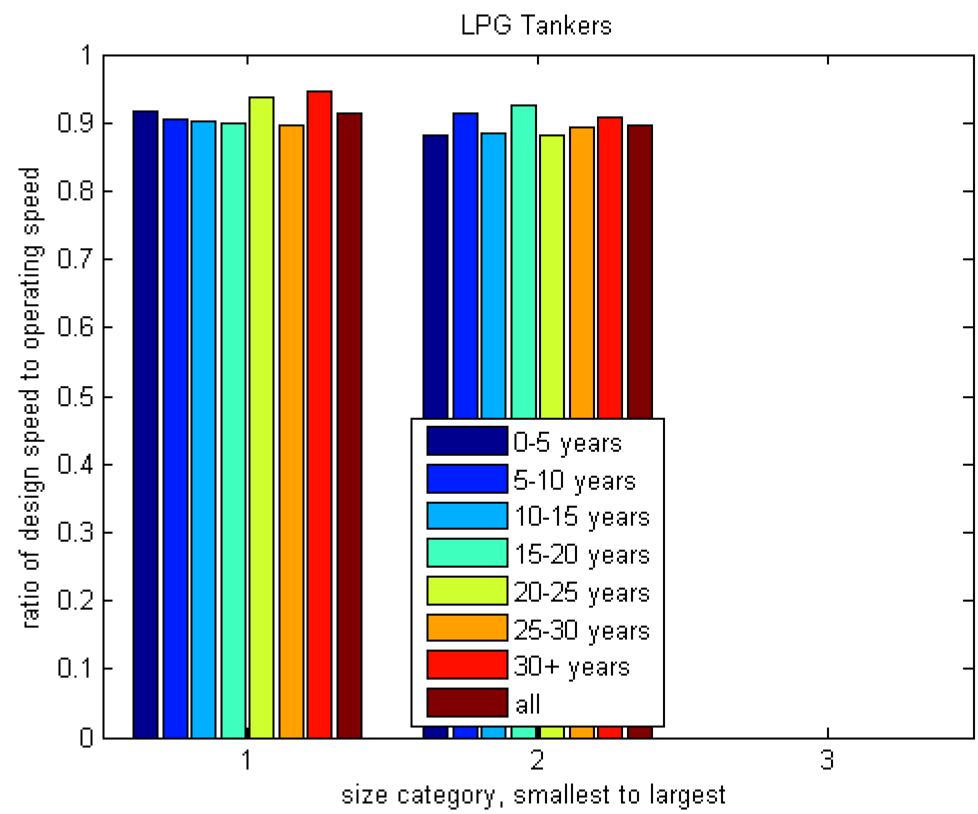

LPG Tankers
Normalised Operational Efficiency gCO2/tnm
CBM
10^1
10^2
10^3
10^4

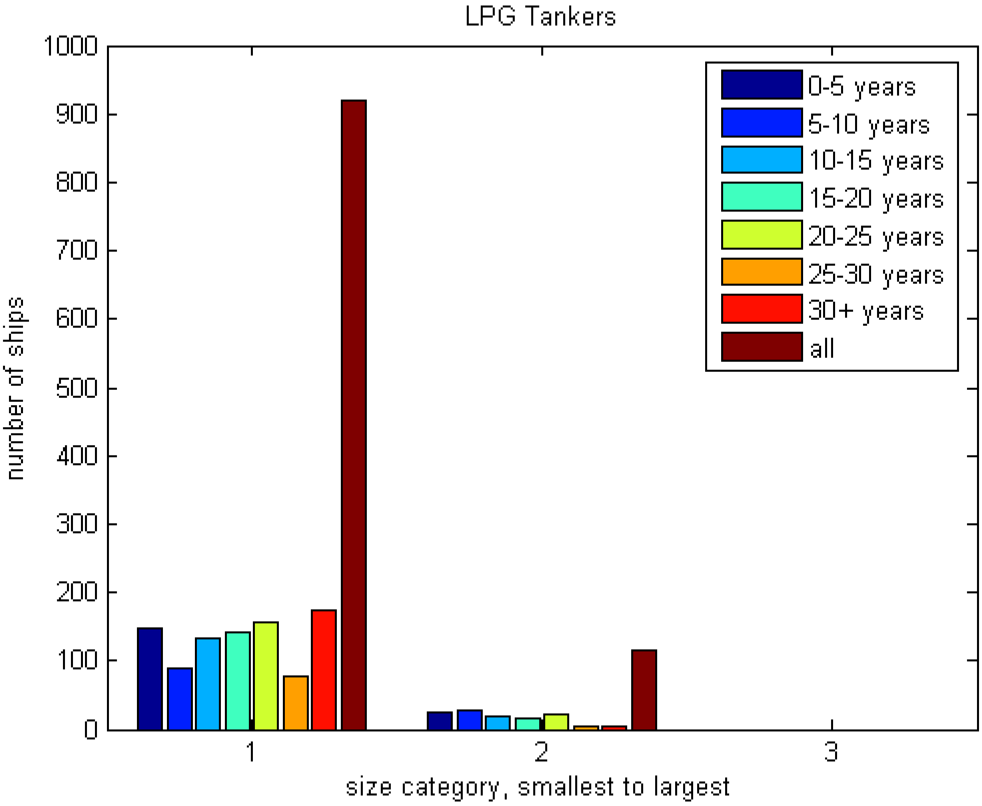

LPG Tankers
Operational Efficiency gCO2/tnm
CBM
normalised operational efficiency
filtered operational efficiency
10^1
10^2
10^3
10^4

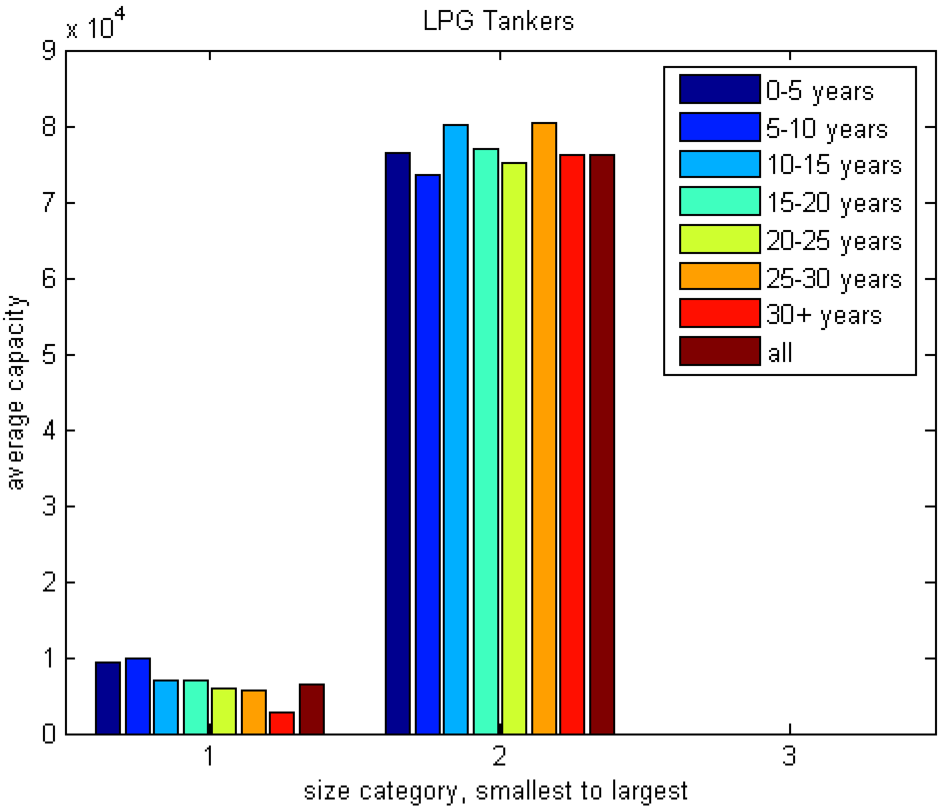

LPG Tankers
Ratio of average operating to design speed
CBM
x 10^4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

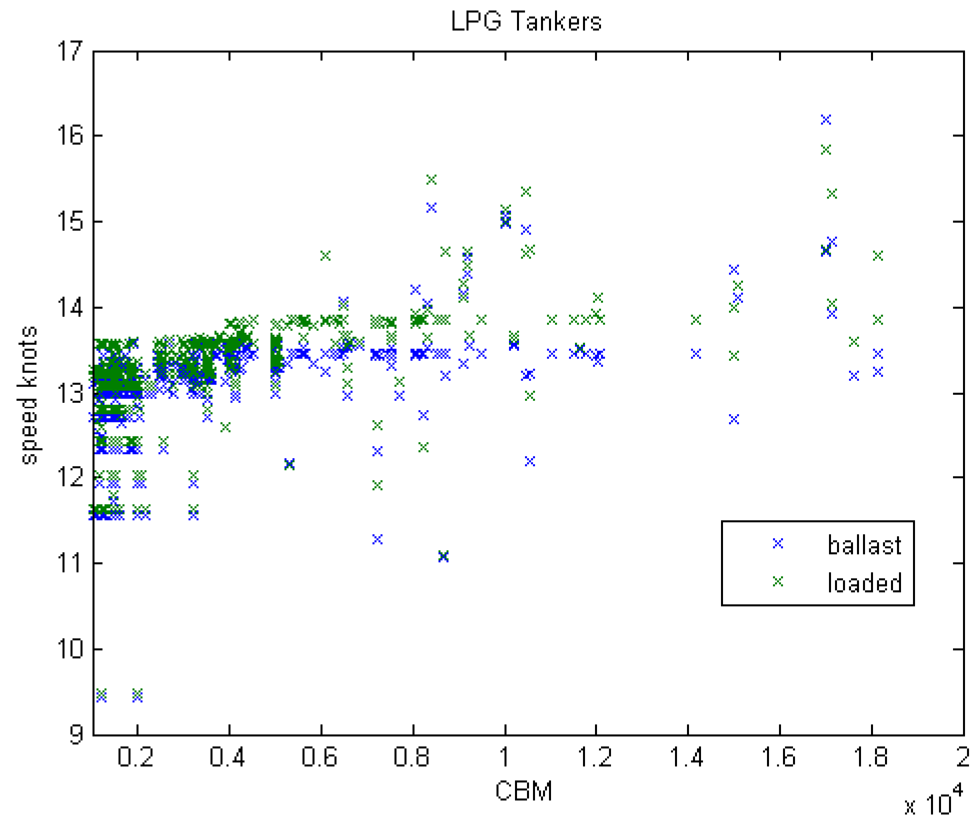

LPG Tankers
Technical efficiency gCO2/tnm
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all
30
25
20
15
10
5
0
1
2
3

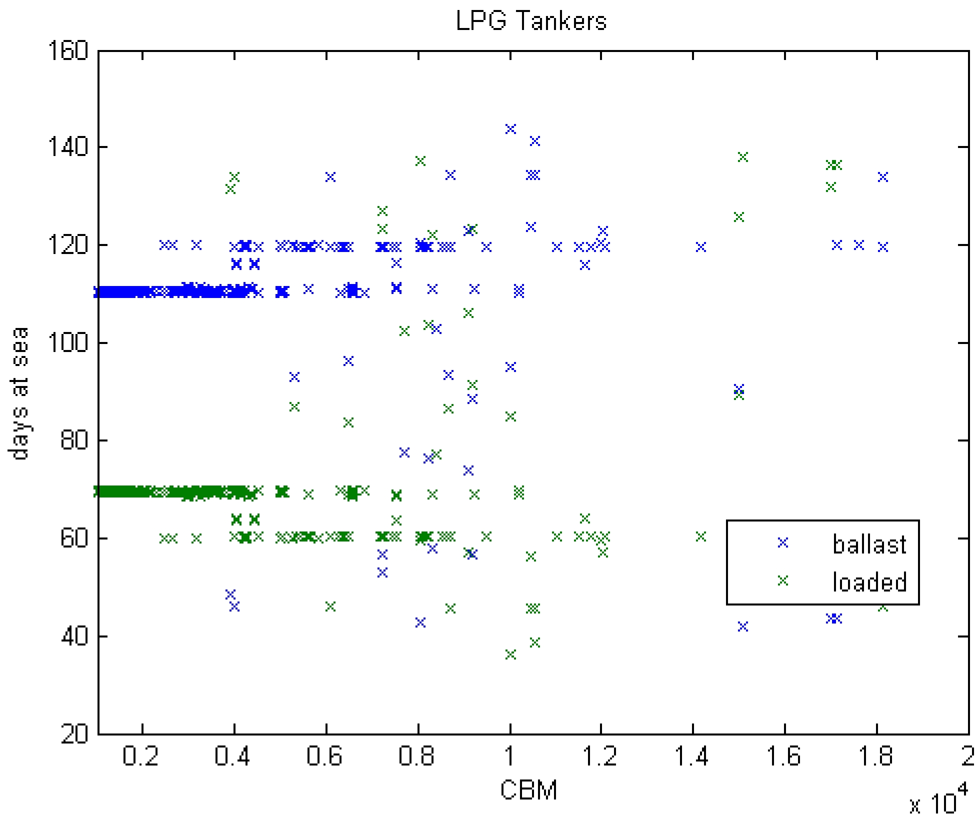

LPG Tankers
Filtered Operational efficiency gCO2/tnm
120
100
80
60
40
20
0
1
2
3
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all

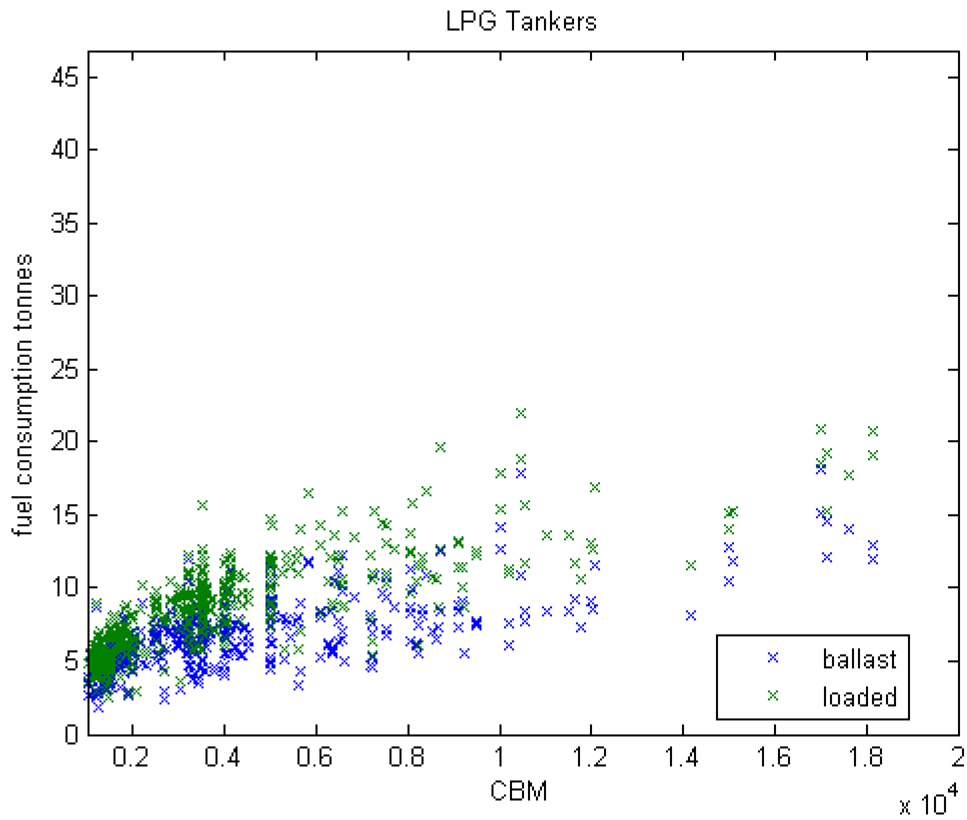

LPG Tankers
ratio of design speed to operating speed
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
2
3
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all

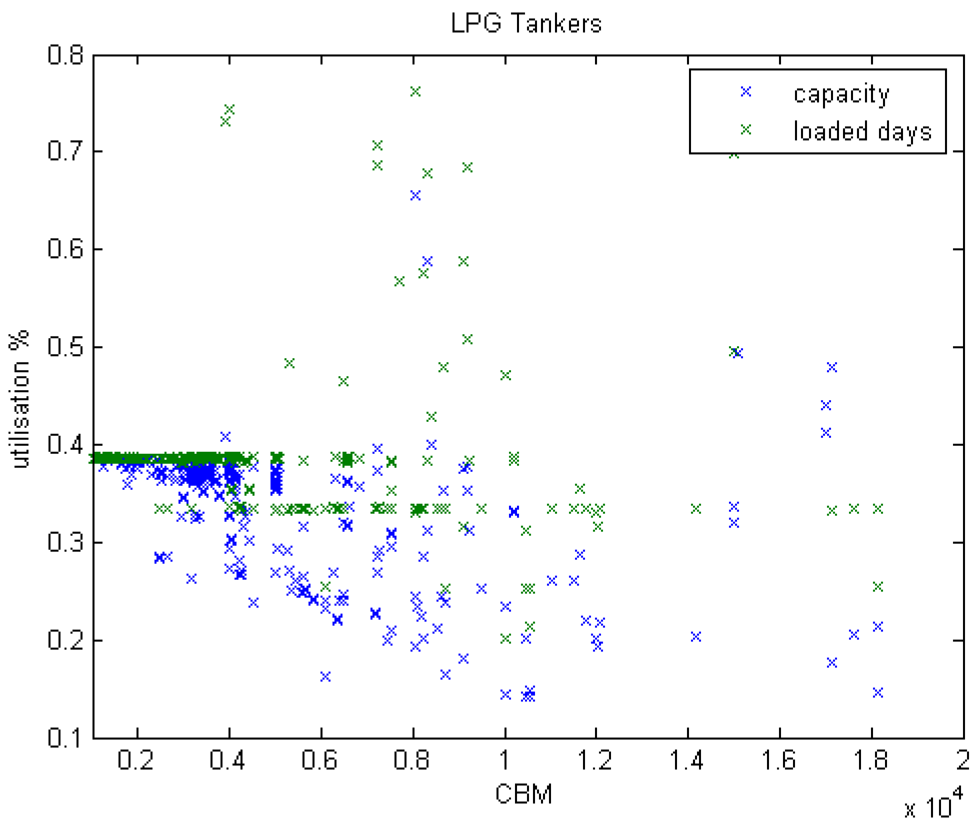

LPG Tankers
number of ships
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all
0
100
200
300
400
500
600
700
800
900
1000
1
2
3

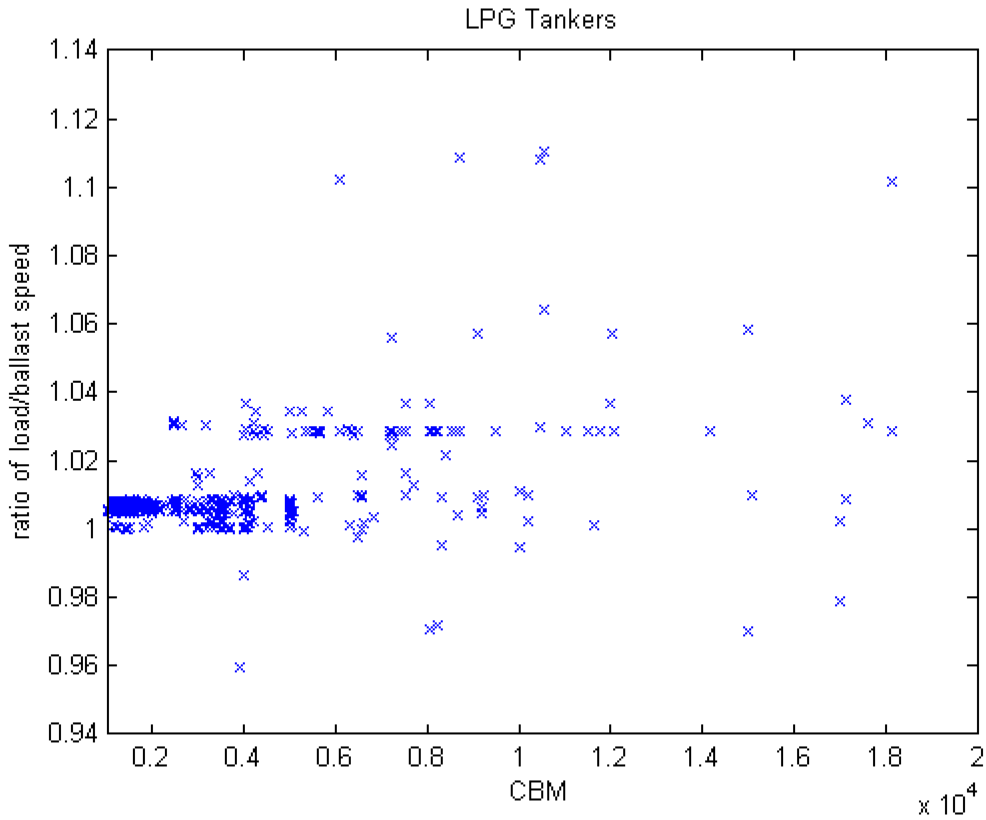

LPG Tankers
x 10^4
average capacity
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all
0
1
2
3
4
5
6
7
8
9
1
2
3

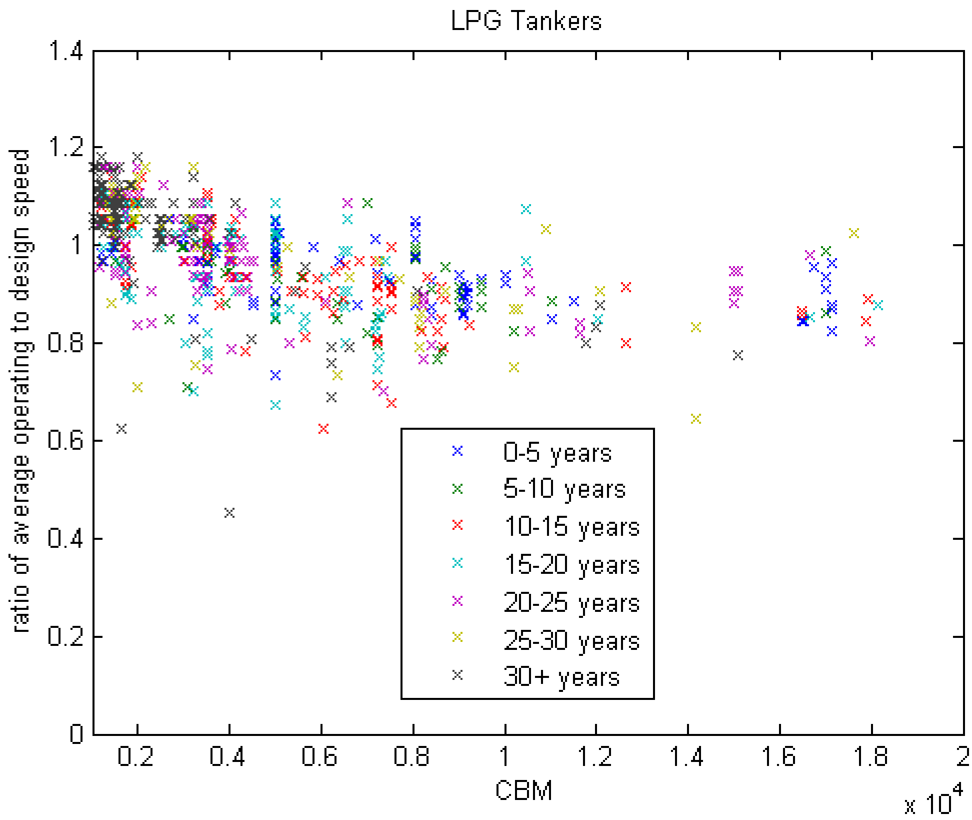

LPG Tankers
speed knots
CBM
x 10^4
ballast
loaded
17
16
15
14
13
12
11
10
9
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

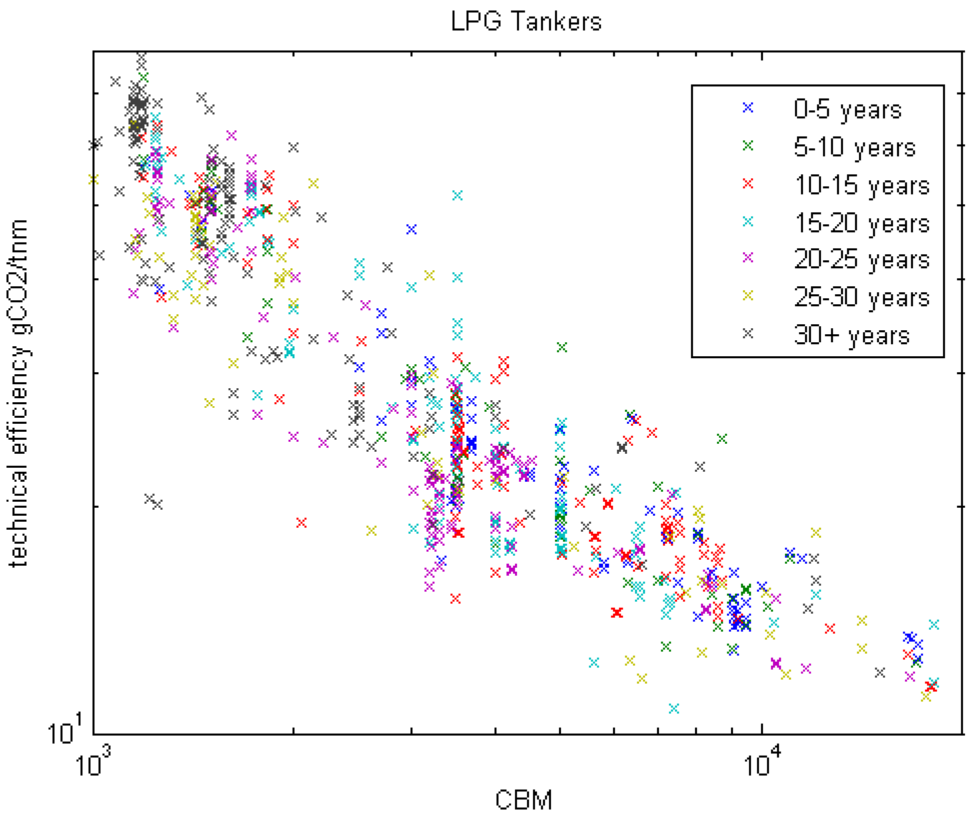

LPG Tankers
days at sea
CBM
x 10^4
ballast
loaded
160
140
120
100
80
60
40
20
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

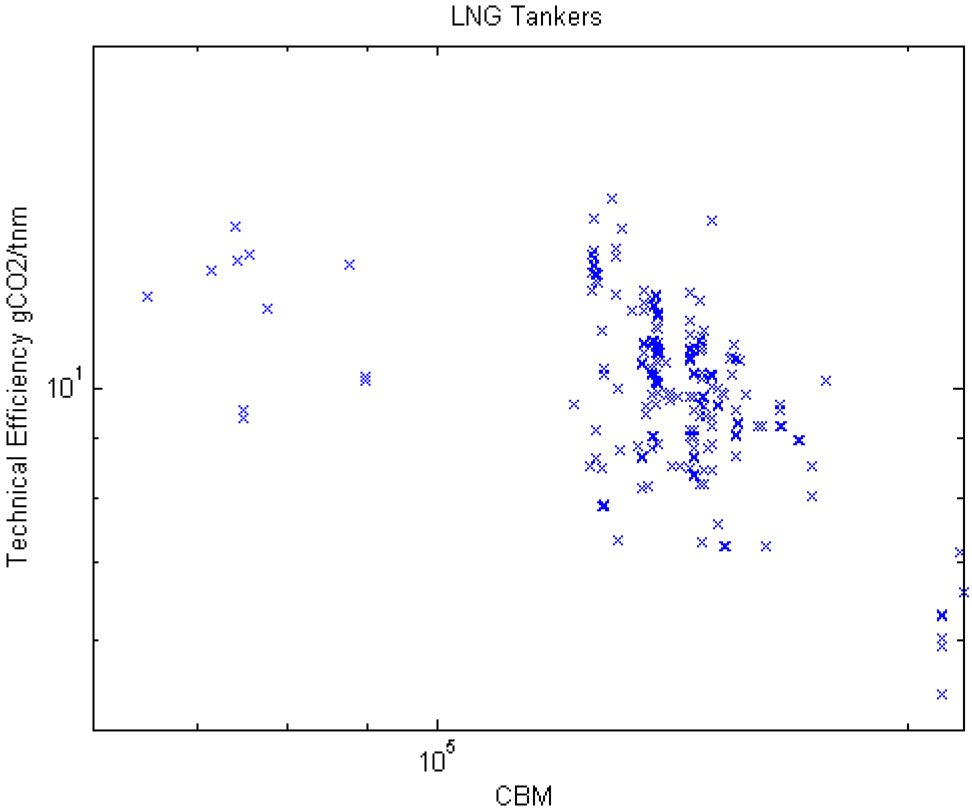

LPG Tankers
fuel consumption tonnes
45
40
35
30
25
20
15
10
5
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
CBM
x 10^4
ballast
loaded

