Understanding the Energy Efficiency Operational Indicator:

An empirical analysis of ships from the Royal Belgian Shipowners' Association

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Understanding the Energy Efficiency Operational Indicator: an empirical analysis of ships from the Belgian Shipowners' Association

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Abstract

This paper explores the determinants of the Energy Efficiency Operational Indicator (EEOI[1]) by decomposing the indicator into sub-indices that reflect the technical characteristics and logistics of ships. We examine these sub-indices by first constructing a model that mathematically describes the components that comprise the EEOI. A panel dataset of ships' fuel consumption parameters and transport work is used to estimate these sub-indices. We find that there is a relationship between technical efficiency (EEDI) and EEOI across different ship sizes, but there is a wide dispersion of EEOI values within a ship size class. This can be explained by the variation in logistics factors, with little evidence of correlation between EEOI and any one logistics factor. For all of the types and sizes considered, variations in EEOI can be explained only by considering contributions from a combination of the logistics factors.

Keywords: Energy Efficiency Operational Indicator (EEOI), shipping, MRV, energy efficiency, carbon intensity

1. 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 detailed energy efficiency characteristics of the existing ship fleet have been met with criticism. For example, among the objections to previous analyses, studies have had issues related to unrepresentative input data, limited real-world operational data to reflect actual operational conditions, and incomplete quantification of technical versus operational efficiency characteristics. Many of these objections are well-founded, due to the generally poor quality of data describing the existing fleet of ships and the wide-ranging parameters that influence the performance and therefore efficiency of ships in their day-to-day operation (as opposed to an artificial 'calm' sea or acceptance trial).

Increasing the motivation for a more comprehensive analysis of energy efficiency is the ongoing debate about how shipping's air pollution and greenhouse gas emissions should

[1] The EEOI is the total carbon emissions in a given time period per unit of revenue tonne-miles. A lower EEOI means a ship is more energy efficient in its operations.

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) as a measurement of the energy efficiency of existing ships.

The EEOI, or annual fuel consumption divided by transport work, can be considered as the annual average carbon intensity of a ship in its real operating condition, taking into account actual speeds, draughts, capacity utilization, distance travelled, and the effects of hull and machinery deterioration and weather. Although the EEOI is referred to as an indicator of energy efficiency, it is technically more accurate to refer to the EEOI as a measure of carbon intensity as the units are in gCO2/t.nm. The US energy efficiency indicator is measured in joules/hour and therefore is more defensibly energy efficiency because the numerator is measured in joules of energy. Despite these differences, if the fuels are similar in carbon content then the CO2 and joules should be consistent so that carbon intensity is a proxy for energy efficiency. On the other hand, a ship that consumes LNG would differ in energy content compared to one using HFO and therefore a correction would need to be applied for the relative carbon and energy intensities of the fuel before their energy efficiency can be compared. For the rest of the report, we will refer to the EEOI as an energy efficiency indicator, except in Section 6, when the merits of carbon intensity are discussed in light of alternative indicators proposed at the IMO.

The EEOI and the data and methods associated with it were originally conceived for policy purposes, evidenced by the European Commission's proposal to require ships exceeding 5,000 GT to monitor and report their operational energy efficiency starting in 2018 on all voyages to, from, and between EU ports. In light of this potential legislation, ship owners and their associations are trying to better understand the drivers of the proposed Energy Efficiency Operational Indicator (EEOI) in order to prepare themselves for future environmental regulation. Discussions at the IMO indicate that such MRV initiatives could serve as initial phases toward eventual in-use ship fleet efficiency standards.

The collection of fuel consumption data, as required by the MRV policy, has lead to speculation about how the EEOI could be extended to other regulations or for commercial purposes. One of the commonly cited barriers in the shipping industry is the lack of sufficient information on the technical efficiency of a ship operated in real operating conditions when a ship is chartered (Rojon & Smith, 2014). Although there is publicly available data that approximates the technical efficiency of a ship when it is built, the efficiency of a ship in its designed condition at age 0 does not necessarily equal the ship's technical efficiency because the formula (EEDI) makes assumptions[2] about parameters

[2] The EEDI is measured the design speed, and the specific fuel consumption

that determine efficiency. Furthermore, as a ship ages, the specific parameters that determine its fuel consumption change over time due to a gradual deterioration of the hull's surface and fouling due to marine growth. For example, two ships which appear identical in their design characteristics can perform differently due to a difference in maintenance or retrofitting which would not be observed in the EEDI.

Although ship owners measure fuel consumption and cargo information, it is not known to what extent this data is used for improving operations. 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, including work undertaken already by the RBSA. In 2009, the RBSA collaborated with the Flemish Institute for Technological Research (VITO) to create a study on the Energy Efficiency Operational Indicator. The purpose of the study was to identify the gaps in the interim guidelines (MEPC/Circ. 471) developed within the IMO to determine the EEOI. The index was tested on 41 ships under the Belgian flag. The results of the study were presented to the IMO (GHG-WG 2/3/1) through the Belgian maritime administration in 2009. As the EEOI is an aggregate number, it is difficult to disentangle the influence of these confounding factors. Therefore a database was established in order to determine the contribution of factors such as ballast voyages and port time to the index due for each individual ship. The main message of the study was that breaking down the basic formula leads to better transparency of the causes of variation of the EEOI and may help to improve operational and environmental performance for ship operators.