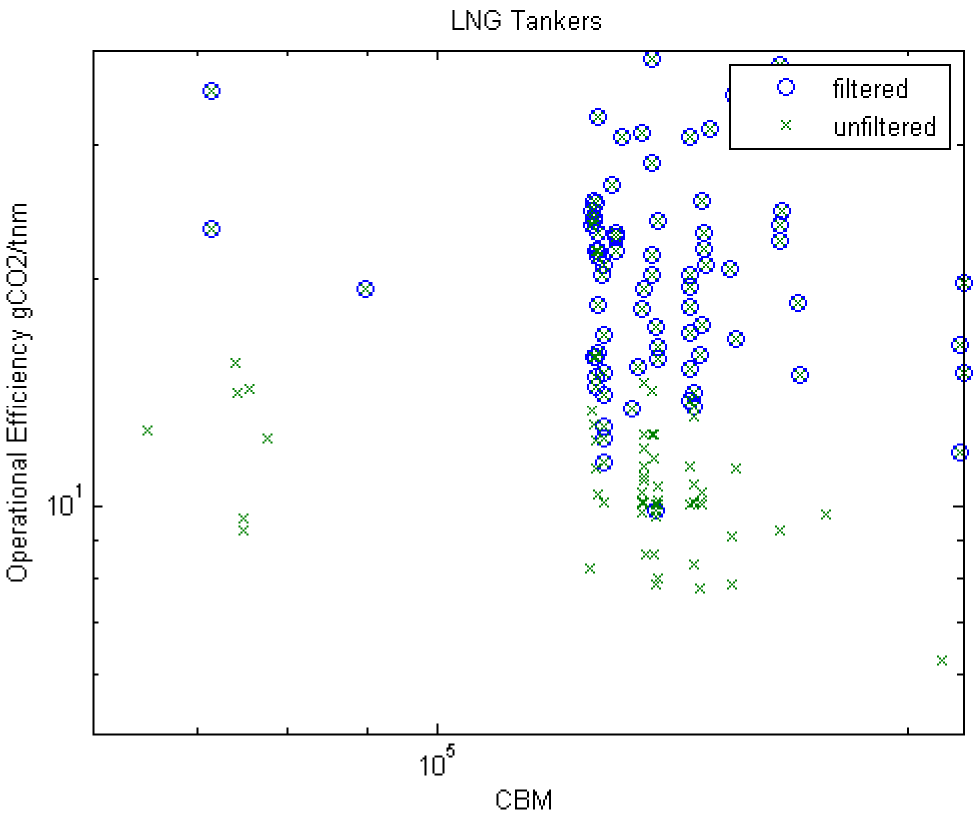

LPG Tankers
utilisation %
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
CBM
x 10^4
capacity
loaded days

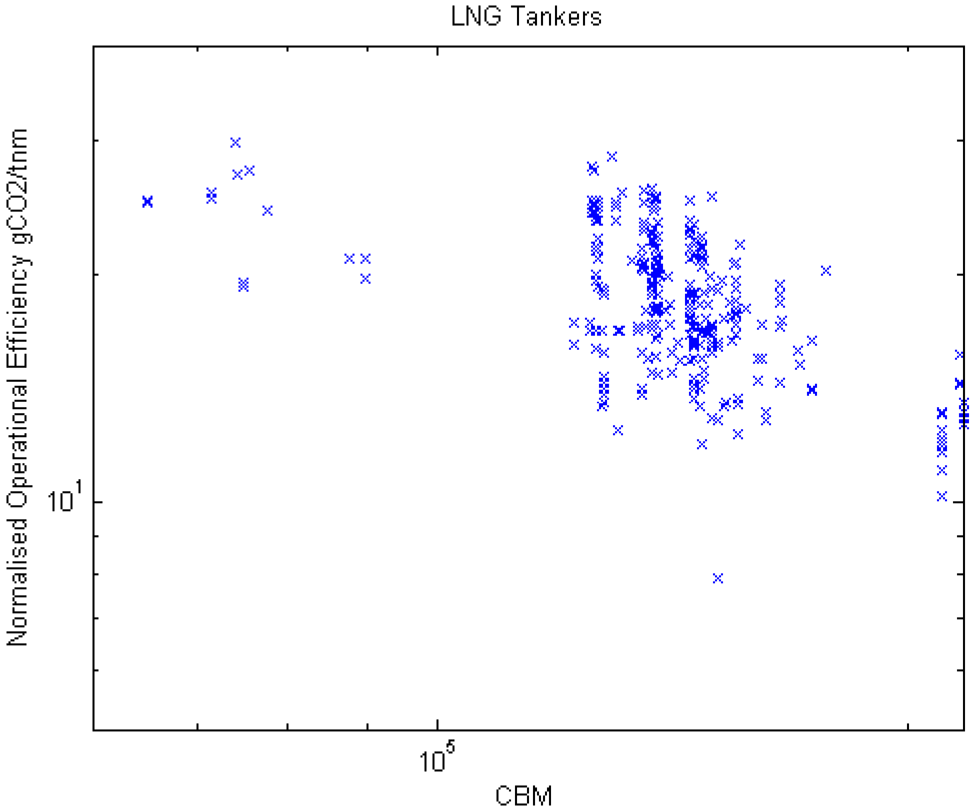

LPG Tankers
ratio of load/ballast speed
1.14
1.12
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
CBM
x 10^4

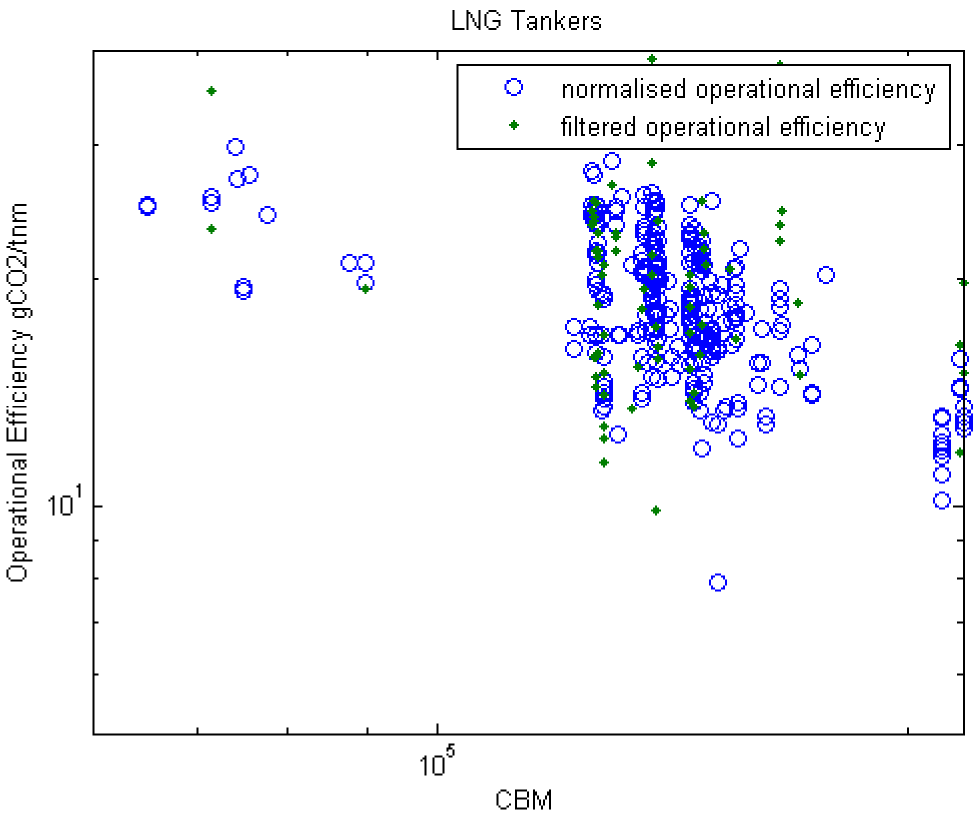

LPG Tankers
ratio of average operating to design speed
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
CBM
x 10^4
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years

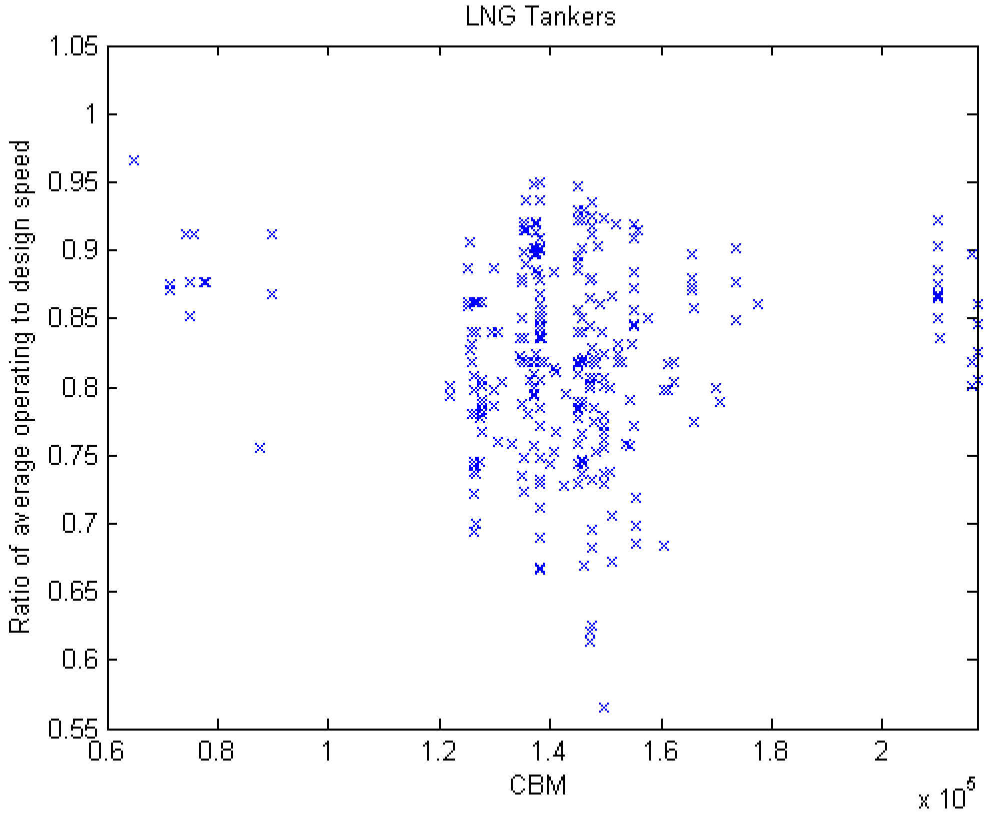

LPG Tankers
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
technical efficiency gCO2/tnm
10^1
10^3
10^4
CBM


LNG Tankers
Technical Efficiency gCO2/tnm
10^1
10^5
CBM

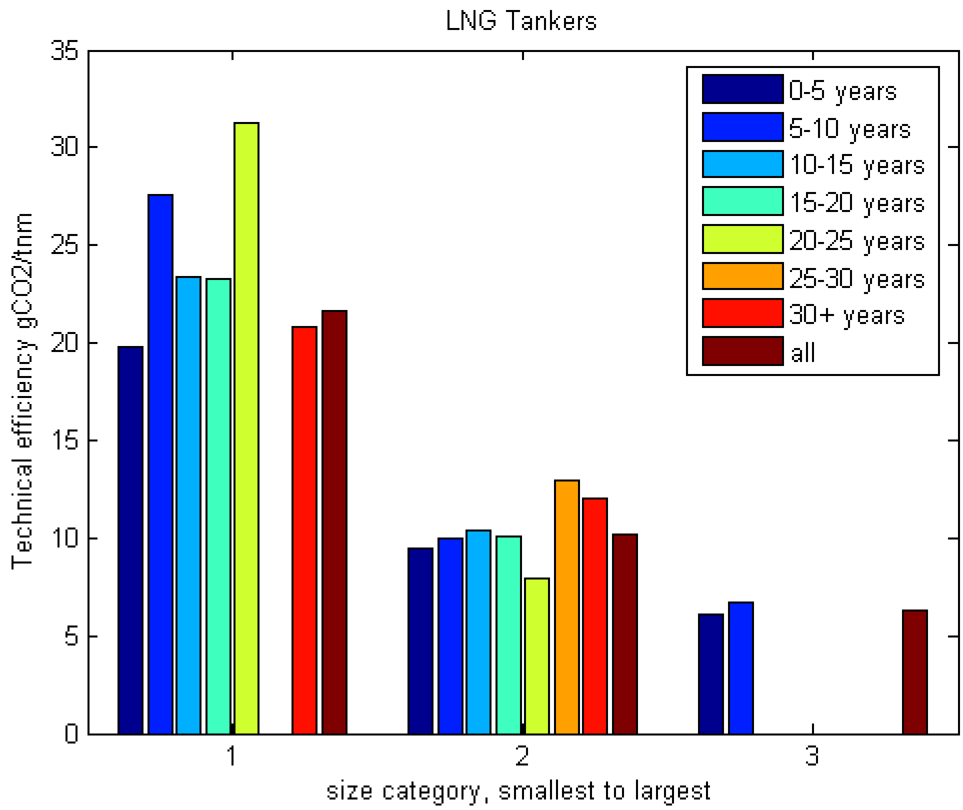

LNG Tankers
filtered
unfiltered
Operational Efficiency gCO2/tnm
10^1
10^5
CBM


LNG Tankers
Normalised Operational Efficiency gCO2/tnm
10^1
10^5
CBM

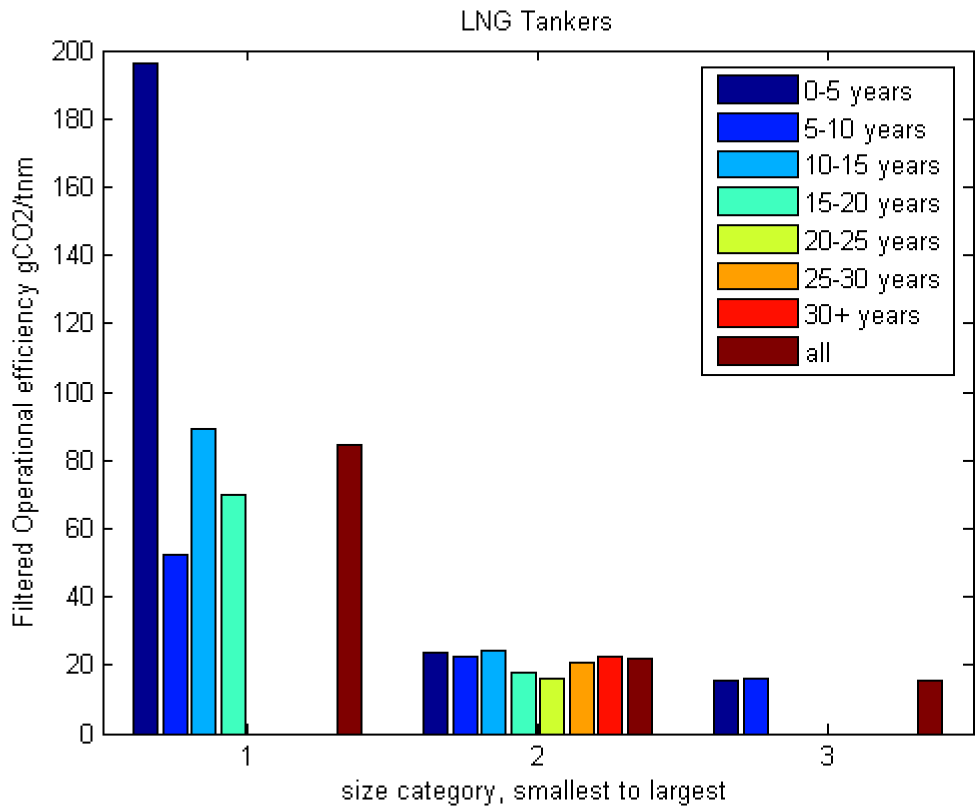

LNG Tankers
normalised operational efficiency
filtered operational efficiency
Operational Efficiency gCO2/tnm
10^1
10^5
CBM



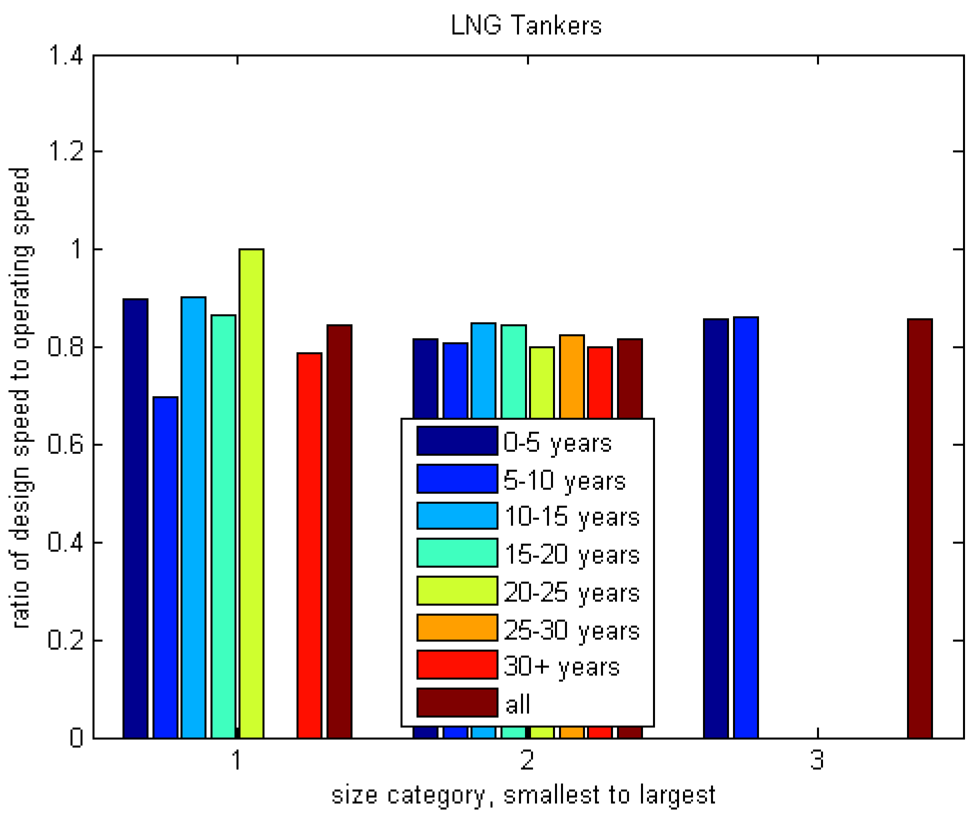
LNG Tankers
Ratio of average operating to design speed
CBM
x 10^5
1.05
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.6
0.8
1
1.2
1.4
1.6
1.8
2



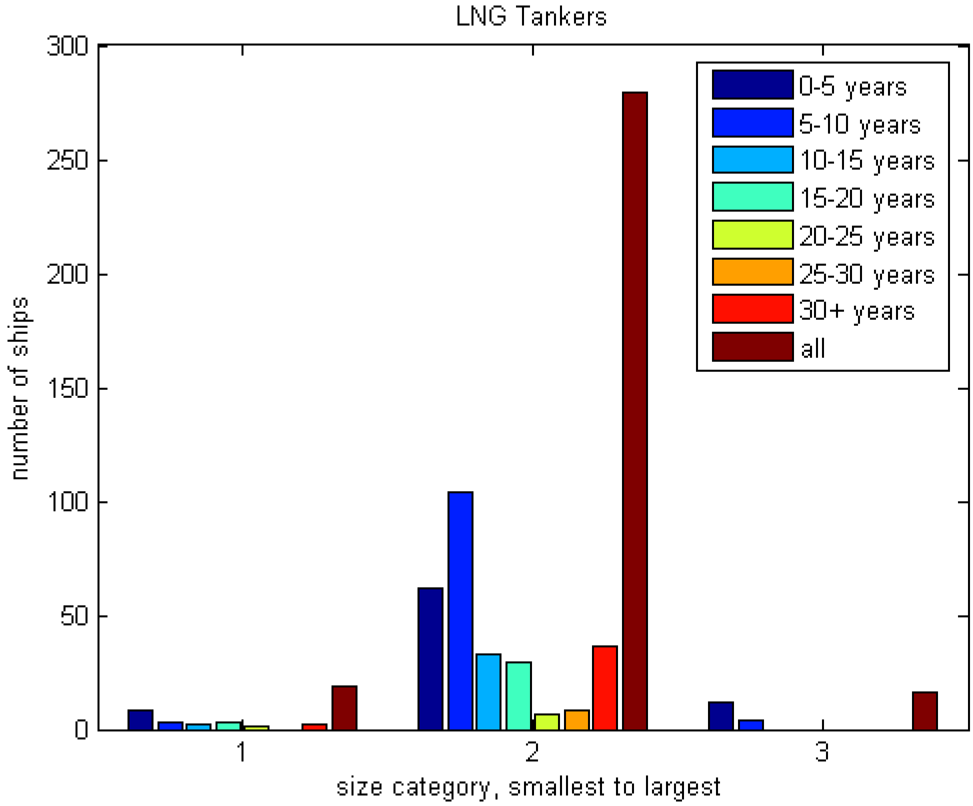
LNG Tankers
Technical efficiency gCO2/tnm
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all
35
30
25
20
15
10
5
0
1
2
3

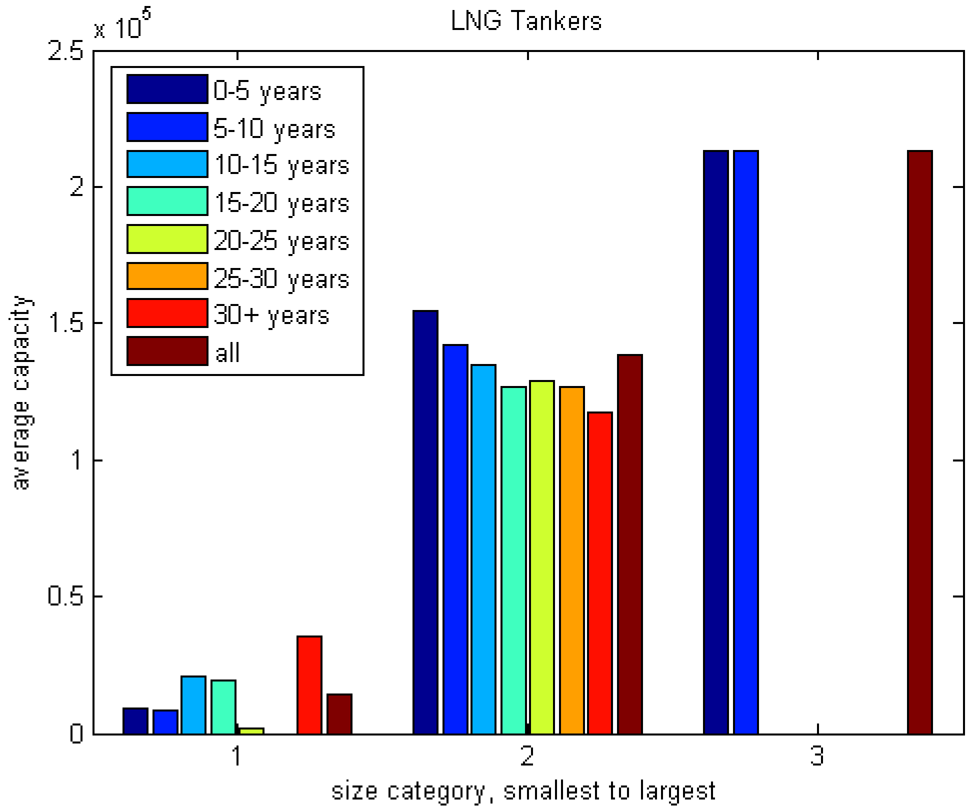


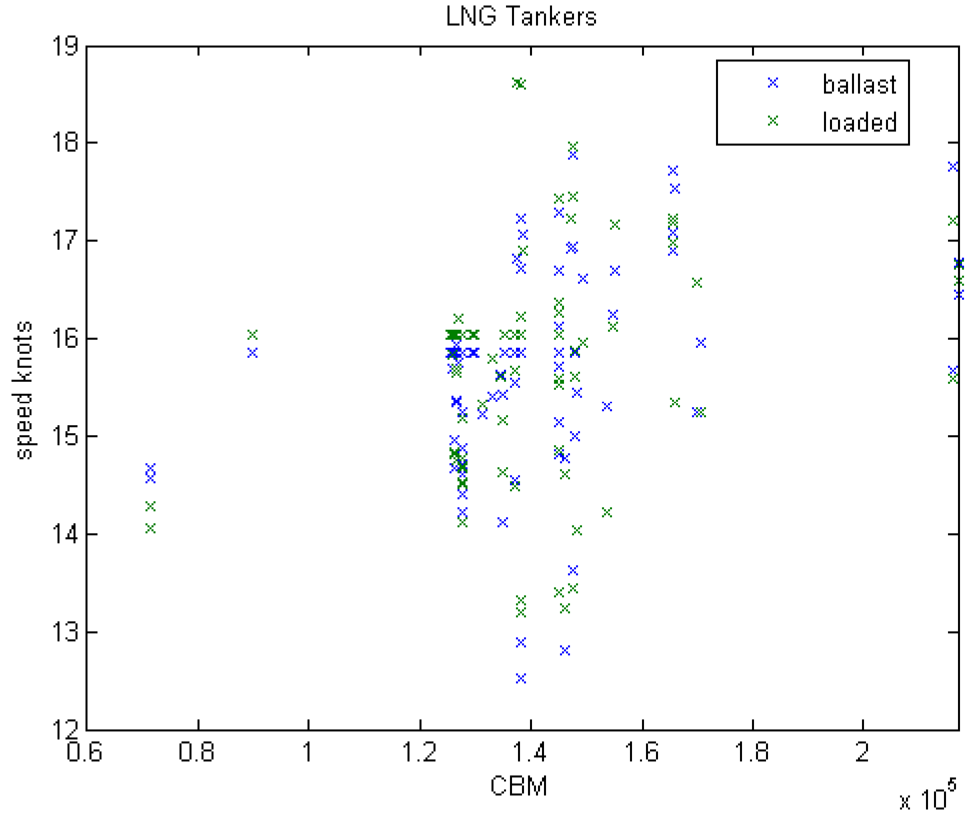
LNG Tankers
Filtered Operational efficiency gCO2/tnm
200
180
160
140
120
100
80
60
40
20
0
1
2
3
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all

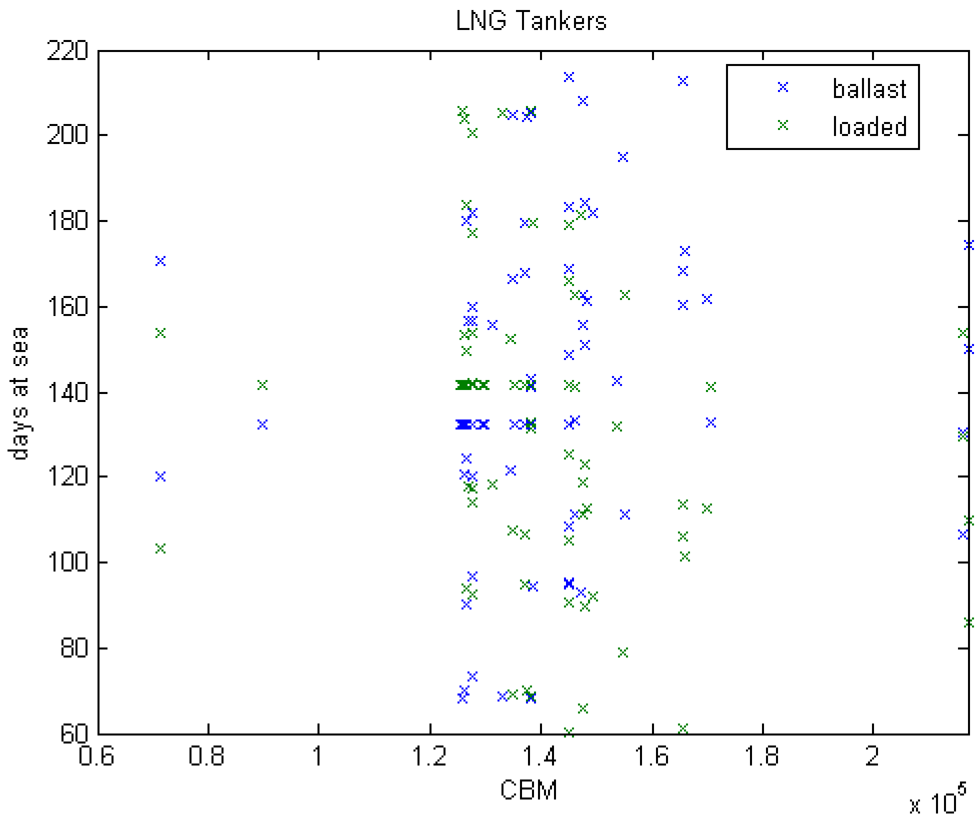


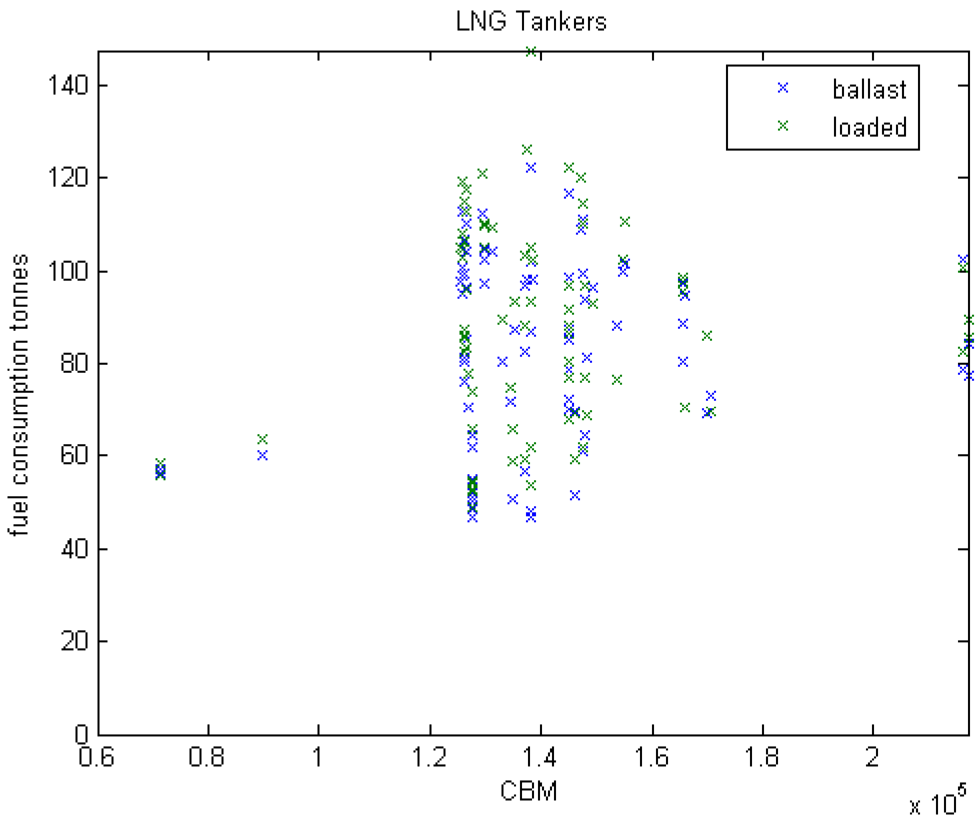
LNG Tankers
ratio of design speed to operating speed
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1
2
3
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all

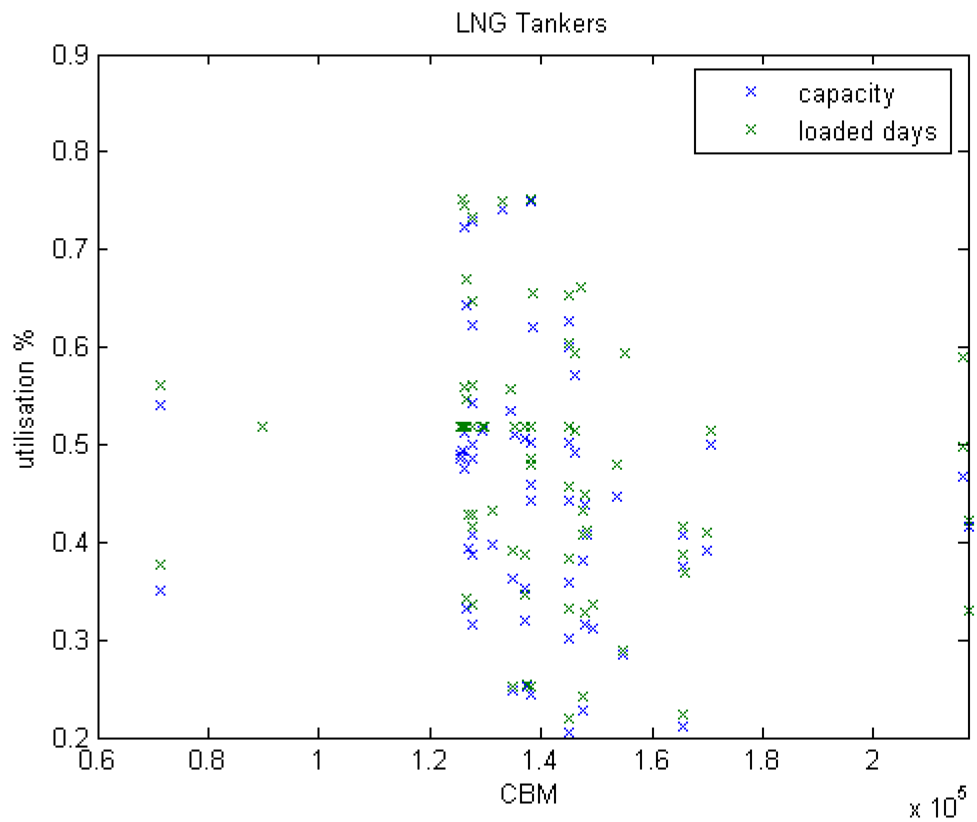

LNG Tankers
number of ships
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all
300
250
200
150
100
50
0
1
2
3

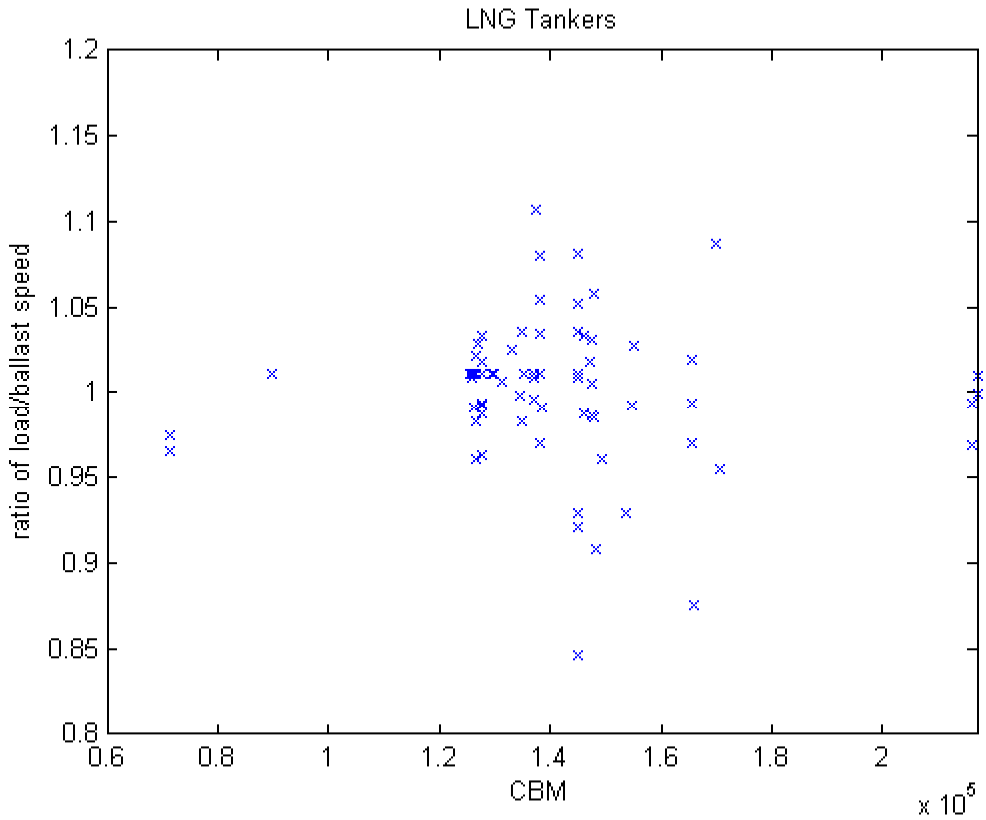

LNG Tankers
x 10^5
average capacity
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all
2.5
2
1.5
1
0.5
0
1
2
3

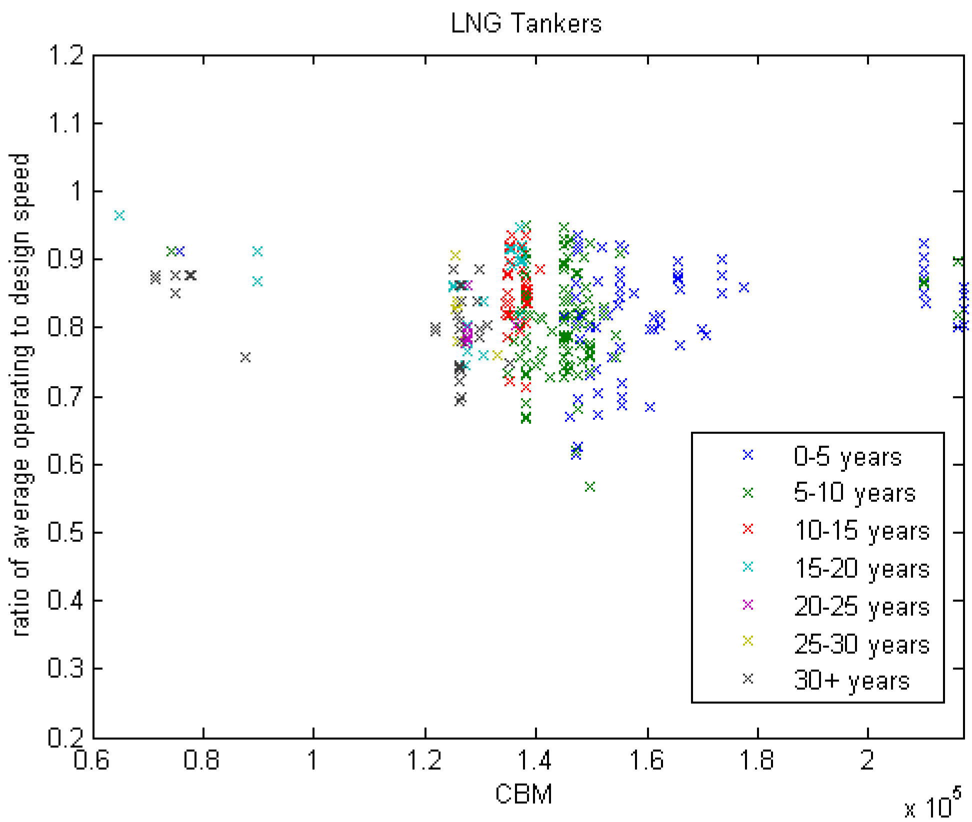

LNG Tankers
speed knots
CBM
x 10^5
ballast
loaded
19
18
17
16
15
14
13
12
0.6
0.8
1
1.2
1.4
1.6
1.8
2

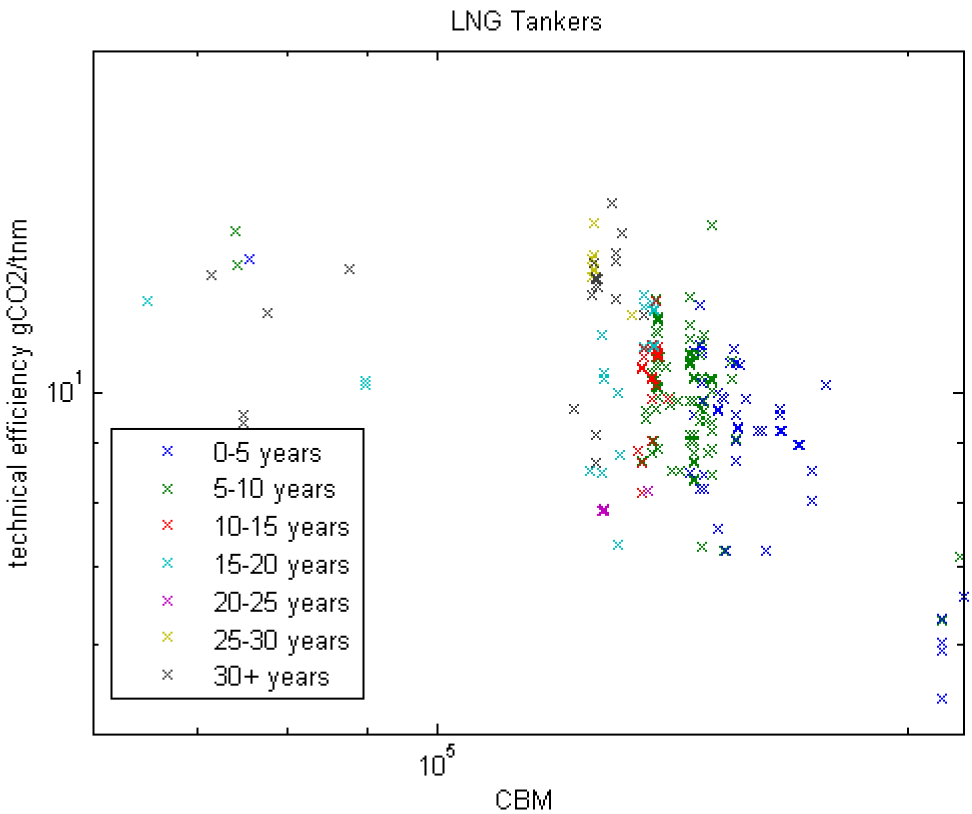

LNG Tankers
days at sea
CBM
x 10^5
ballast
loaded
220
200
180
160
140
120
100
80
60
0.6
0.8
1
1.2
1.4
1.6
1.8
2


LNG Tankers
ballast
loaded
fuel consumption tonnes
CBM
x 10^5
0
20
40
60
80
100
120
140
0.6
0.8
1
1.2
1.4
1.6
1.8
2

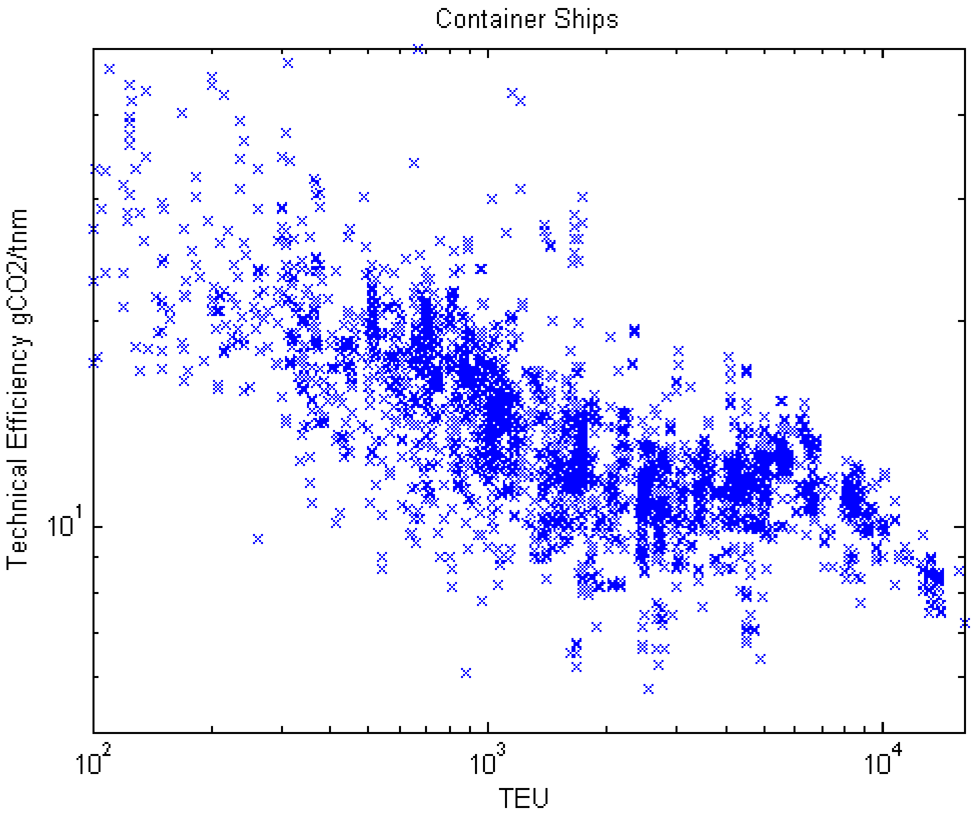

LNG Tankers
capacity
loaded days
utilisation %
CBM
x 10^5
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0.6
0.8
1
1.2
1.4
1.6
1.8
2

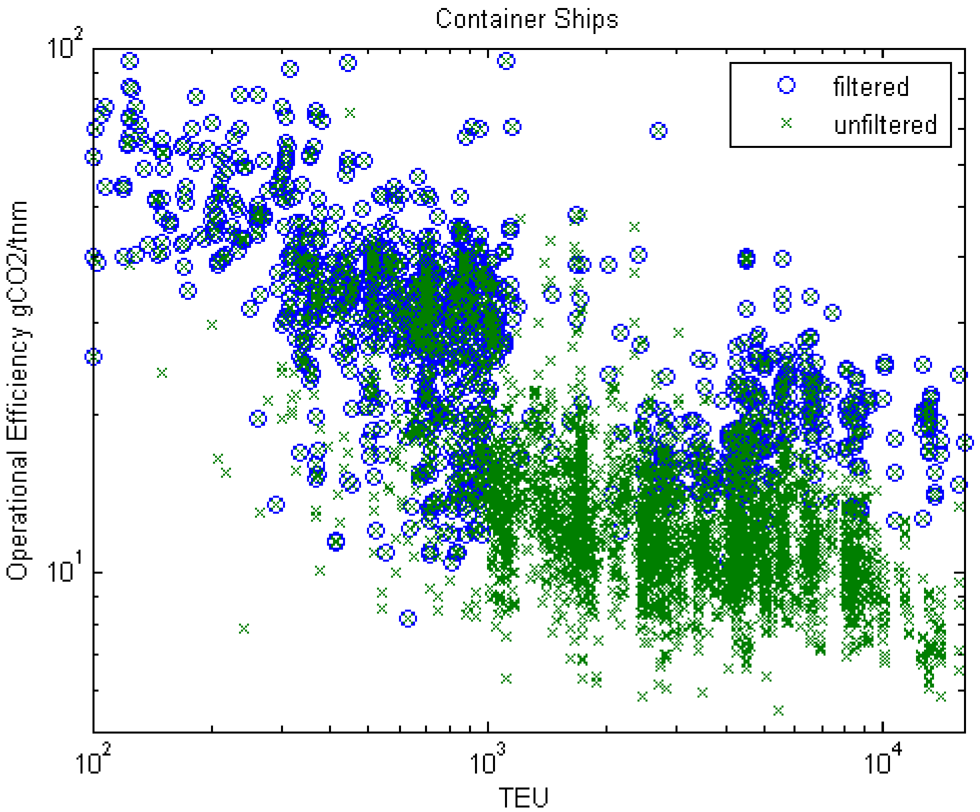

LNG Tankers
ratio of load/ballast speed
CBM
x 10^5
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
0.6
0.8
1
1.2
1.4
1.6
1.8
2

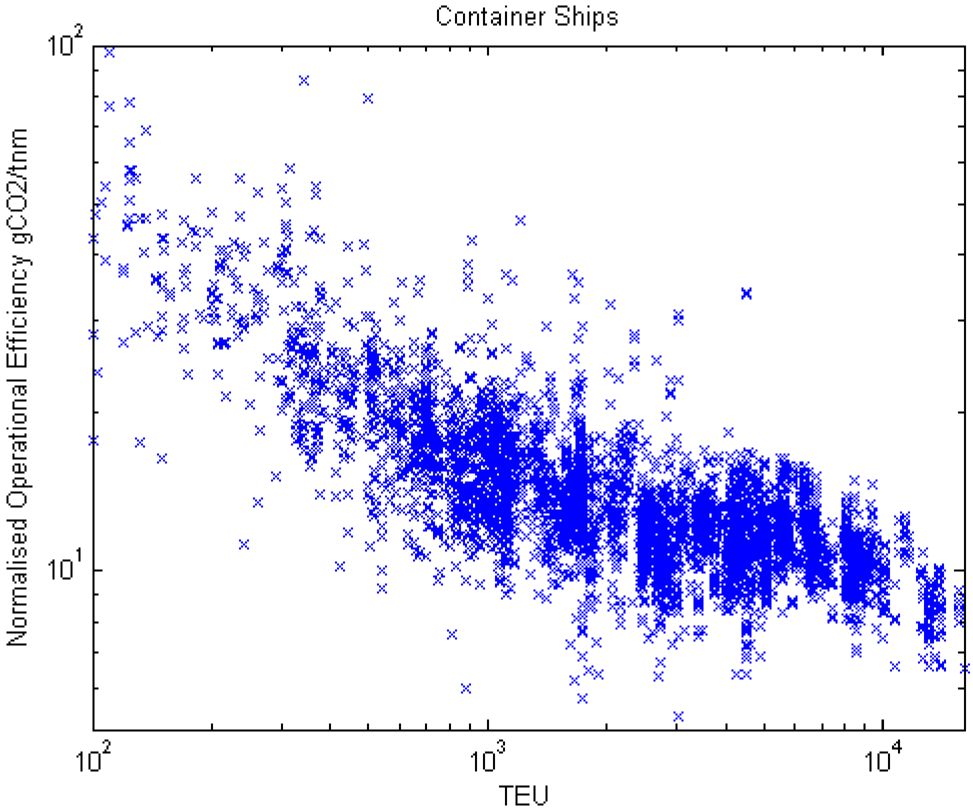

LNG Tankers
ratio of average operating to design speed
CBM
x 10^5
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.6
0.8
1
1.2
1.4
1.6
1.8
2

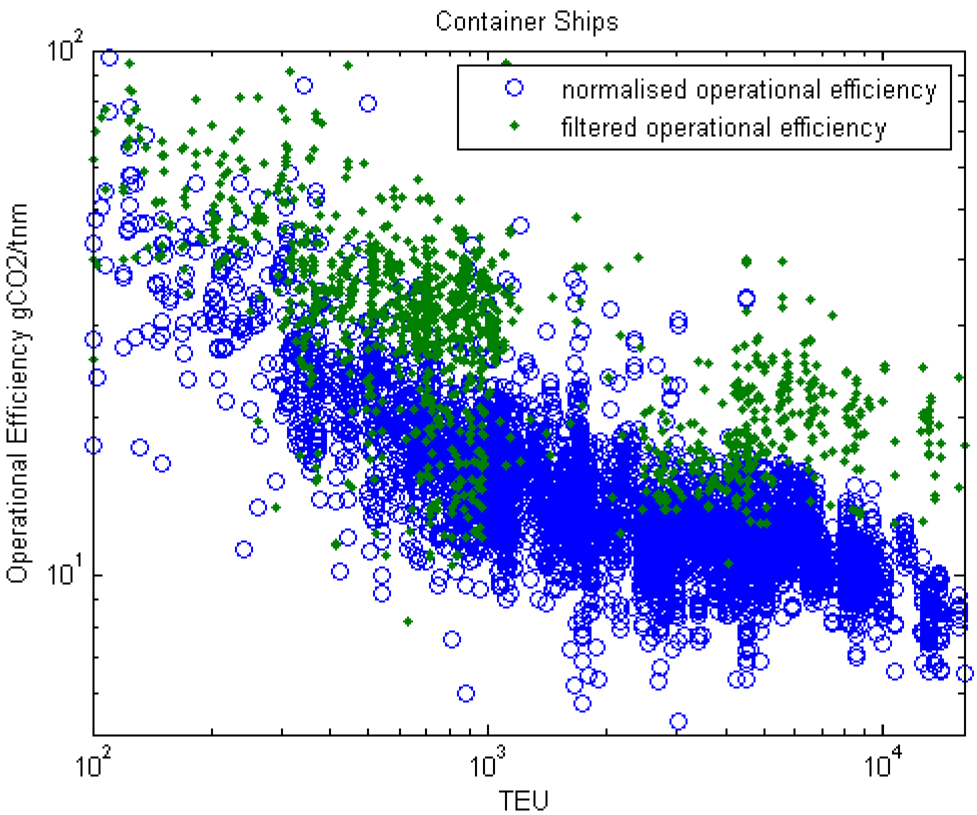


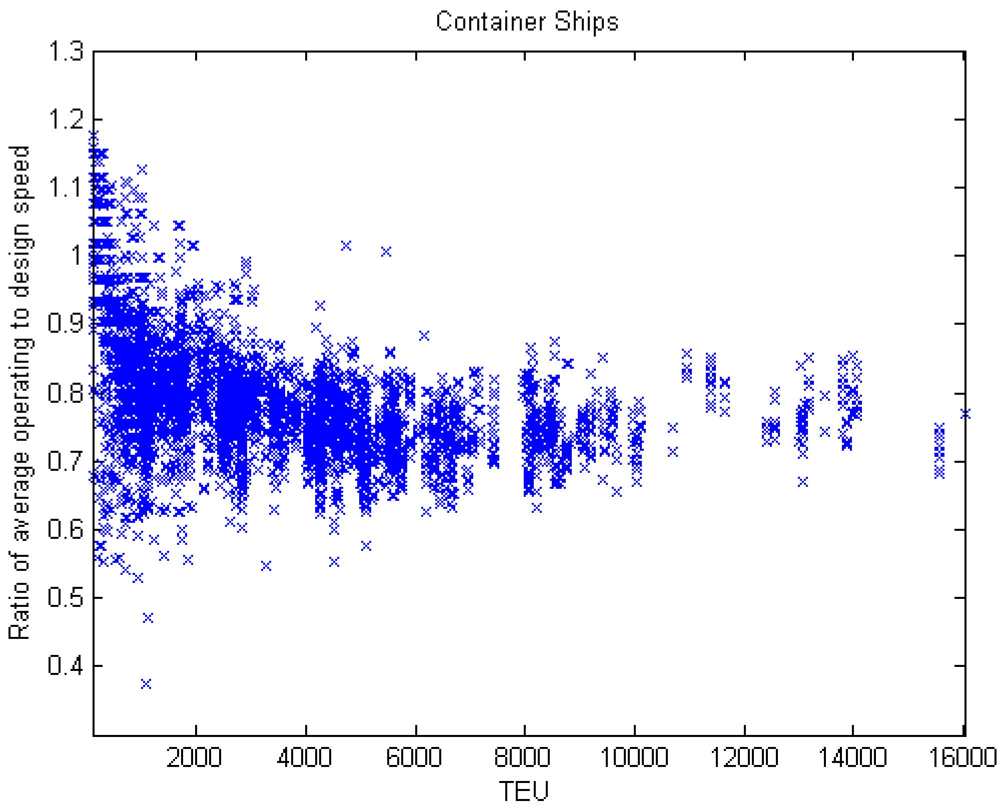
LNG Tankers
technical efficiency gCO2/tnm
10^1
10^5
CBM
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years

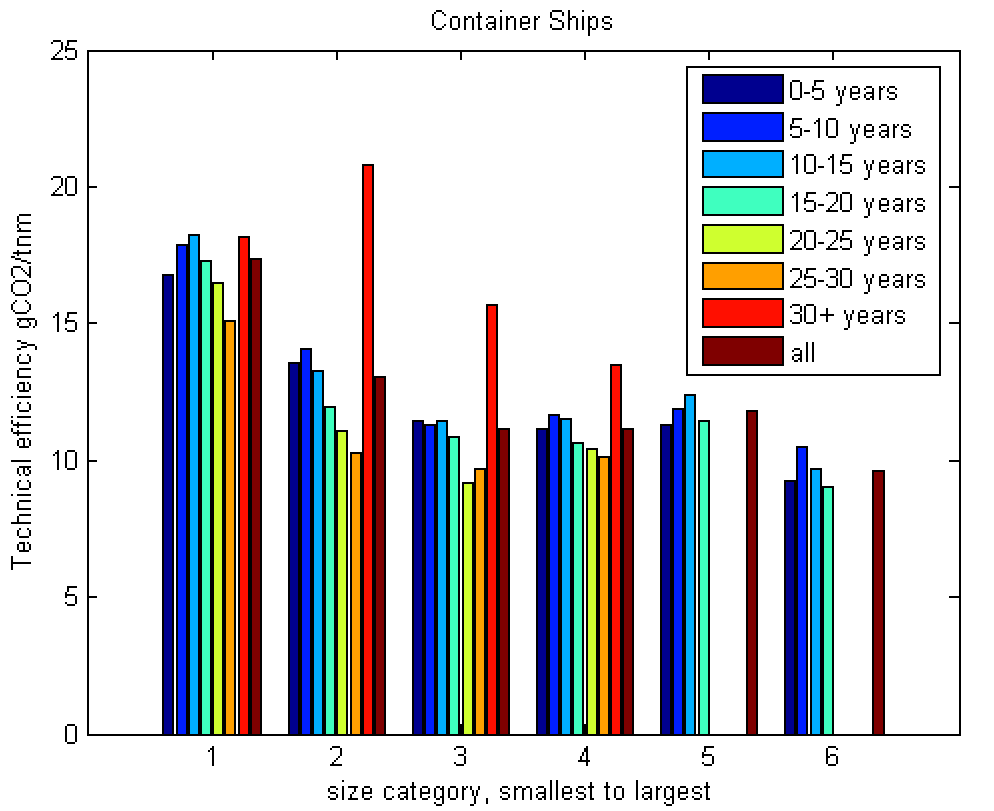

Container Ships
Technical Efficiency gCO2/tnm
10^1
10^2
10^3
10^4
TEU

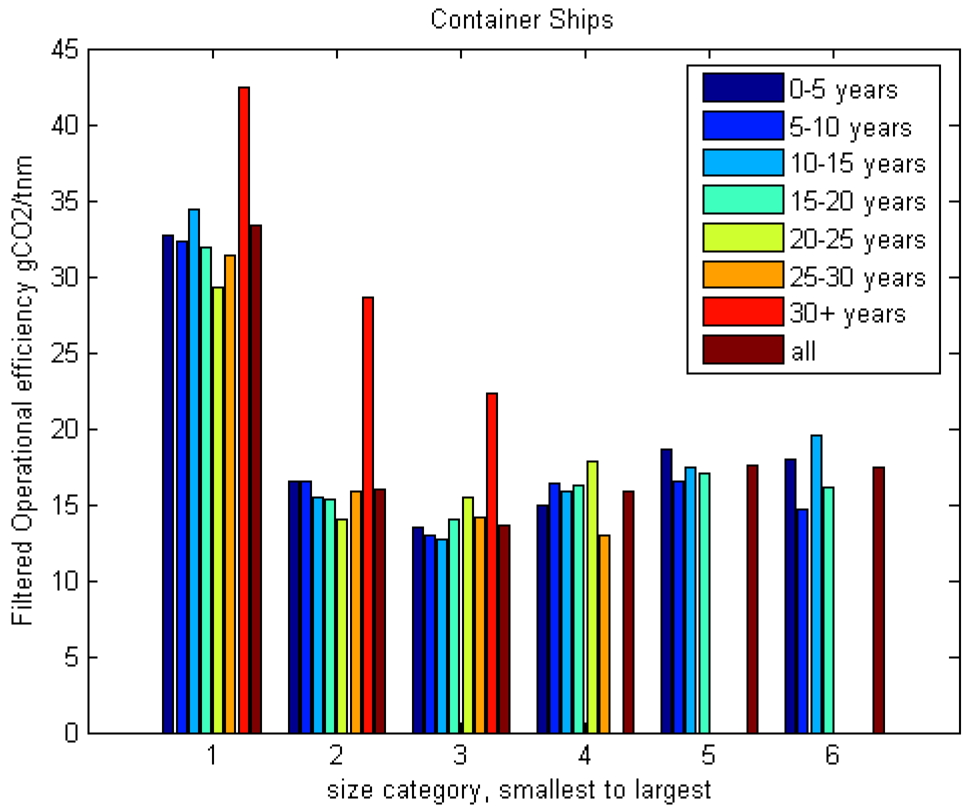

Container Ships
Operational Efficiency gCO2/tnm
10^2
10^1
filtered
unfiltered
10^2
10^3
10^4
TEU

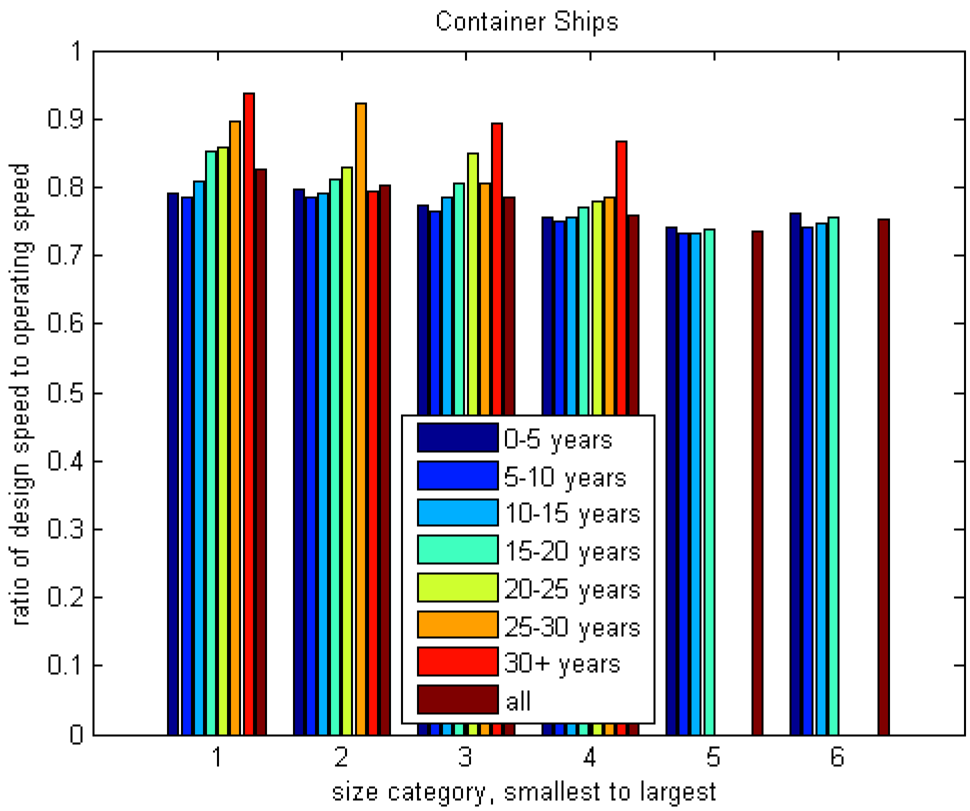

Container Ships
Normalised Operational Efficiency gCO2/tnm
TEU
10^2
10^1
10^2
10^3
10^4

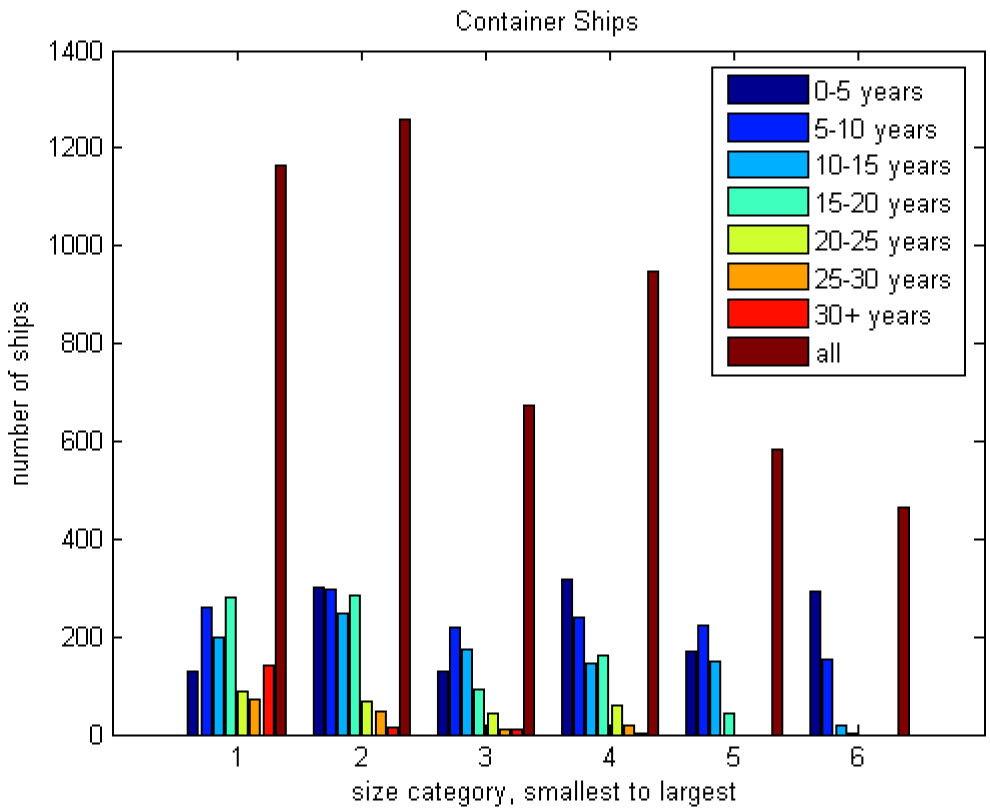

Container Ships
Operational Efficiency gCO2/tnm
TEU
normalised operational efficiency
filtered operational efficiency
10^2
10^1
10^2
10^3
10^4

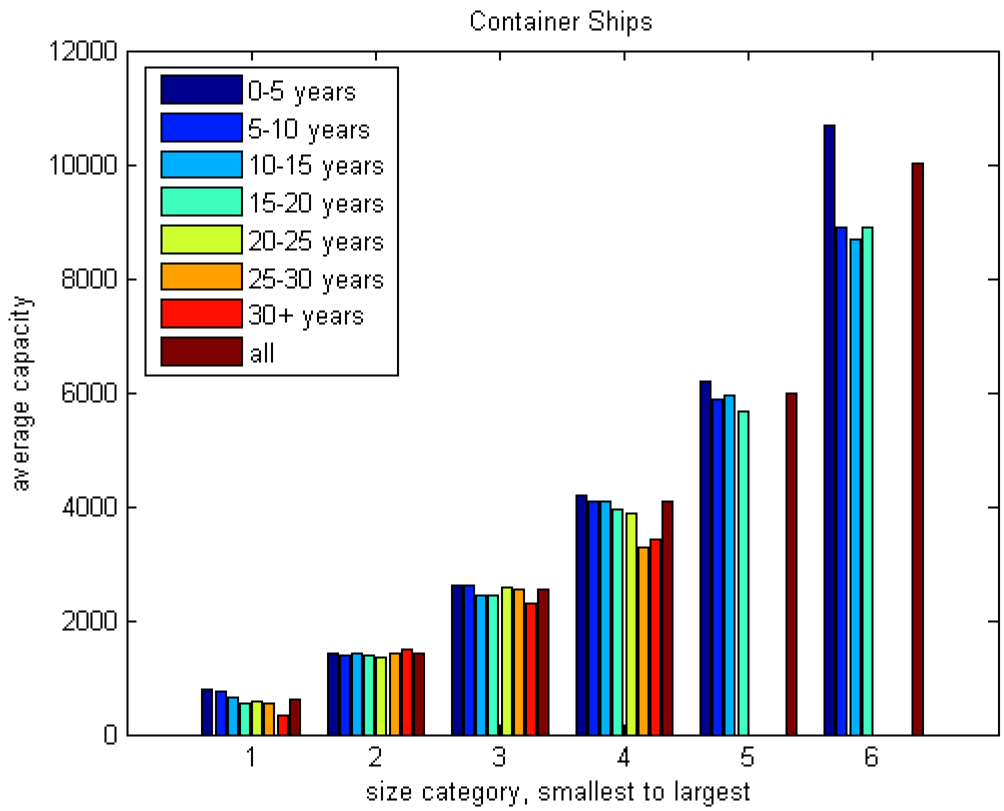

Container Ships
Ratio of average operating to design speed
TEU
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
2000
4000
6000
8000
10000
12000
14000
16000

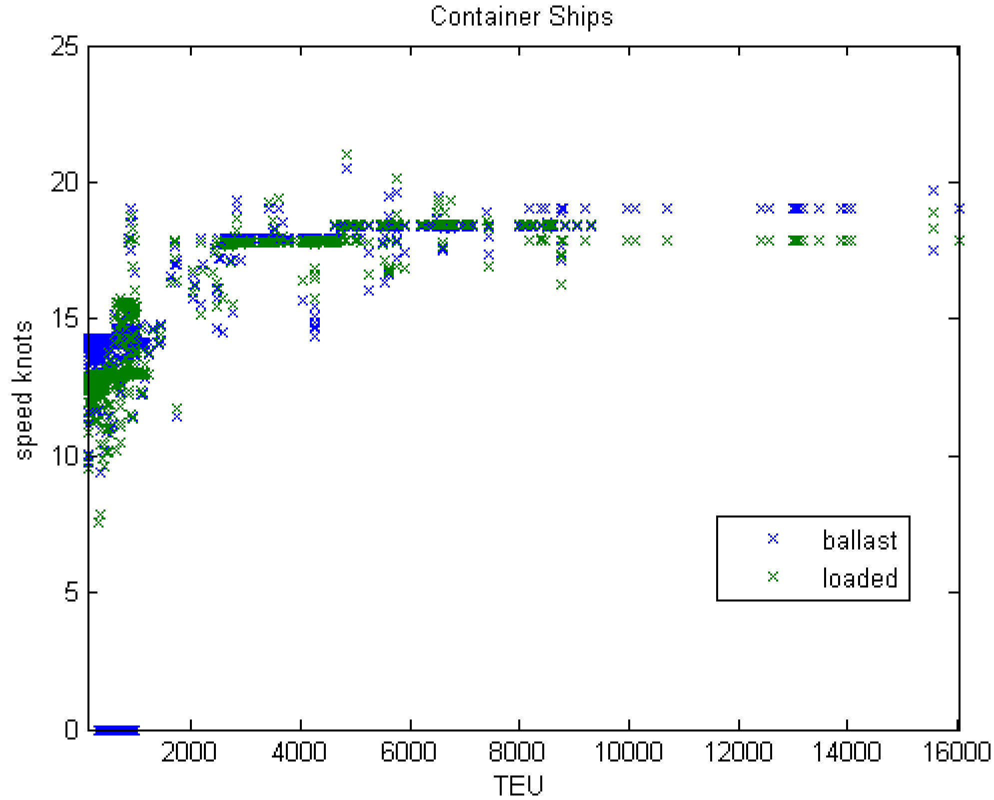

Container Ships
Technical efficiency gCO2/tnm
size category, smallest to largest
25
20
15
10
5
0
1
2
3
4
5
6
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all

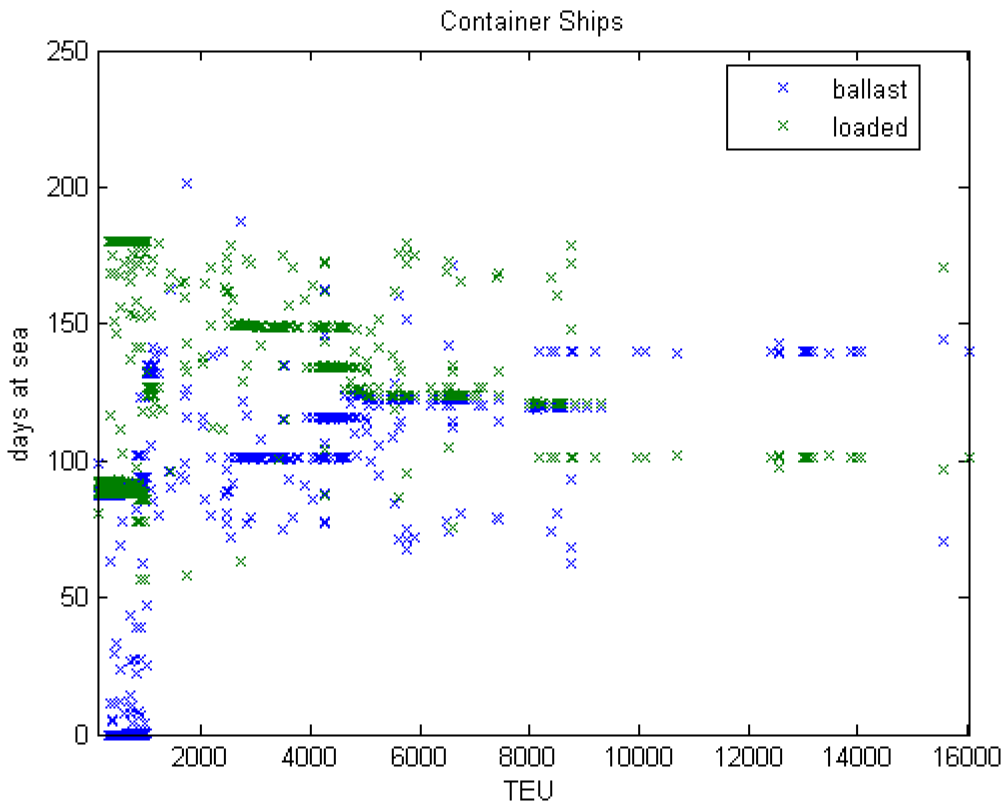

Container Ships
Filtered Operational efficiency gCO2/tnm
0
5
10
15
20
25
30
35
40
45
1
2
3
4
5
6
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all

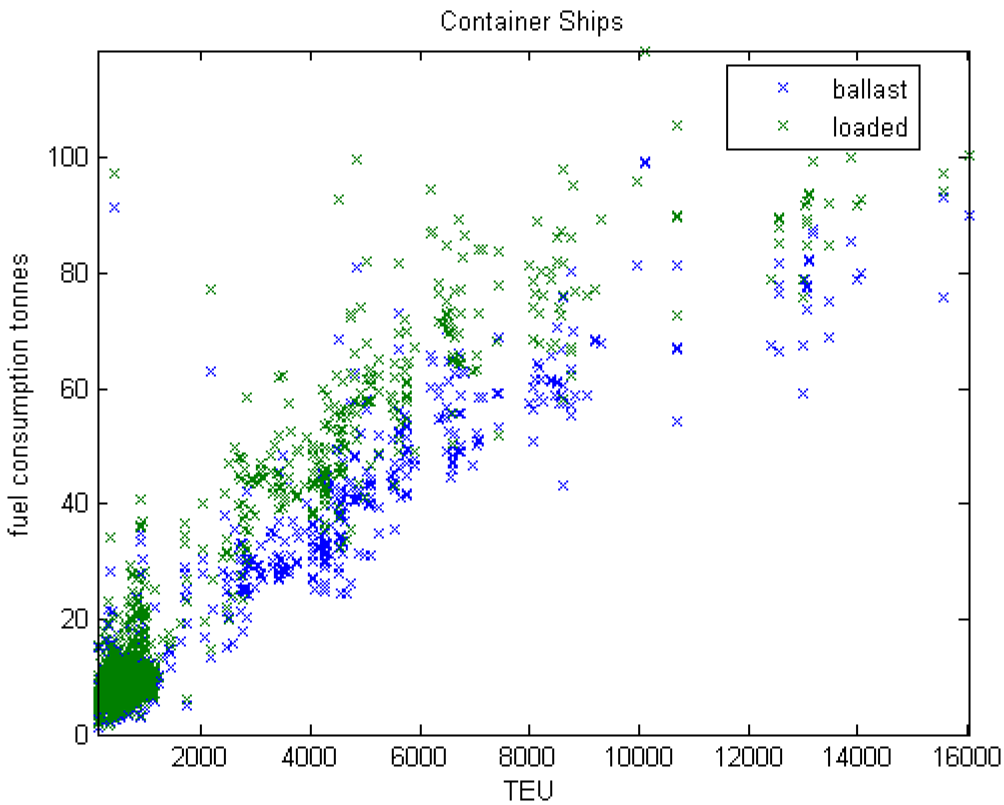

Container Ships
ratio of design speed to operating speed
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1
2
3
4
5
6
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all

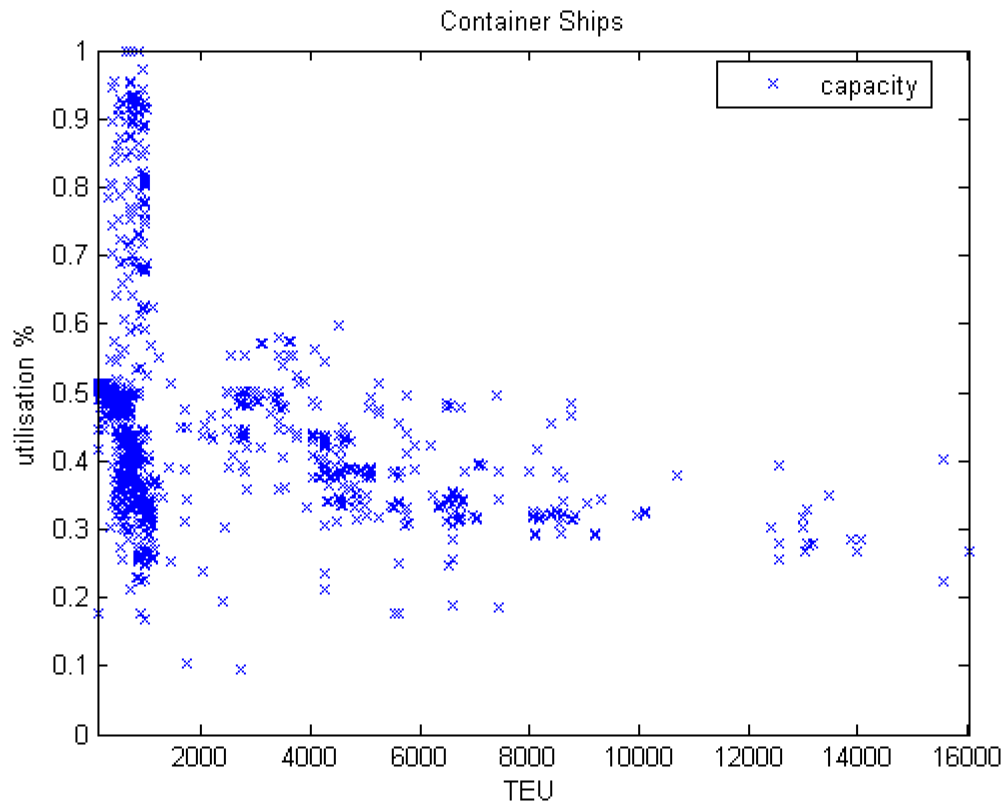

Container Ships
number of ships
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all
0
200
400
600
800
1000
1200
1400
1
2
3
4
5
6

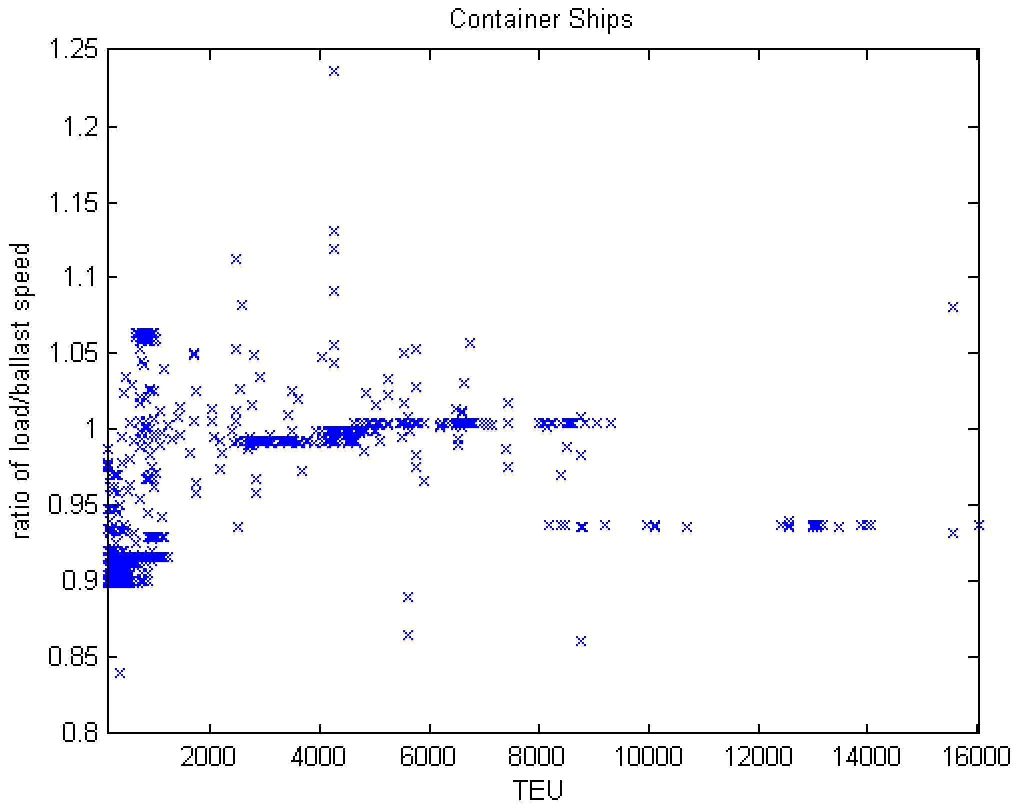

Container Ships
average capacity
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all
0
2000
4000
6000
8000
10000
12000
1
2
3
4
5
6

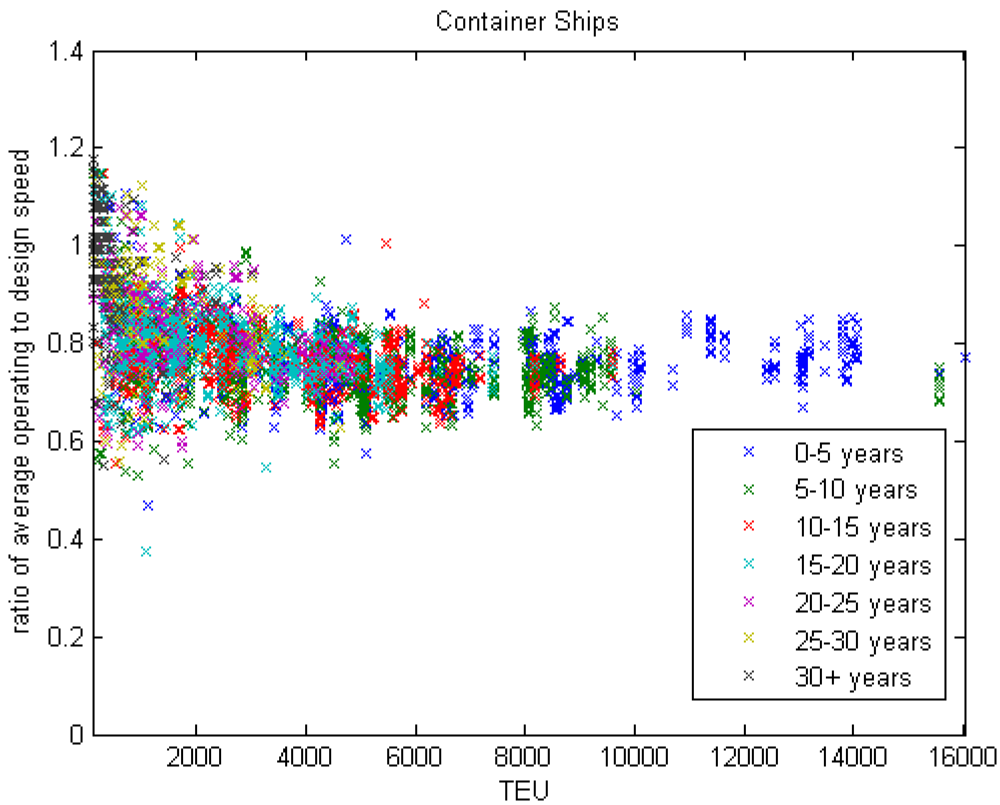

Container Ships
speed knots
TEU
ballast
loaded
0
5
10
15
20
25
2000
4000
6000
8000
10000
12000
14000
16000

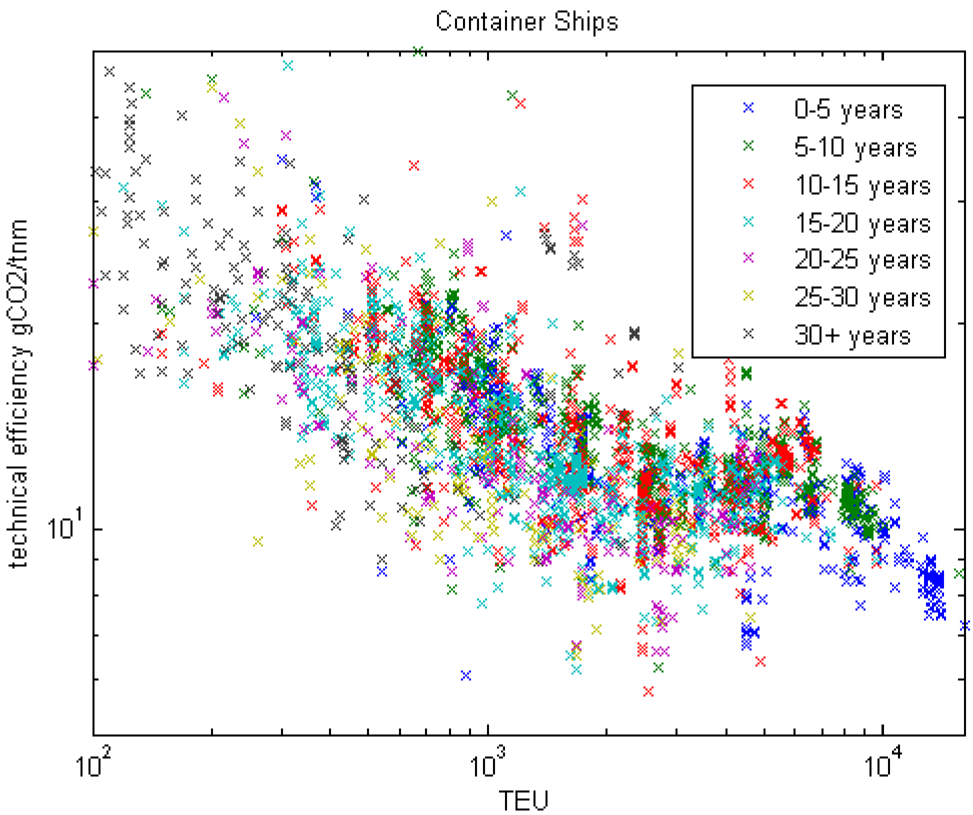

Container Ships
days at sea
TEU
ballast
loaded
0
50
100
150
200
250
2000
4000
6000
8000
10000
12000
14000
16000


Container Ships
ballast
loaded
fuel consumption tonnes
TEU
0
20
40
60
80
100
2000
4000
6000
8000
10000
12000
14000
16000

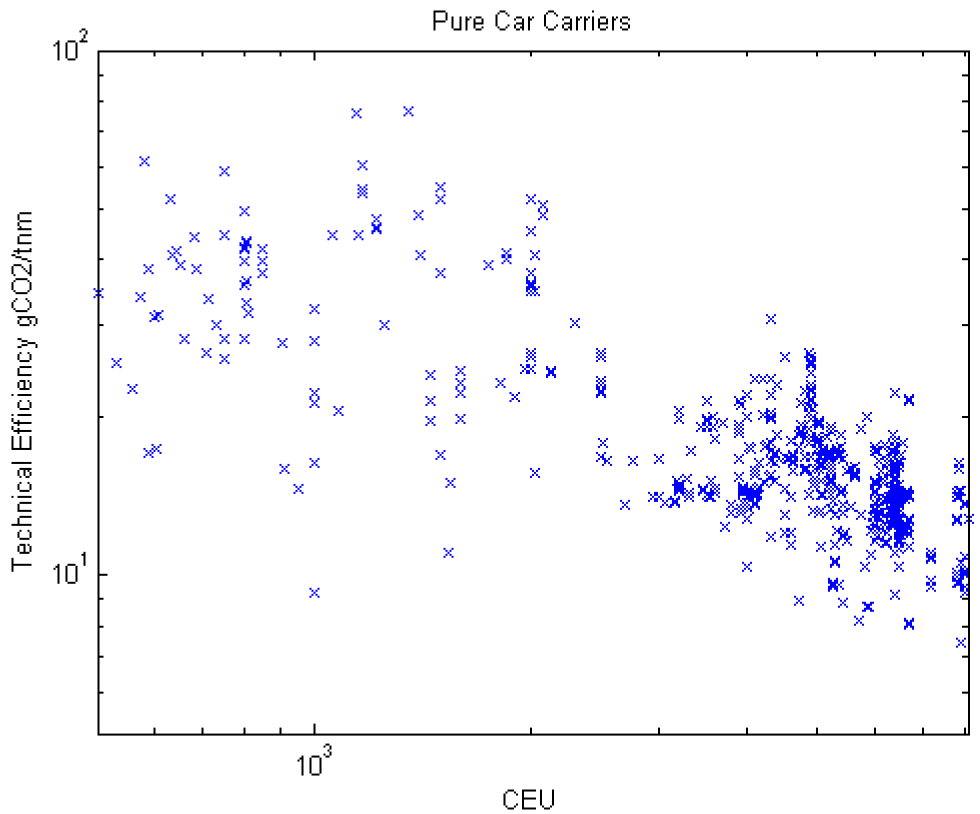

Container Ships
capacity
utilisation %
TEU
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
2000
4000
6000
8000
10000
12000
14000
16000

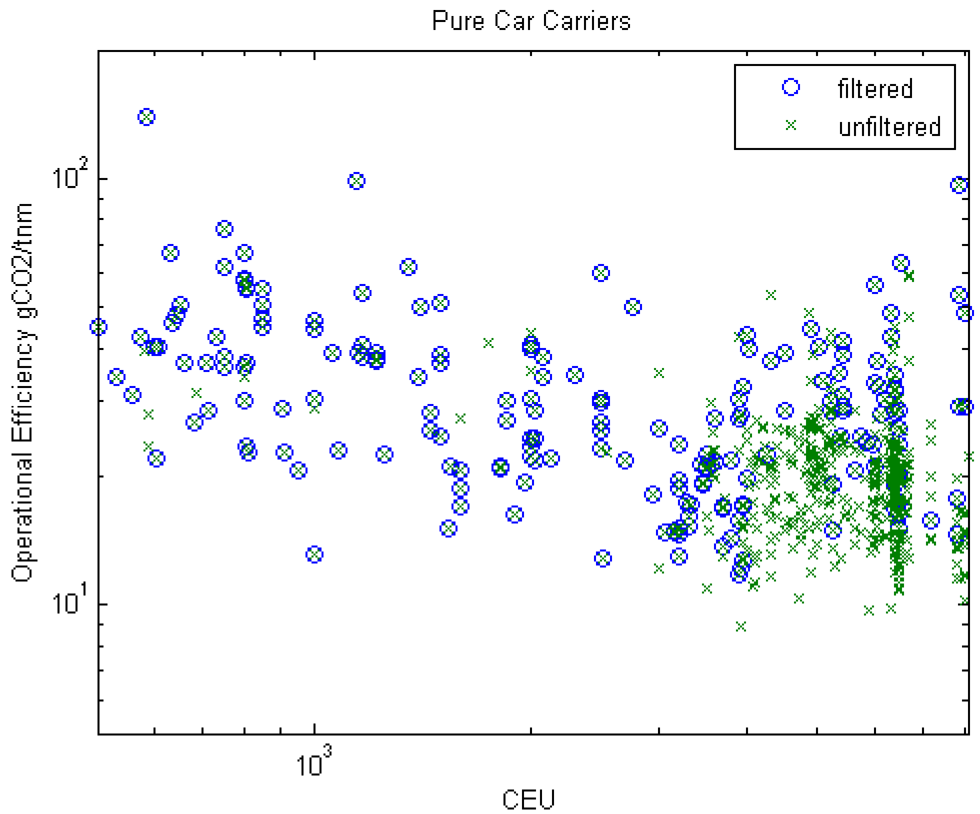

Container Ships
ratio of load/ballast speed
1.25
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
2000
4000
6000
8000
10000
12000
14000
16000
TEU

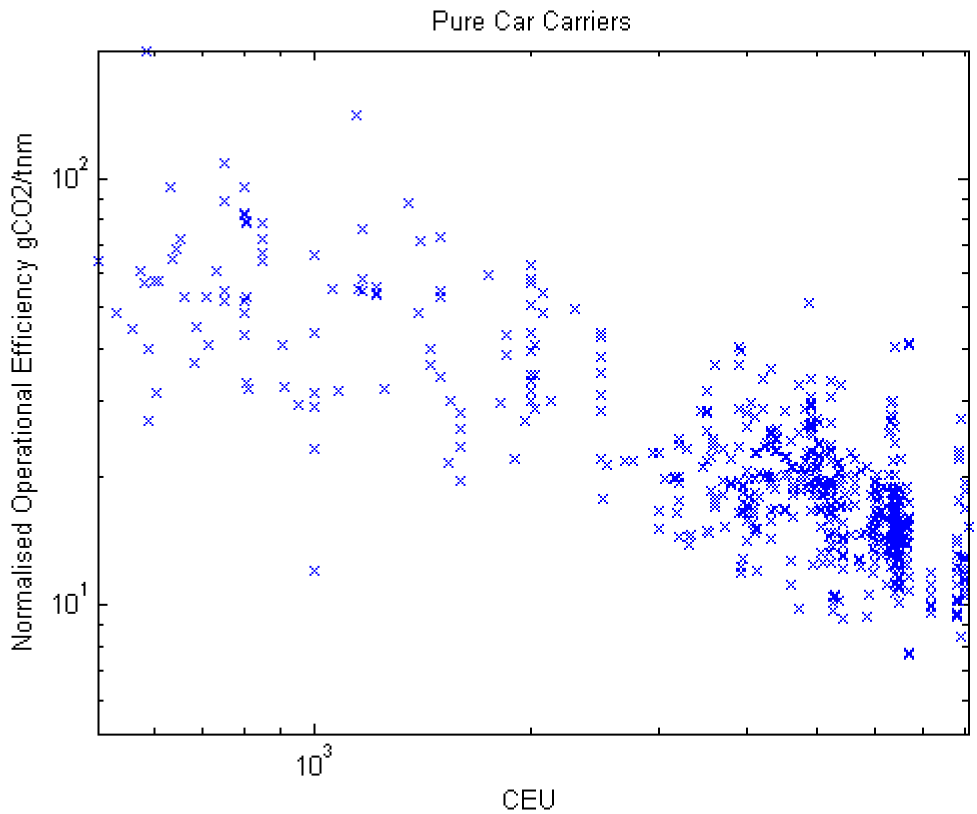

Container Ships
ratio of average operating to design speed
1.4
1.2
1
0.8
0.6
0.4
0.2
0
2000
4000
6000
8000
10000
12000
14000
16000
TEU
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years

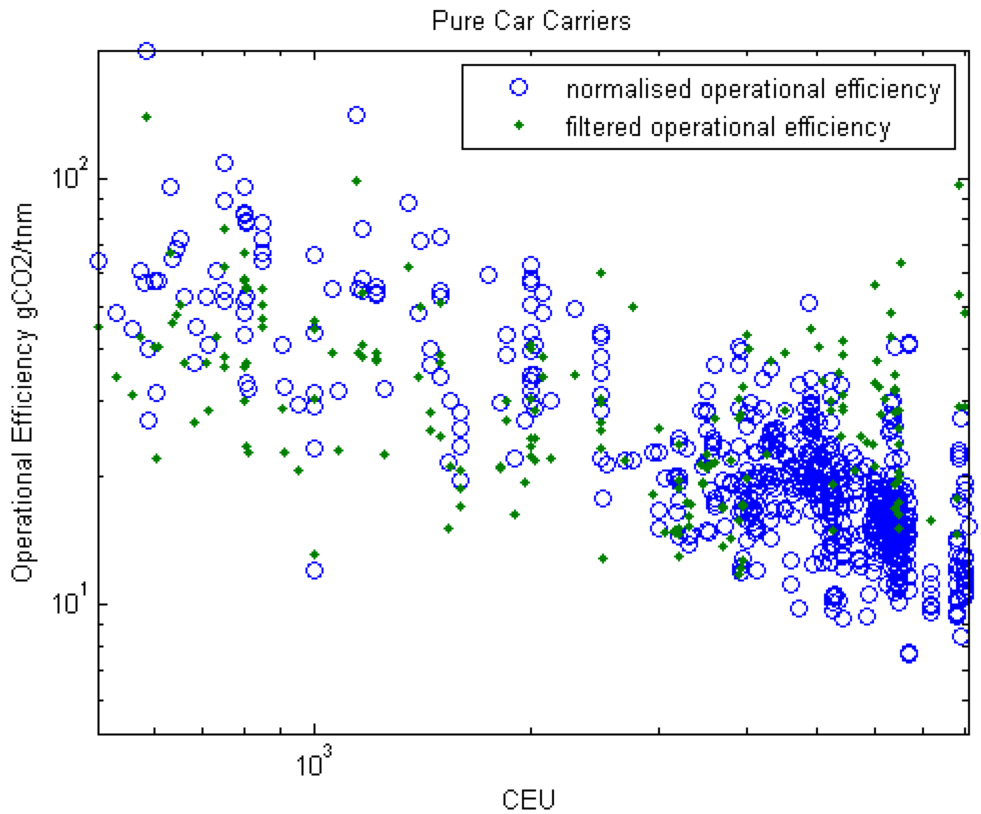


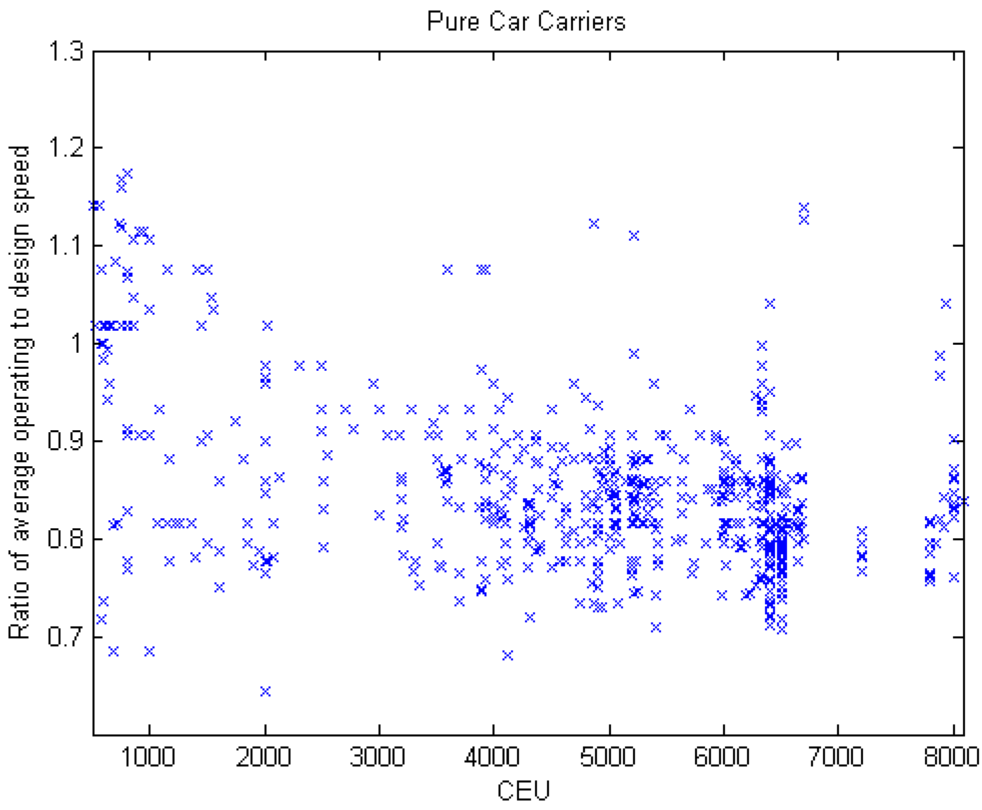
Container Ships
technical efficiency gCO2/tnm
TEU
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years

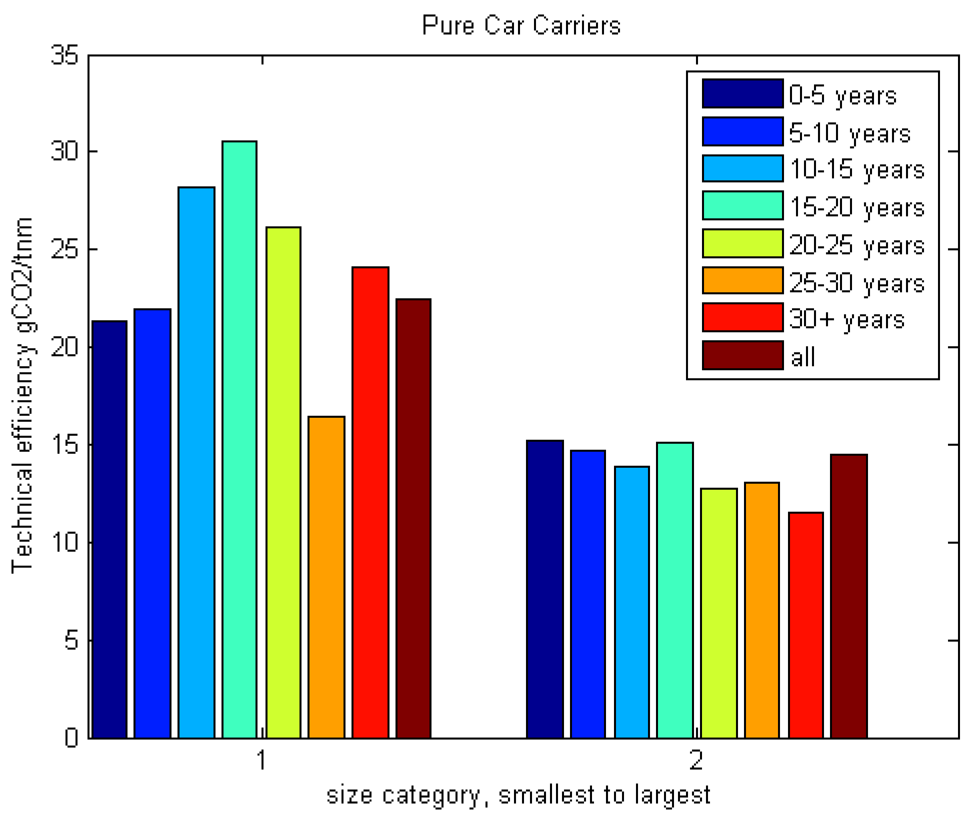

Pure Car Carriers
Technical Efficiency gCO2/tnm
CEU

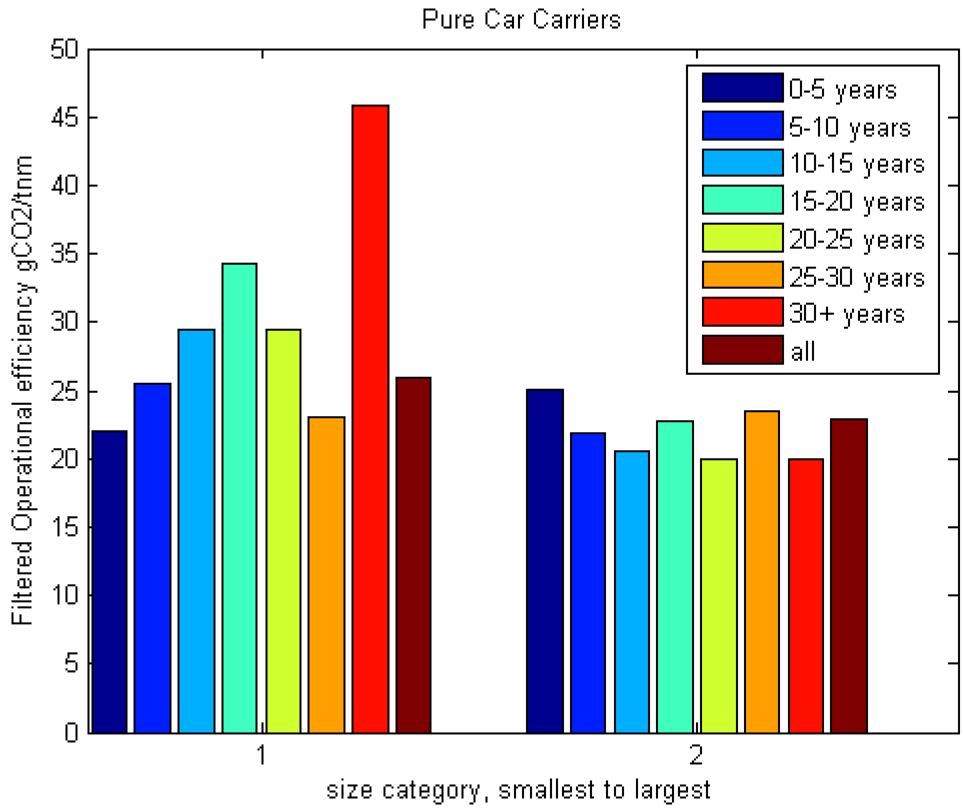

Pure Car Carriers
Operational Efficiency gCO2/tnm
CEU
filtered
unfiltered


Pure Car Carriers
Normalised Operational Efficiency gCO2/tnm
10^2
10^1
10^3
CEU

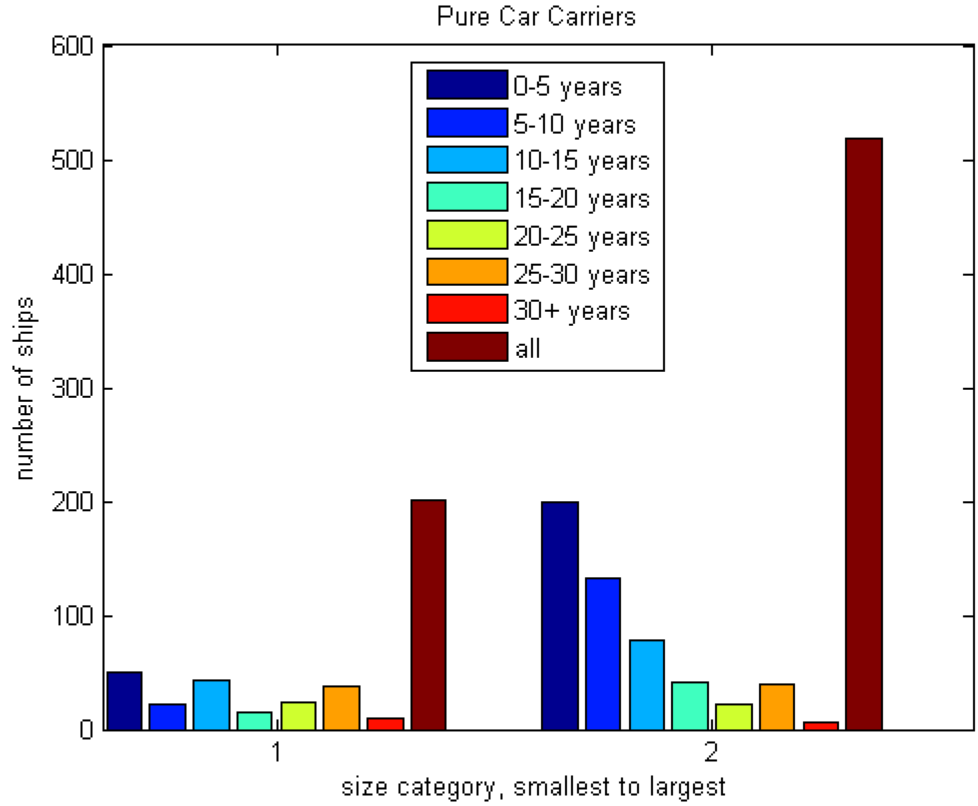

Pure Car Carriers
normalised operational efficiency
filtered operational efficiency
Operational Efficiency gCO2/tnm
10^2
10^1
10^3
CEU

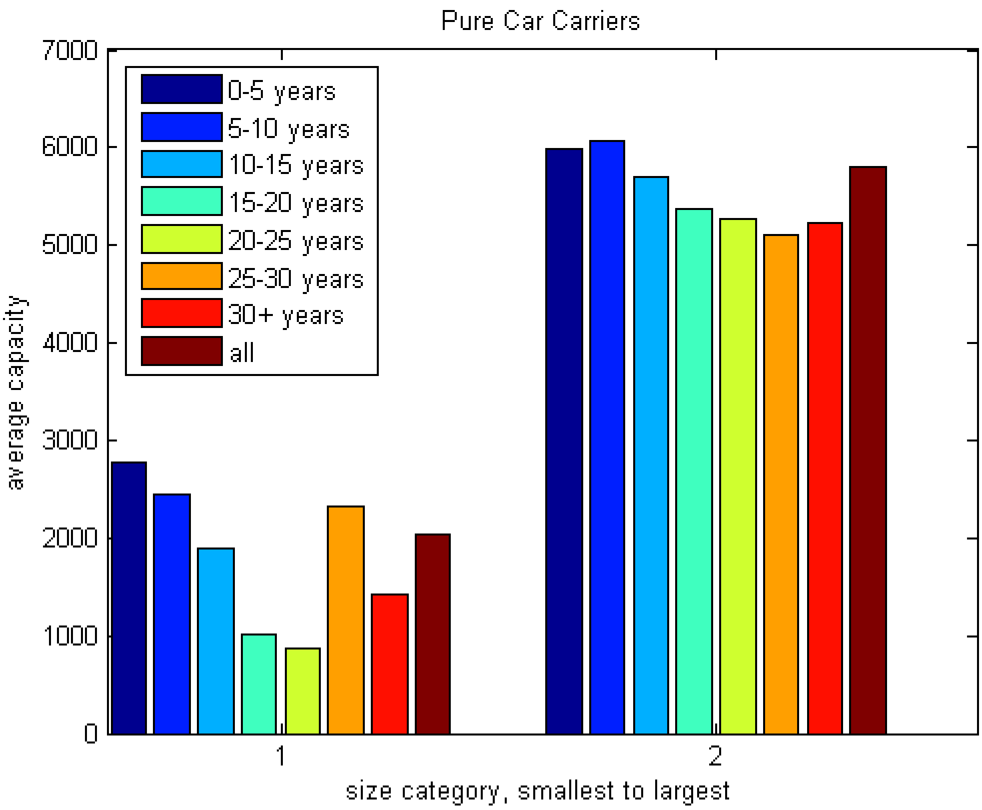

Pure Car Carriers
Ratio of average operating to design speed
CEU
1.3
1.2
1.1
1
0.9
0.8
0.7
1000
2000
3000
4000
5000
6000
7000
8000

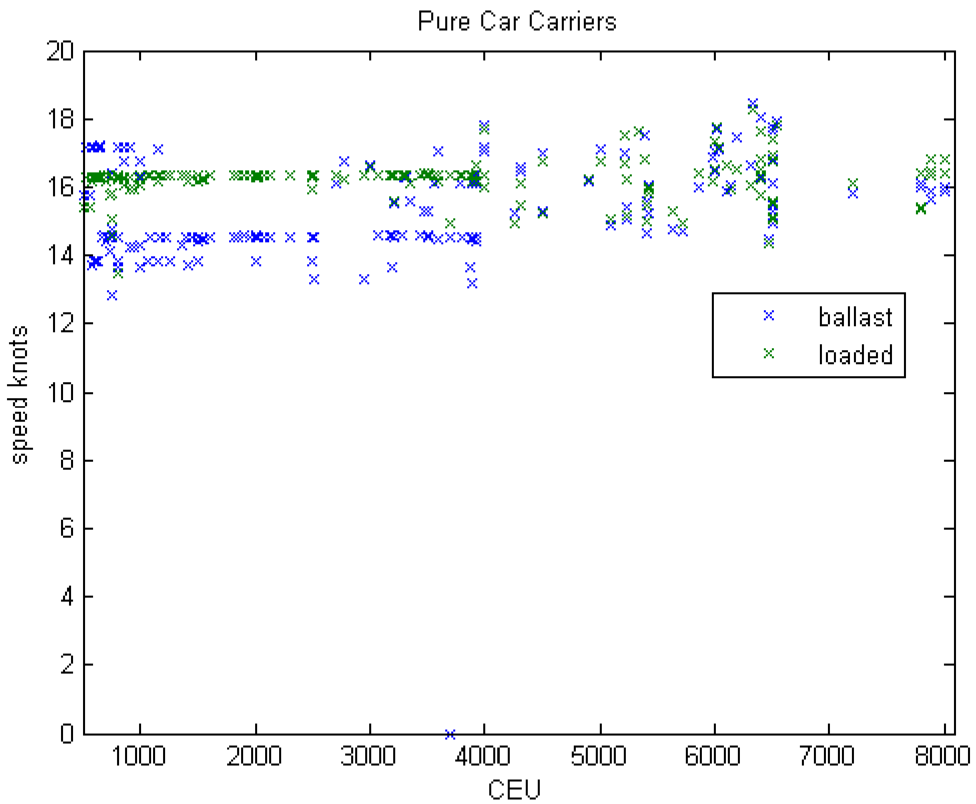

Pure Car Carriers
Technical efficiency gCO2/tnm
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all
35
30
25
20
15
10
5
0
1
2

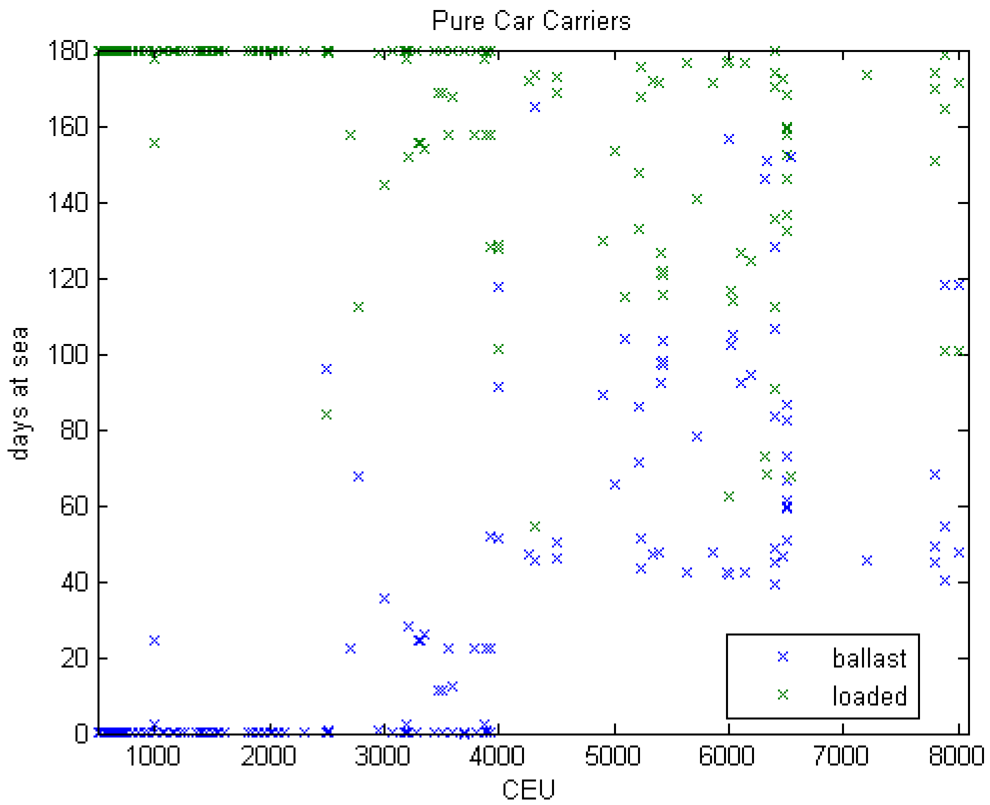

Pure Car Carriers
Filtered Operational efficiency gCO2/tnm
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all
size category, smallest to largest

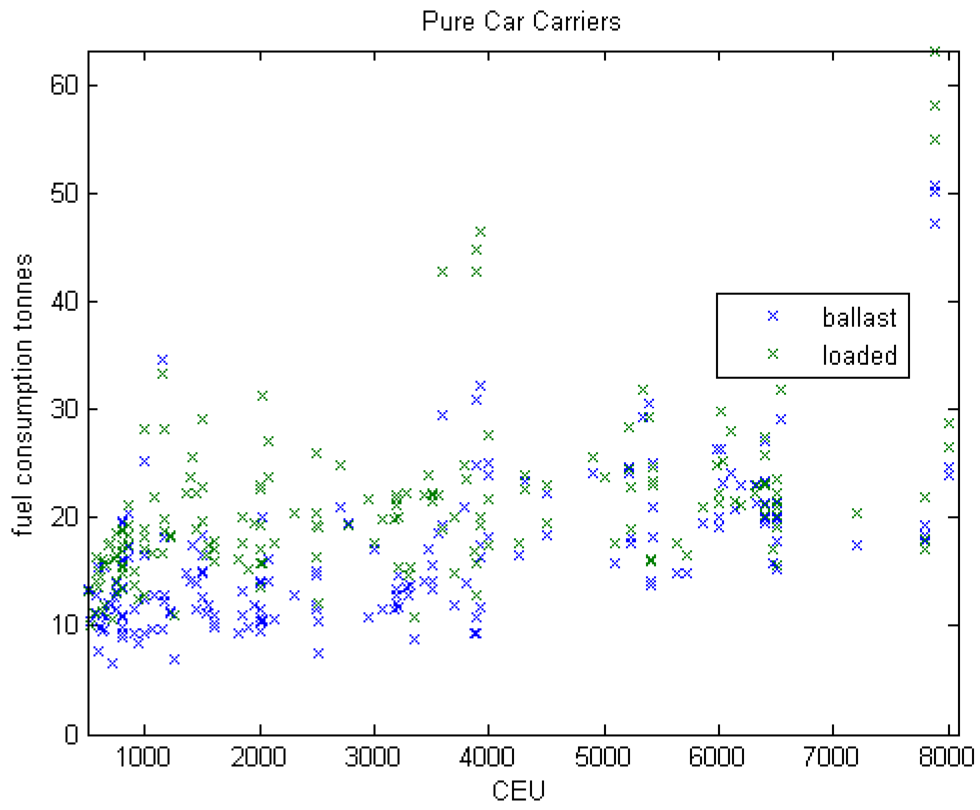

Pure Car Carriers
ratio of design speed to operating speed
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all
size category, smallest to largest

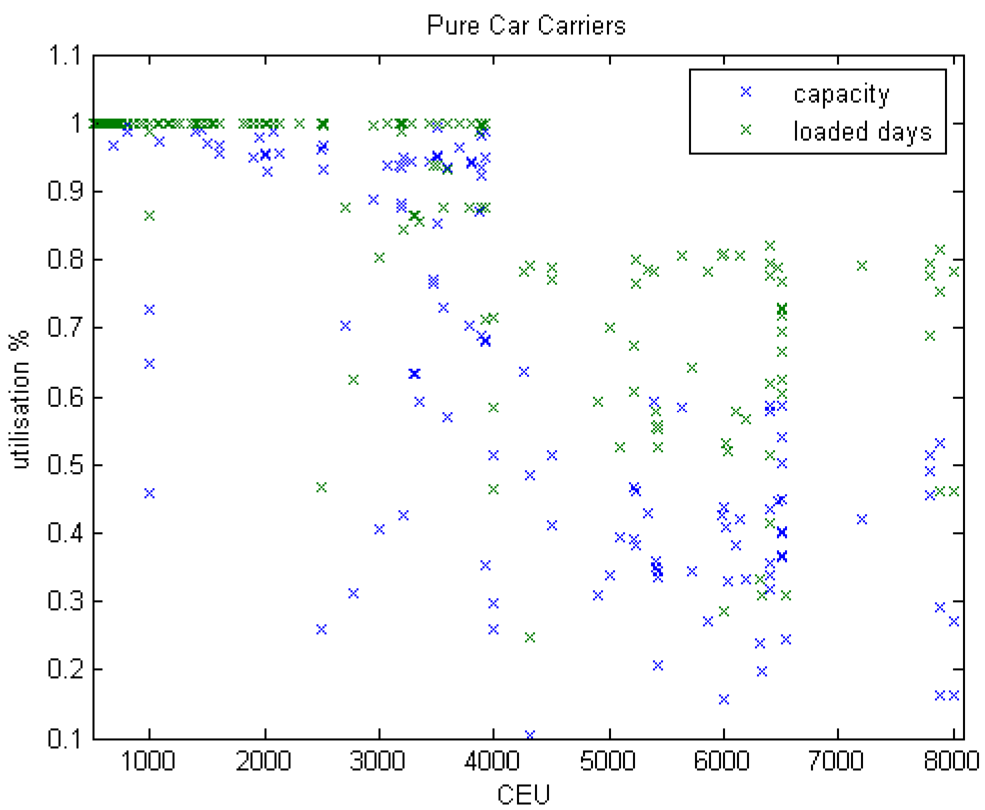

Pure Car Carriers
number of ships
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all
0
100
200
300
400
500
600
1
2

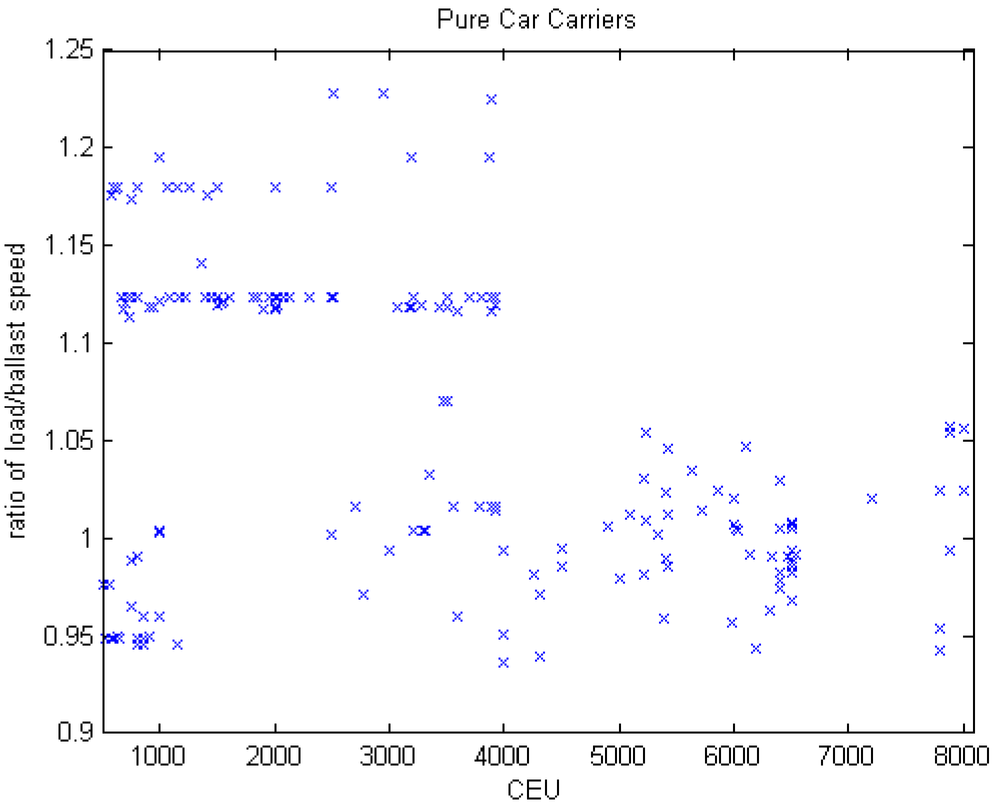

Pure Car Carriers
average capacity
size category, smallest to largest
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years
all
0
1000
2000
3000
4000
5000
6000
7000
1
2

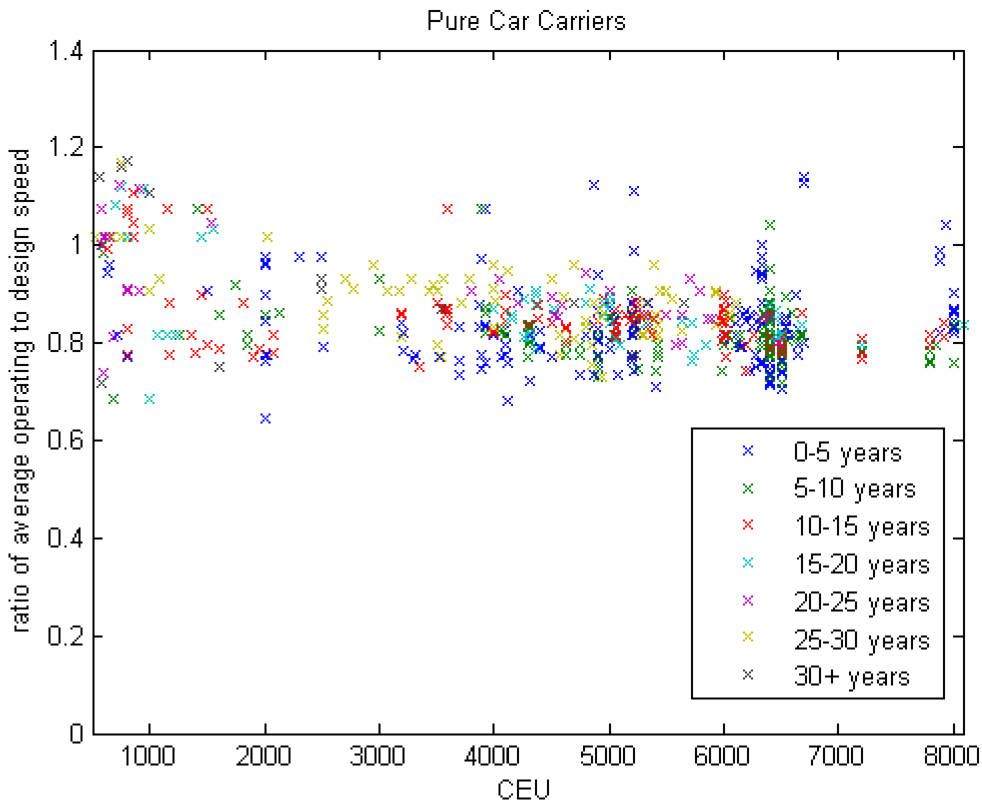

Pure Car Carriers
speed knots
CEU
ballast
loaded
20
18
16
14
12
10
8
6
4
2
0
1000
2000
3000
4000
5000
6000
7000
8000

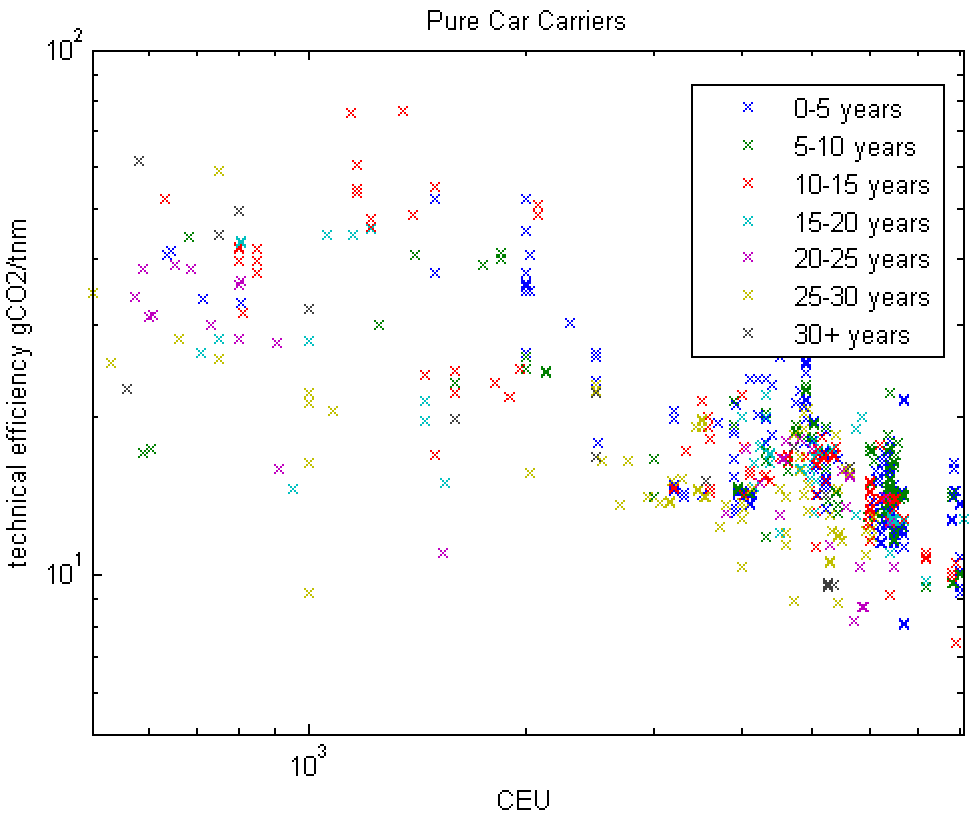

Pure Car Carriers
days at sea
CEU
ballast
loaded
180
160
140
120
100
80
60
40
20
0
1000
2000
3000
4000
5000
6000
7000
8000


Pure Car Carriers
fuel consumption tonnes
CEU
ballast
loaded
0
10
20
30
40
50
60
1000
2000
3000
4000
5000
6000
7000
8000

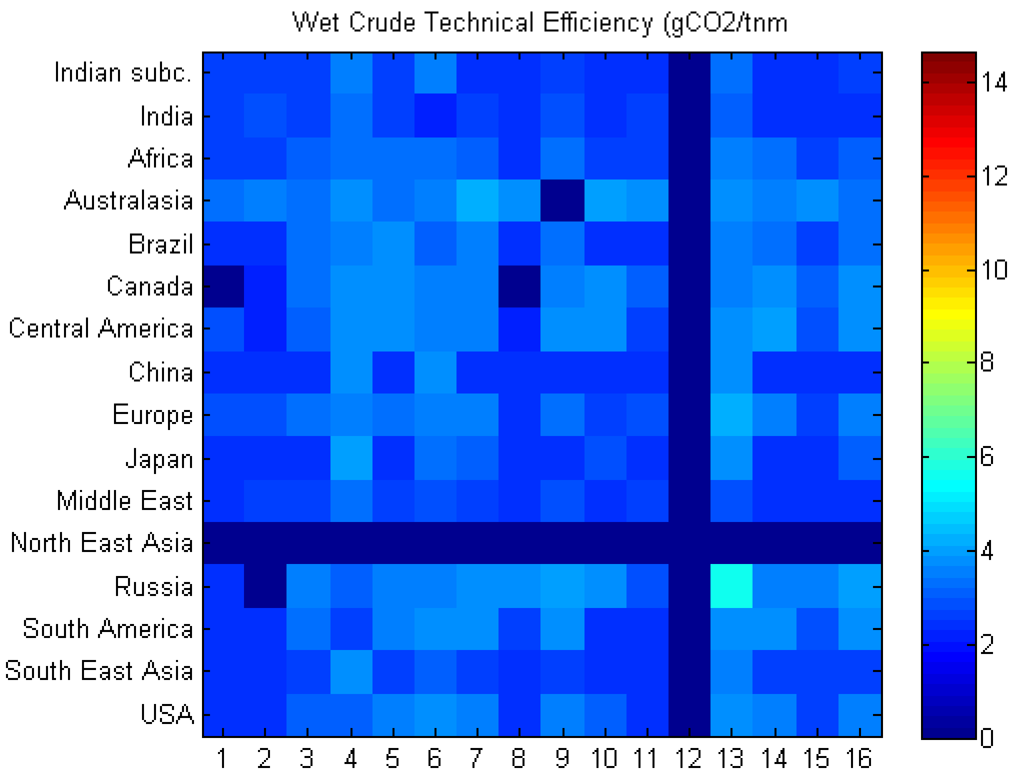

Pure Car Carriers
utilisation %
CEU
capacity
loaded days
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1000
2000
3000
4000
5000
6000
7000
8000

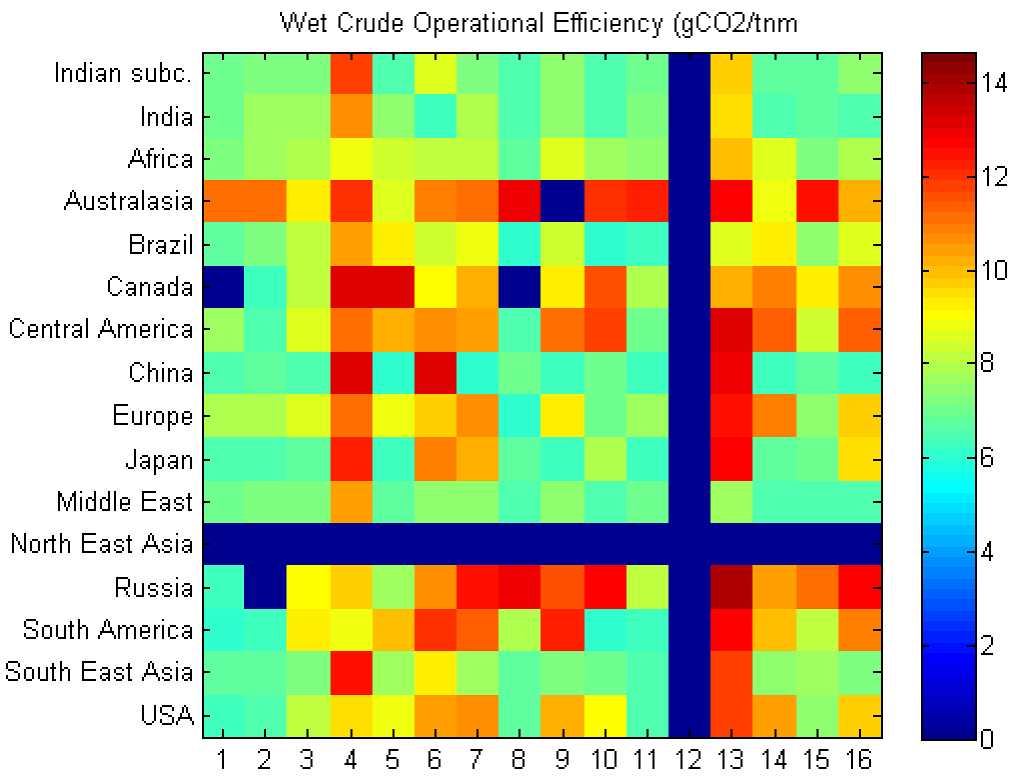

Pure Car Carriers
ratio of load/ballast speed
CEU
1.25
1.2
1.15
1.1
1.05
1
0.95
0.9
1000
2000
3000
4000
5000
6000
7000
8000

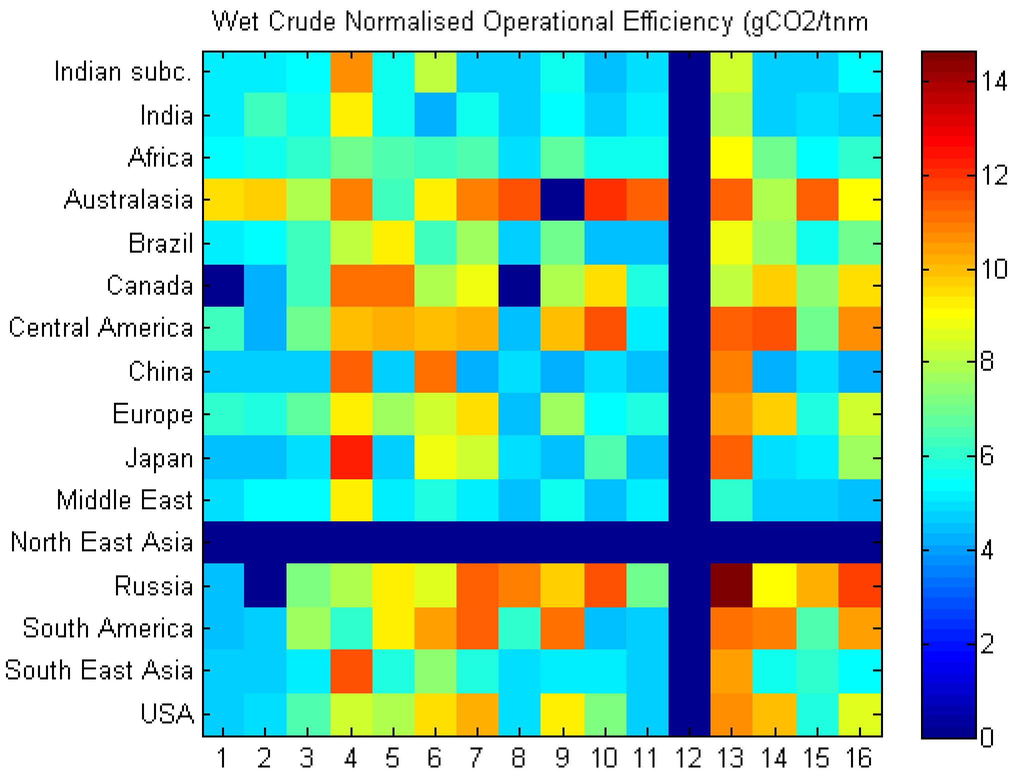

Pure Car Carriers
ratio of average operating to design speed
CEU
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1000
2000
3000
4000
5000
6000
7000
8000
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years

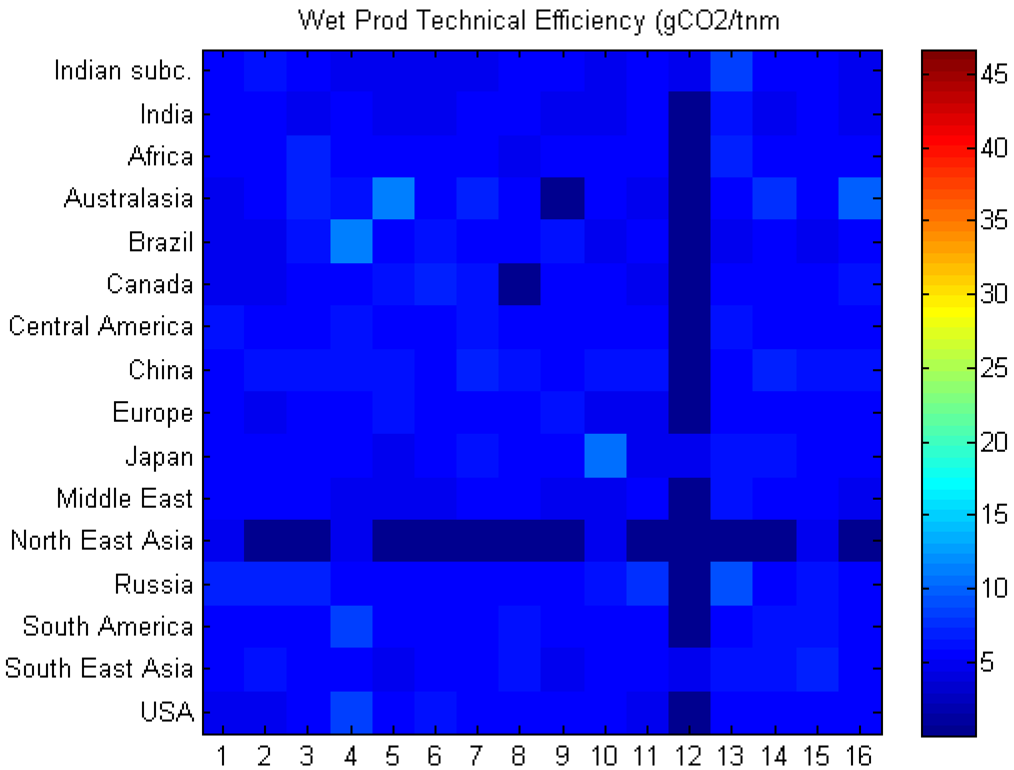

Pure Car Carriers
technical efficiency gCO2/tnm
CEU
0-5 years
5-10 years
10-15 years
15-20 years
20-25 years
25-30 years
30+ years

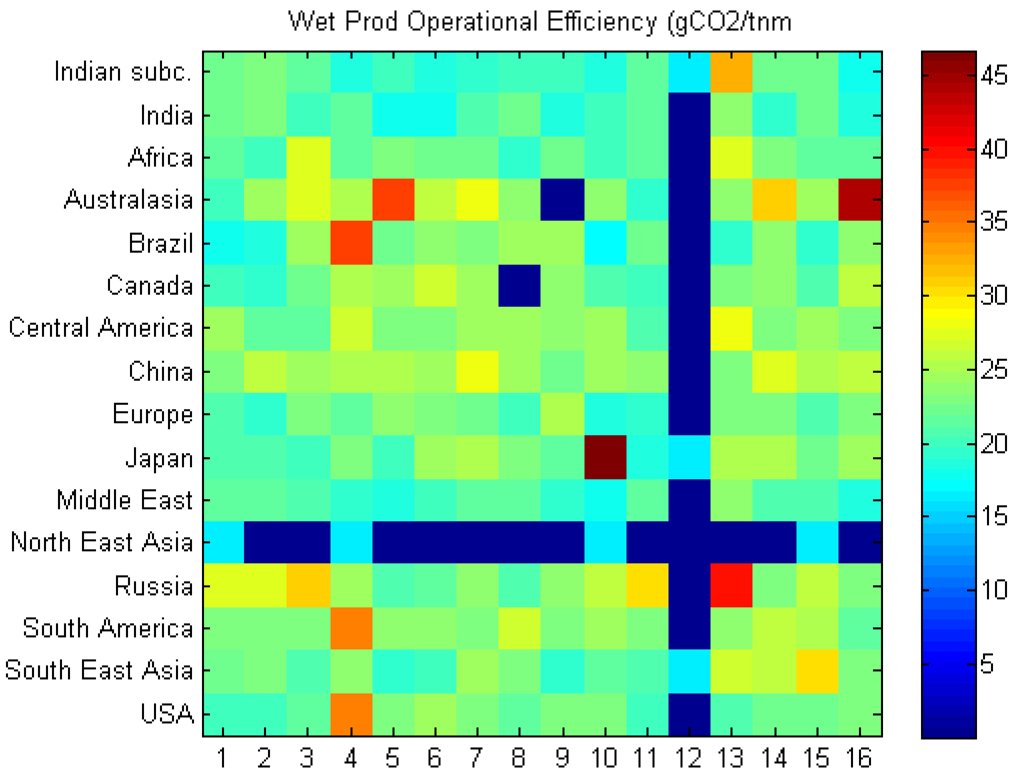
ANNEX 5 – ROUTE EFFICIENCY

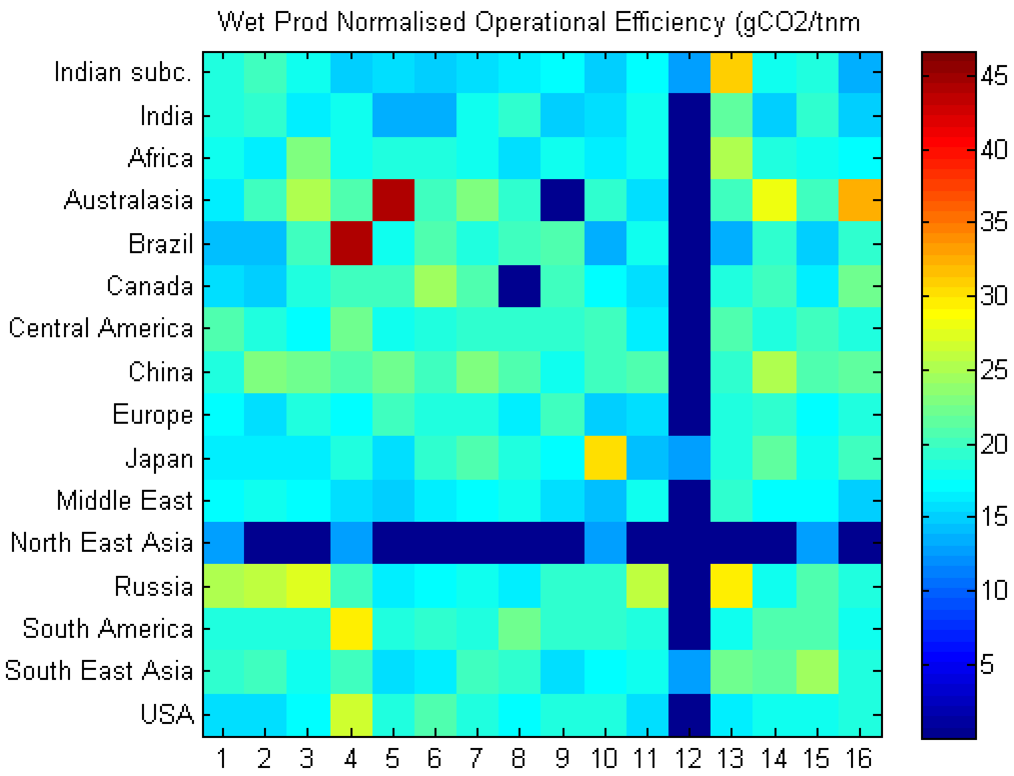


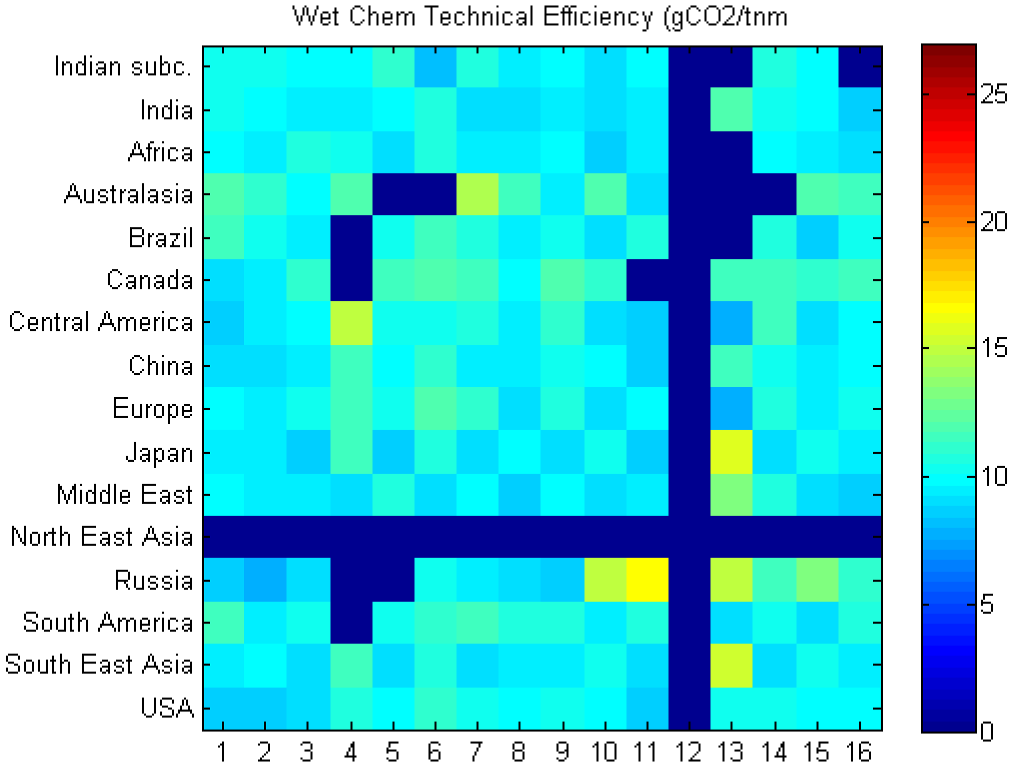


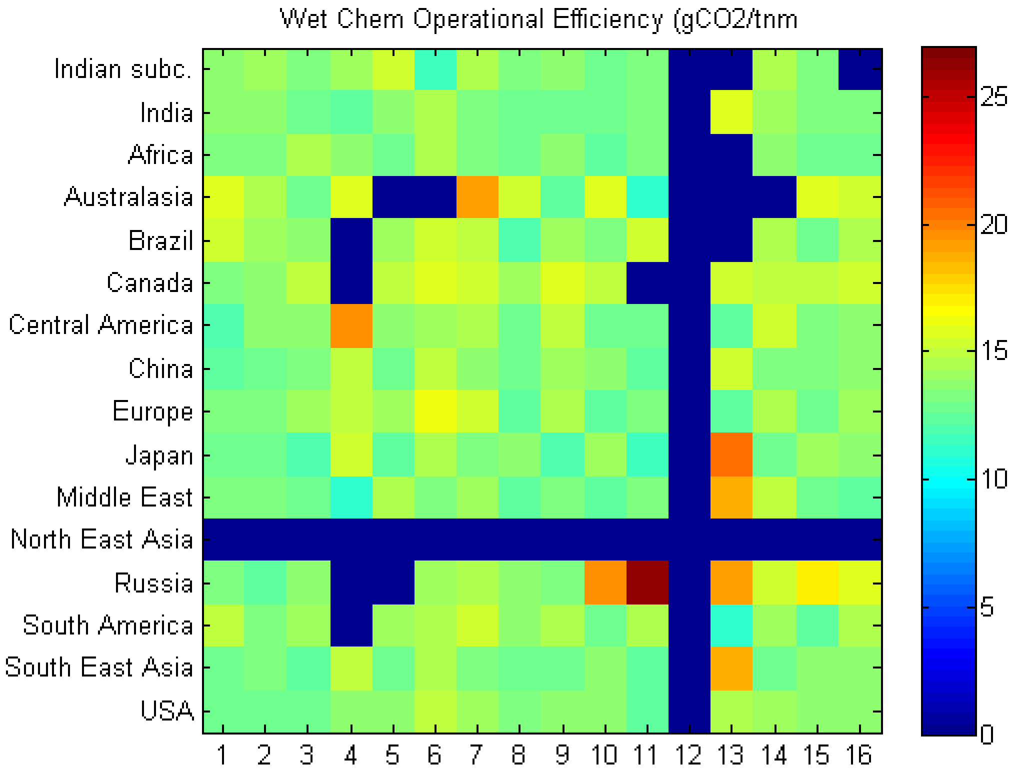

Wet Crude Normalised Operational Efficiency (gCO2/tnm
Indian subc.
India
Africa
Australasia
Brazil
Canada
Central America
China
Europe
Japan
Middle East
North East Asia
Russia
South America
South East Asia
USA
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
14
12
10
8
6
4
2
0

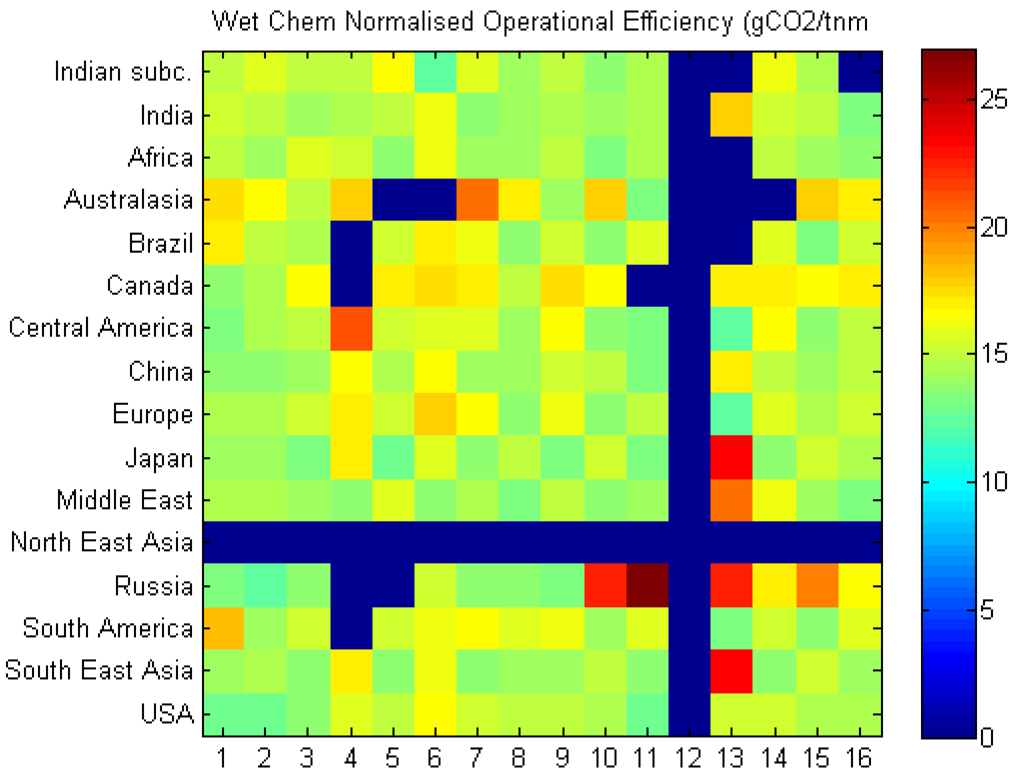

Wet Prod Technical Efficiency (gCO2/tnm
Indian subc.
India
Africa
Australasia
Brazil
Canada
Central America
China
Europe
Japan
Middle East
North East Asia
Russia
South America
South East Asia
USA
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
45
40
35
30
25
20
15
10
5


Wet Prod Operational Efficiency (gCO2/tnm
Indian subc.
India
Africa
Australasia
Brazil
Canada
Central America
China
Europe
Japan
Middle East
North East Asia
Russia
South America
South East Asia
USA
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
45
40
35
30
25
20
15
10
5

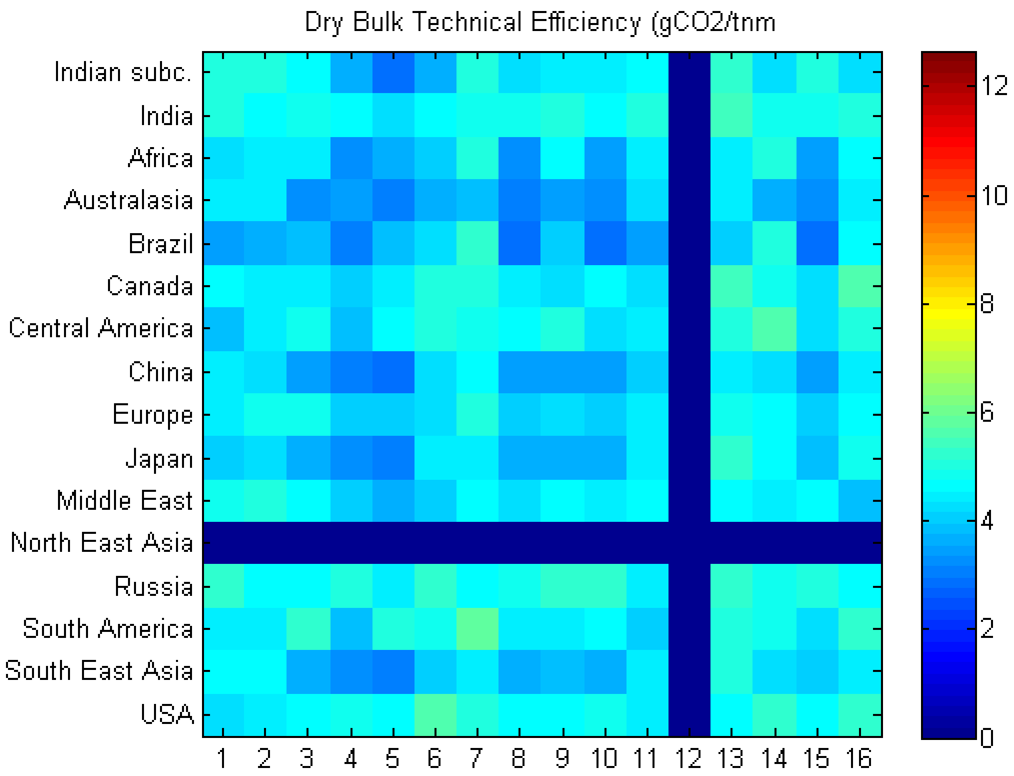

Wet Prod Normalised Operational Efficiency (gCO2/tnm
Indian subc.
India
Africa
Australasia
Brazil
Canada
Central America
China
Europe
Japan
Middle East
North East Asia
Russia
South America
South East Asia
USA
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
45
40
35
30
25
20
15
10
5


Wet Chem Technical Efficiency (gCO2/tnm
Indian subc.
India
Africa
Australasia
Brazil
Canada
Central America
China
Europe
Japan
Middle East
North East Asia
Russia
South America
South East Asia
USA
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
0 5 10 15 20 25

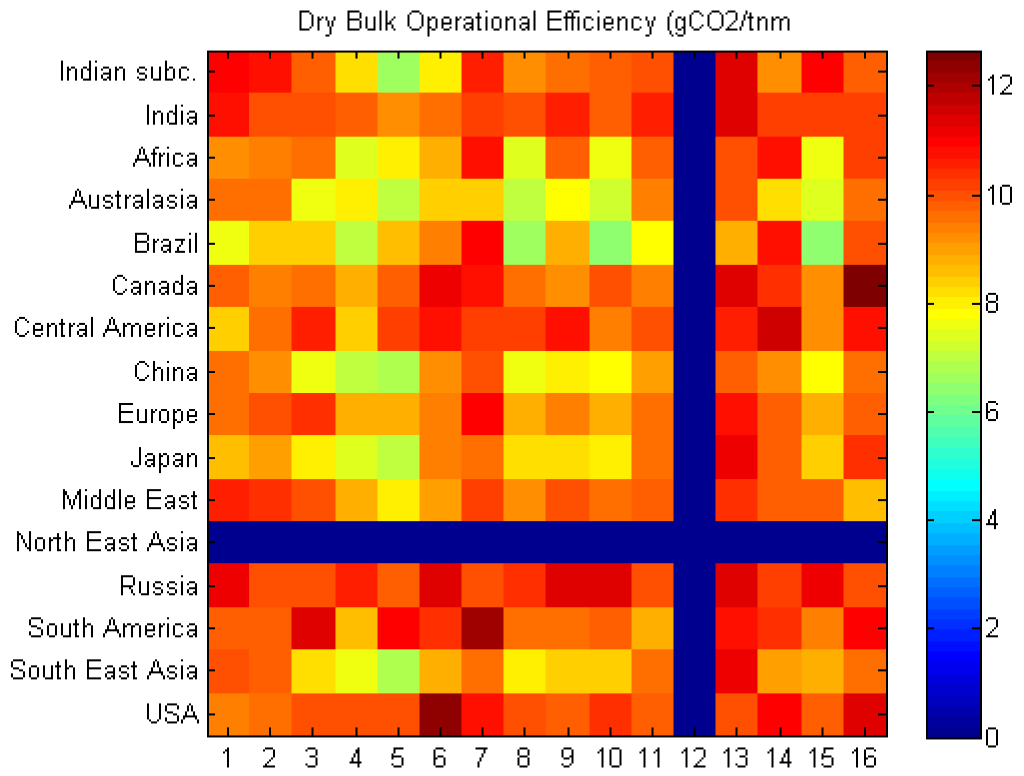

Wet Chem Operational Efficiency (gCO2/tnm
Indian subc.
India
Africa
Australasia
Brazil
Canada
Central America
China
Europe
Japan
Middle East
North East Asia
Russia
South America
South East Asia
USA
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
0 5 10 15 20 25

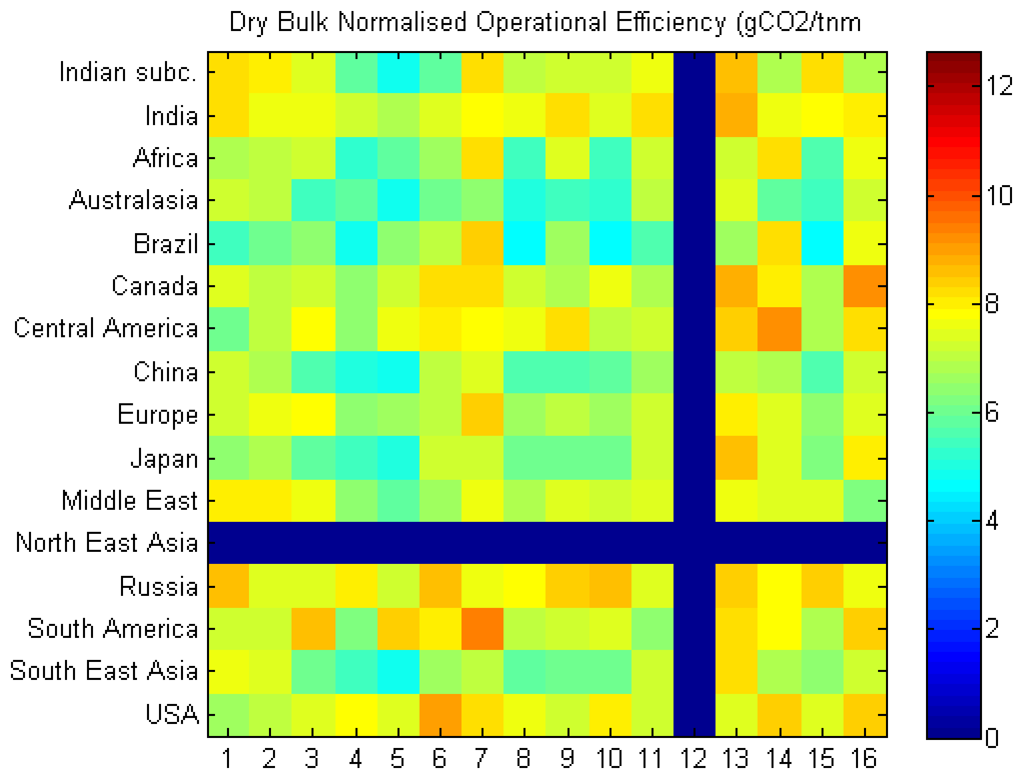


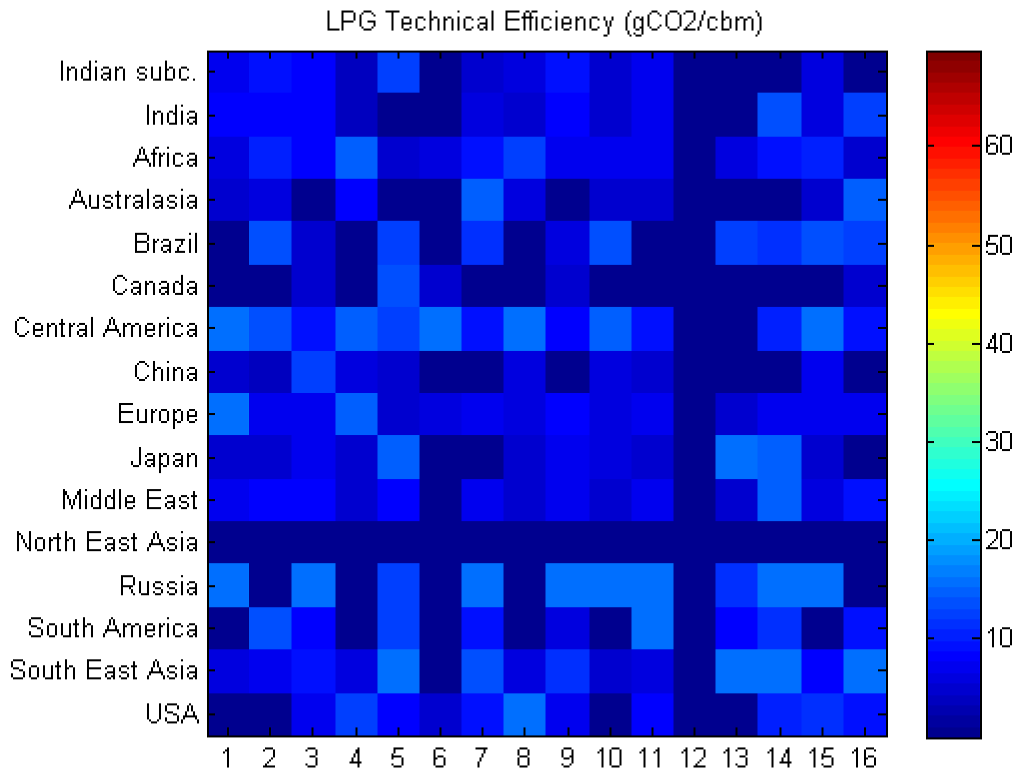
Wet Chem Normalised Operational Efficiency (gCO2/tnm
Indian subc.
India
Africa
Australasia
Brazil
Canada
Central America
China
Europe
Japan
Middle East
North East Asia
Russia
South America
South East Asia
USA
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
25
20
15
10
5
0

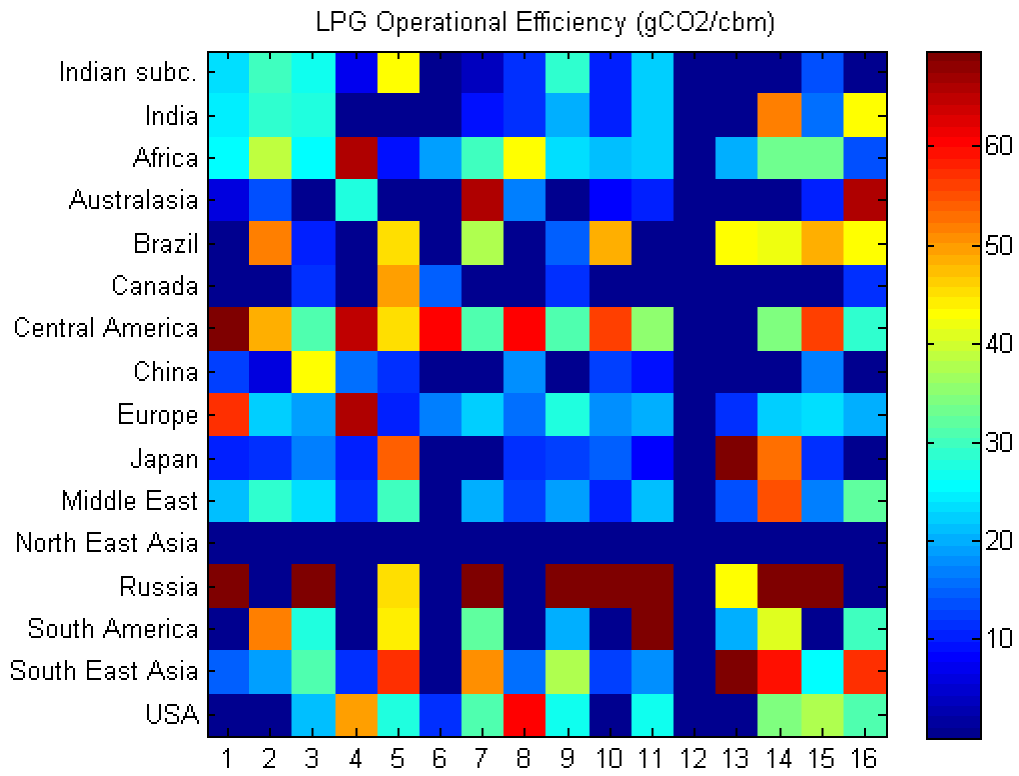


Dry Bulk Technical Efficiency (gCO2/tnm
Indian subc.
India
Africa
Australasia
Brazil
Canada
Central America
China
Europe
Japan
Middle East
North East Asia
Russia
South America
South East Asia
USA
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
12
10
8
6
4
2
0


Dry Bulk Operational Efficiency (gCO2/tnm
Indian subc.
India
Africa
Australasia
Brazil
Canada
Central America
China
Europe
Japan
Middle East
North East Asia
Russia
South America
South East Asia
USA
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
0 2 4 6 8 10 12


Dry Bulk Normalised Operational Efficiency (gCO2/tnm
Indian subc.
India
Africa
Australasia
Brazil
Canada
Central America
China
Europe
Japan
Middle East
North East Asia
Russia
South America
South East Asia
USA
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
0 2 4 6 8 10 12


LPG Technical Efficiency (gCO2/cbm)
Indian subc.
India
Africa
Australasia
Brazil
Canada
Central America
China
Europe
Japan
Middle East
North East Asia
Russia
South America
South East Asia
USA
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
10
20
30
40
50
60


LPG Operational Efficiency (gCO2/cbm)
Indian subc.
India
Africa
Australasia
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1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
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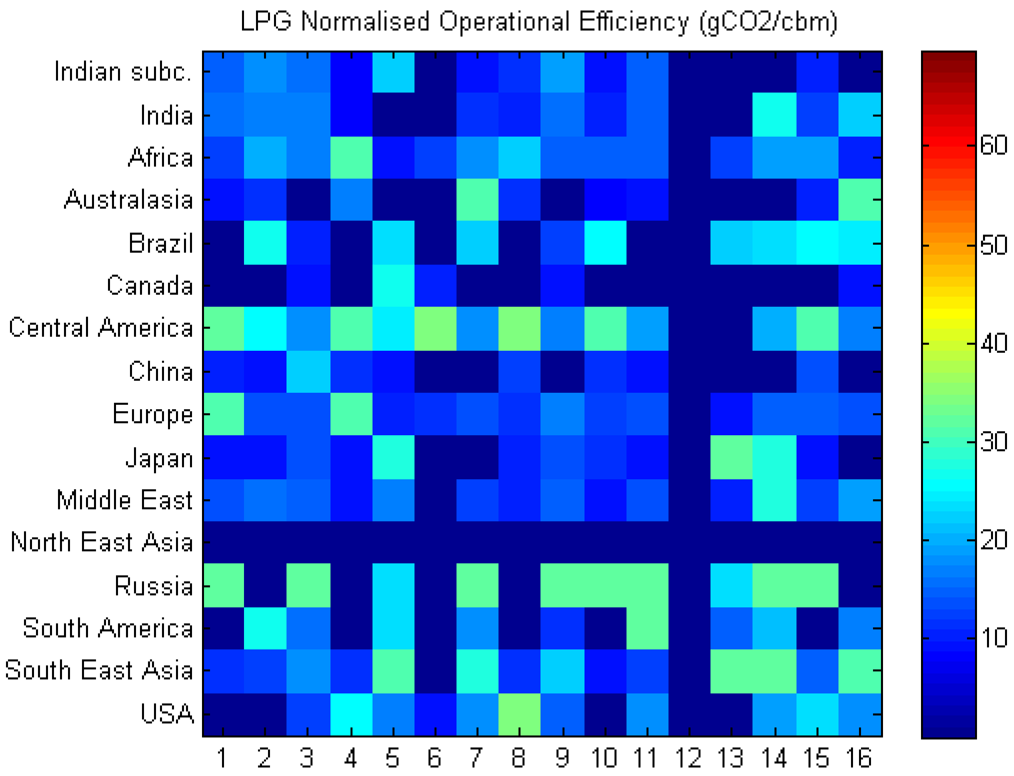
LPG Normalised Operational Efficiency (gCO2/cbm)
Indian subc.
India
Africa
Australasia
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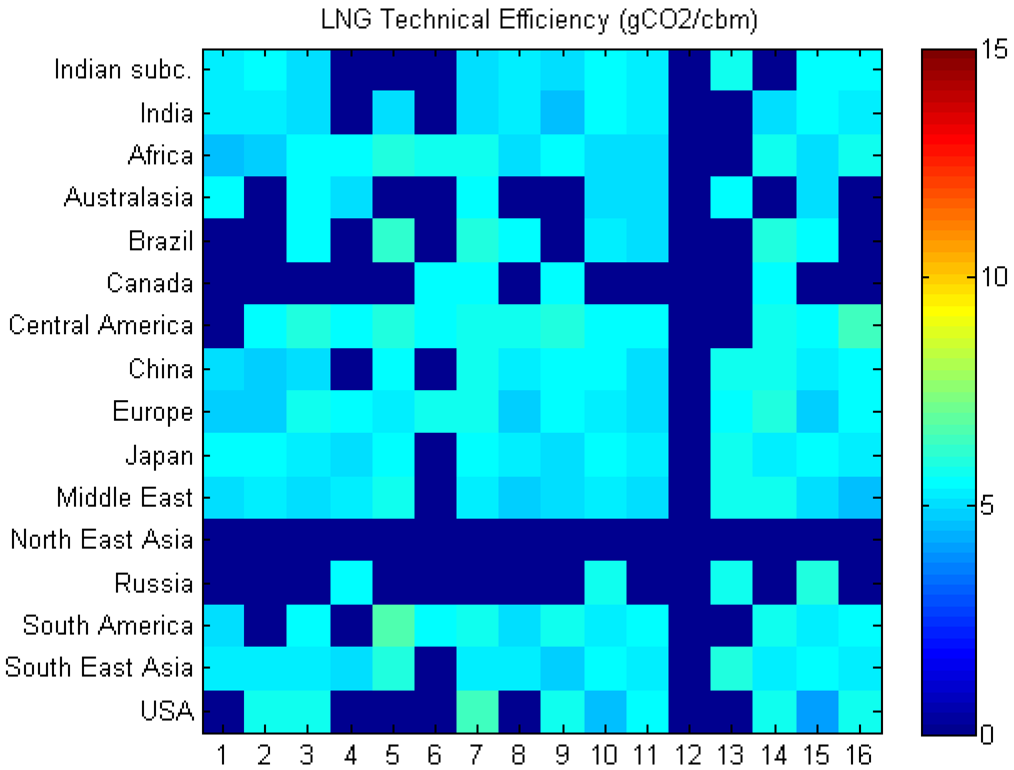
LNG Technical Efficiency (gCO2/cbm)
Indian subc.
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Africa
Australasia
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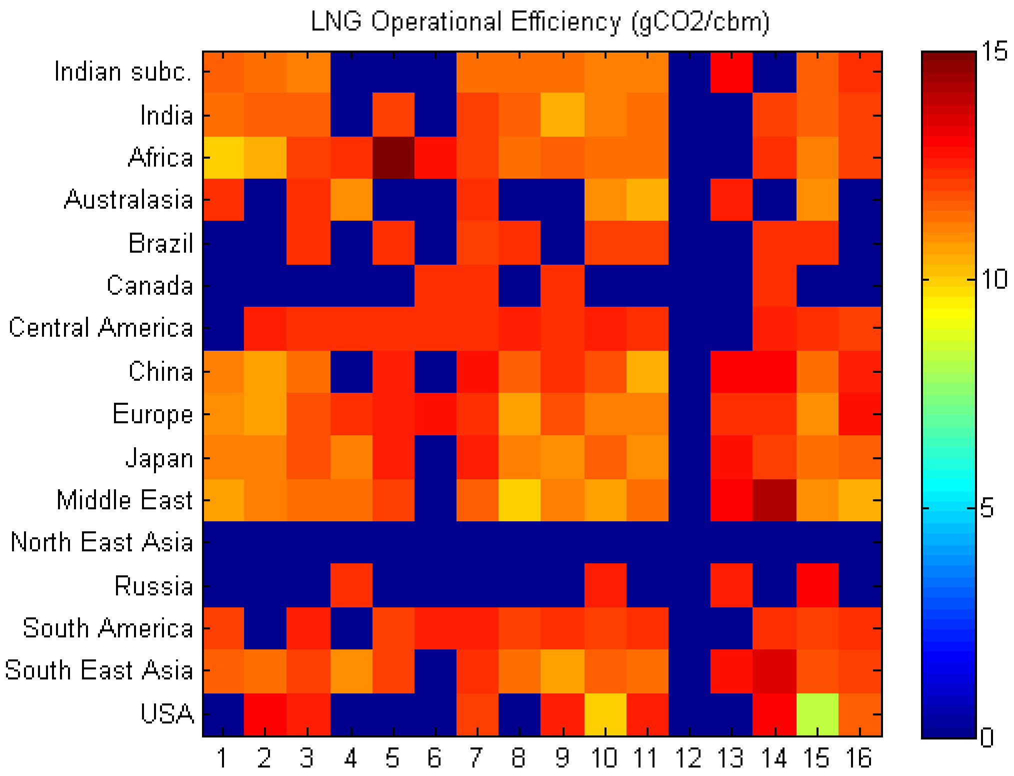
LNG Operational Efficiency (gCO2/cbm)
Indian subc.
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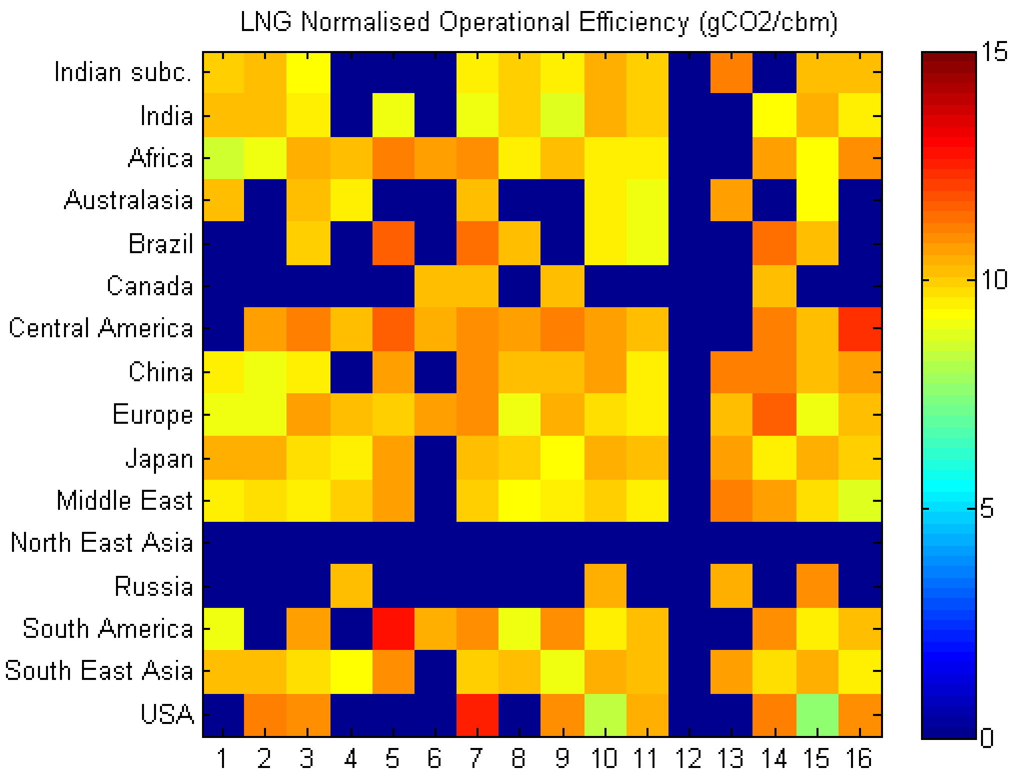
LNG Normalised Operational Efficiency (gCO2/cbm)
Indian subc.
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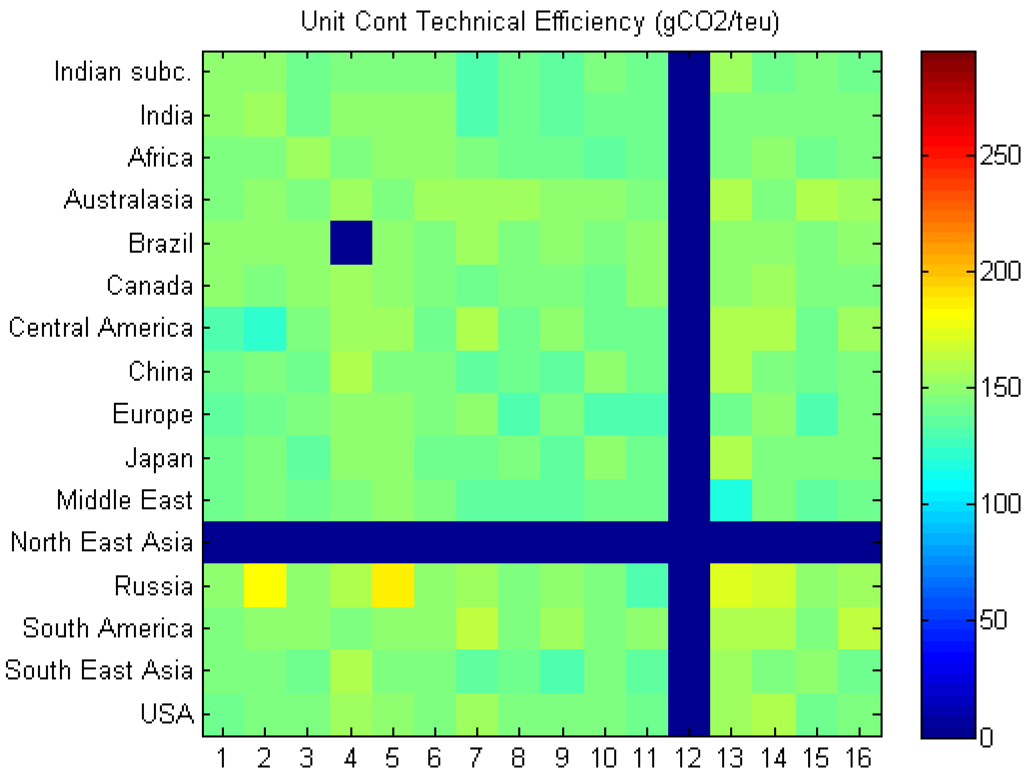

Unit Cont Technical Efficiency (gCO2/teu)
Indian subc.
India
Africa
Australasia
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South East Asia
USA
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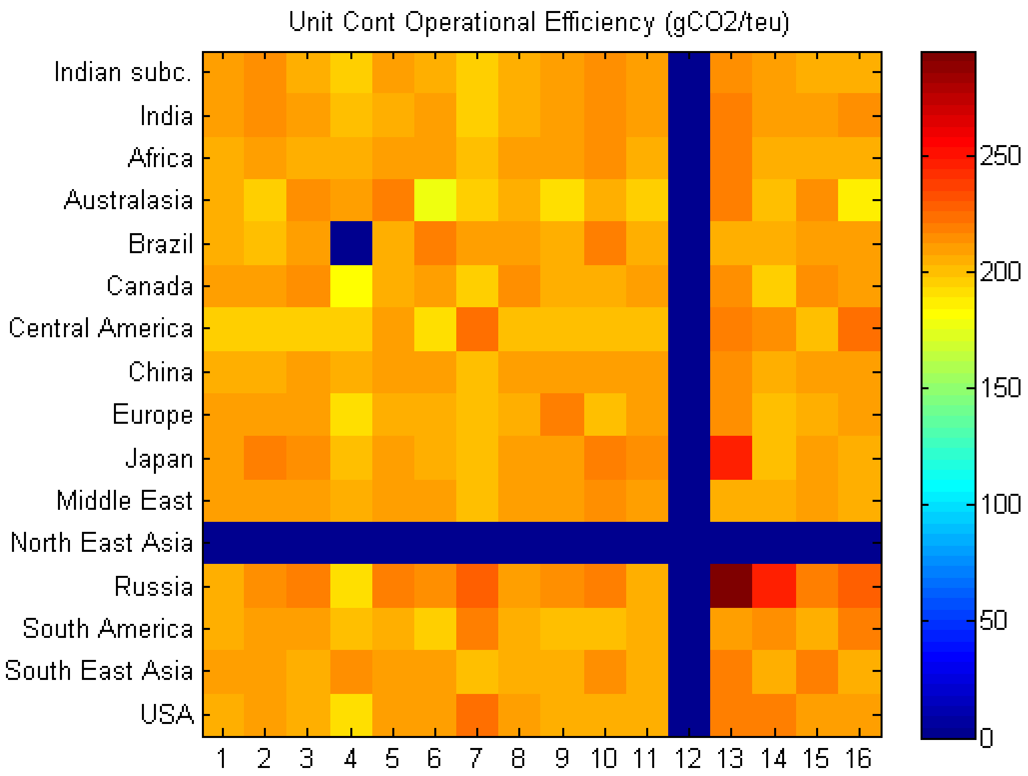

Unit Cont Operational Efficiency (gCO2/teu)
Indian subc.
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USA
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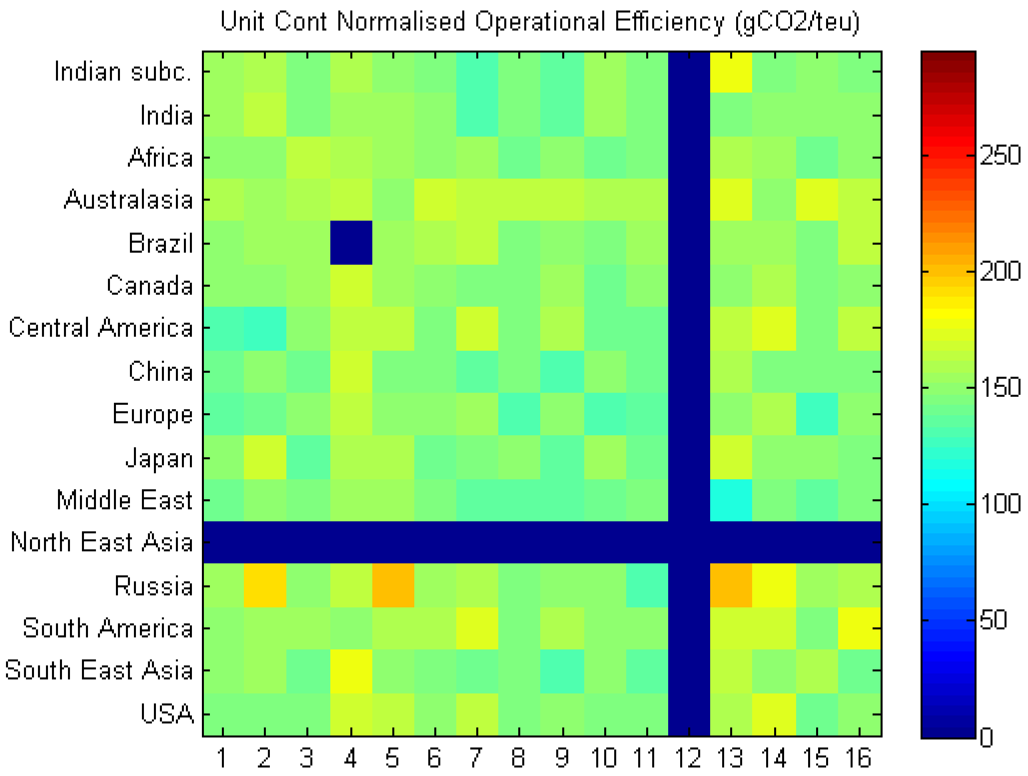
Unit Cont Normalised Operational Efficiency (gCO2/teu)
Indian subc.
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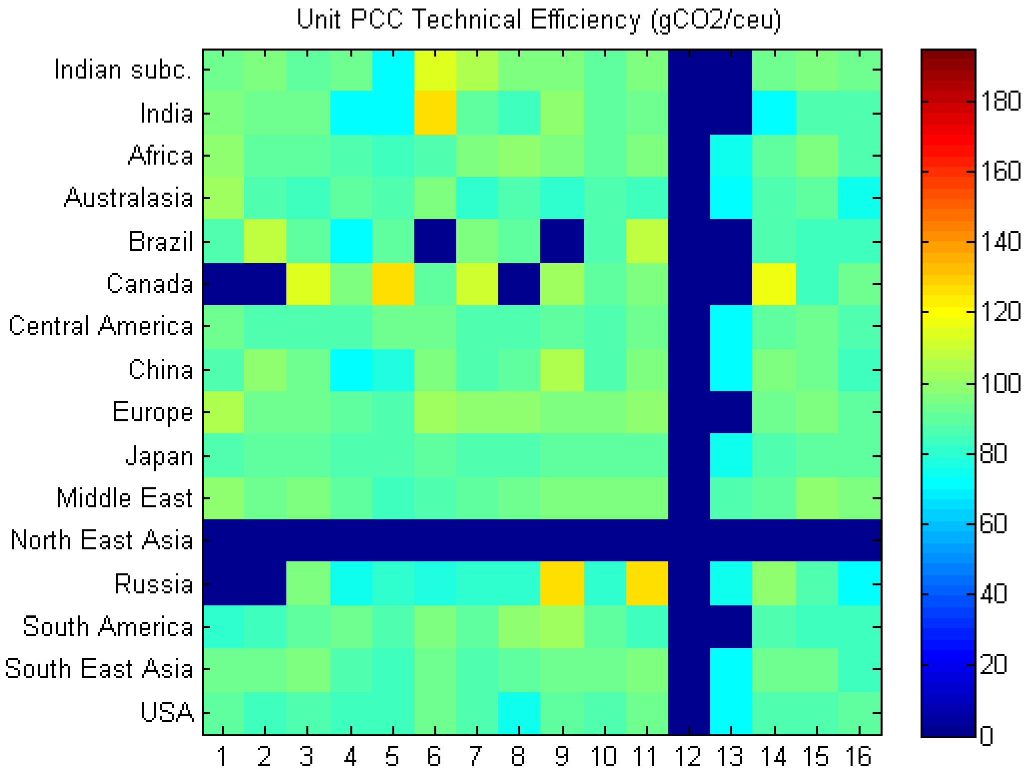
Unit PCC Technical Efficiency (gCO2/ceu)
Indian subc.
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South America
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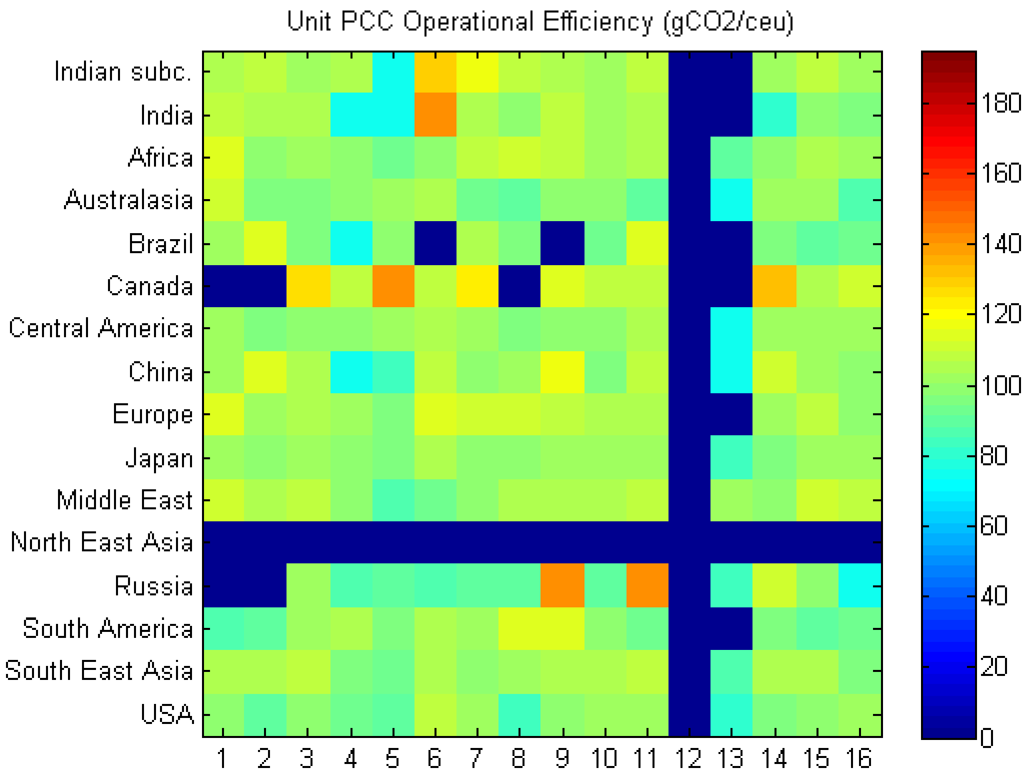
Unit PCC Operational Efficiency (gCO2/ceu)
Indian subc.
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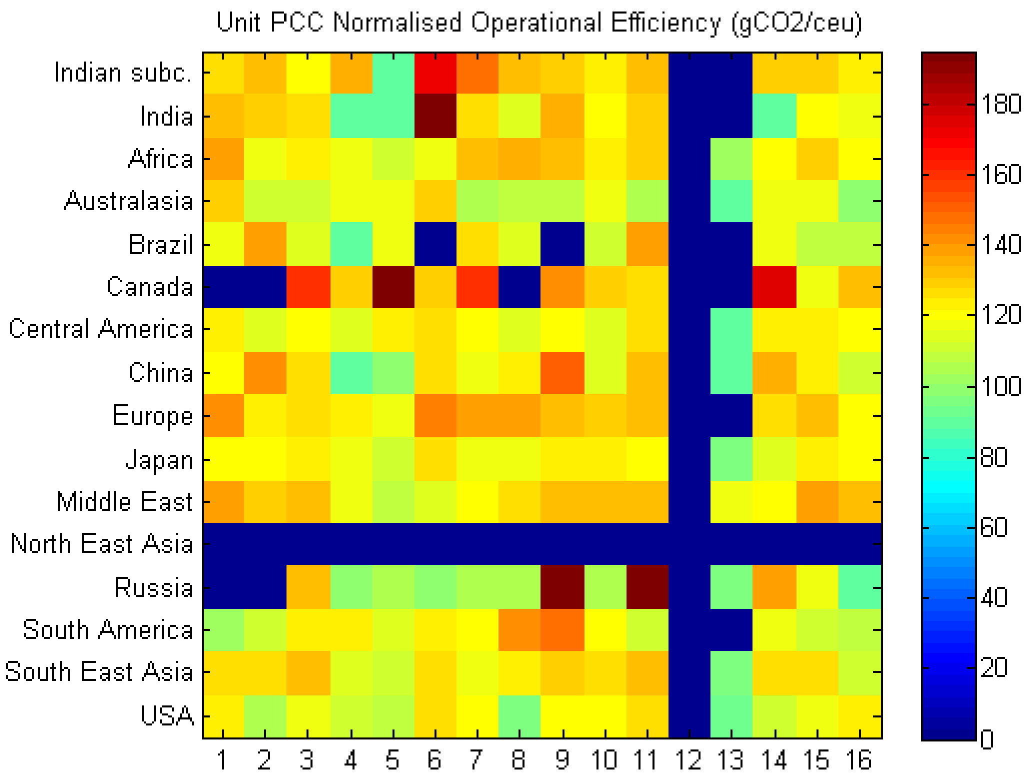
Unit PCC Normalised Operational Efficiency (gCO2/ceu)
Indian subc.
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