This paper further studies the drivers of the indicator by carrying out a series of analyses on a set of owner-reported data, similar to the data that will be used to comply with the future legislation. As well as calculating the carbon emissions and values of EEOI for ships in the RBSA's owner's fleets, the study will decompose the EEOI into sub-indices (technical and logistics factors) and in terms of the contribution of the laden, ballast and port segments to EEOI for 94 ships in the bulk carrier, chemical tanker, container, liquefied petroleum gas and oil tanker sectors over the period 2008-2014, in which there was variation in market factors such as fuel prices and freight rates. These market factors have influenced the way in which the ships were operated, including the speed and the employment opportunities available and undoubtedly has cascaded into changes in the EEOI over time. A number of other operational energy efficiency indicators have been proposed by member states of the IMO. In light of these other efficiency indicators, the analysis will also compare the EEOI to alternative energy efficiency indicators. The experience of computing the EEOI has also not been well documented. This paper will shed light on the process and challenges of calculating the EEOI, as well as the uncertainty in the estimates calculated.

2. Expressions for technical and operational efficiency and the interconnection of the two types of efficiency

This section discusses the formulation of indices for efficiency, including a suggested additional indicator that represents the technical efficiency of a ship at a given point in time. A full derivation of the equations used is contained in Appendix A.1.

The annual EEOI, or annual total carbon emissions divided by transport work, can be considered as the annual average efficiency of a ship in its real operating condition, taking into account actual speeds, draughts, capacity utilization, distance travelled, and the effects of hull and machinery deterioration and weather.

A metric used for quantifying the operational efficiency of shipping is the EEOI (IMO MEPC.1/Circ.684, 2009):

(1)

$$\boxed{EEOI = \frac{\sum_i \sum_j F_{ij} C_j^F}{\sum_i m_i^L D_i^L}}$$

where:

- i = the voyage
- j = the fuel type
- F_{ij} = the amount of fuel consumed for the voyage i and fuel type j
- C_j^F = the carbon factor for fuel type j
- m_i^L = cargo mass of voyage i
- D_i^L = distance travelled in loaded voyage i

Analogous to the use of the EEOI to estimate the operational efficiency of a ship, the technical efficiency of a ship or energy efficiency technical indicator (*EETI*) can be defined as the energy efficiency (gCO_2/tonne-nautical mile) of a ship in a reference operating condition (speed and draught):

(2)

$$\boxed{EETI = \frac{C^F F_d^{ref}}{v_{ref} DWT 24}}$$

where:

- C^F = the average carbon factor of the fuel used

- F_d^{ref} = the daily fuel consumption at a reference speed and draught
- v_{ref}= the reference speed[3]
- DWT = the deadweight tonnage of a ship

The *EETI* is a ship's estimated technical efficiency in real operating conditions at a specific point in time, whereas the *EEDI* (gCO_2/t-nm), is the ship's design technical efficiency at the start of its life and under specific EEDI assessment conditions. Differences between a ship's EEDI and EETI could arise due to fouling, modification of technical specifications (such as retrofitting) or because the EEDI trial performance cannot be recreated in real operating conditions.

The EEOI and the EETI, when estimated from measurements of a ship's daily fuel consumption and activity, are inextricably linked because they have overlaps in their input data. The mathematical derivation of the two formulae can be used to show how EEOI can be decomposed into a number of technical and logistics factors, one of which is the ship's EETI. This is useful as a means to break EEOI down into a series of drivers that each influence the overall value. As the only 'technical factor', the EETI indicates the technical efficiency contribution to the EEOI quantification, while three logistics factors indicate the contribution of the specifics determining the ship's commercial operation (speed and utilization).

(3)

$$EETI \sim EEOI \, \frac{m_t^L}{DWT} \frac{d_t^L}{(d_t^L + d_t^B)} \frac{v_{ht}^L}{\left(\left(\sum_{i=1}^{p} \left(\frac{v_{ht}^{op,i}}{v_{ref}}\right)^n \left(\frac{T^{op,i}}{T^{ref}}\right)^{2/3}\right)/p\right) v_{ref}}$$

where:

- $T^{op,i}$ = the operating draught at passage or passage segment *i*
- T^{ref} = the reference draught
- $v_{ht}^{op,i}$ = the average operating speed for a passage or passage segment *i* (nautical miles/hour).
- *p* = total number of passages or passage segments
- d_t^L= the days a ship is sailing loaded during period *t*
- d_t^B= the days a ship is sailing ballast during period *t*
- d_t^P= the days a ship is in port during period *t*
- m_t^L = the average cargo mass during period *t*
- v_{ht}^l = the average loaded speed per hour *h* in time period *t*

[3] The reference speed may or may not equal the design speed.

Equations (3) shows that it is possible to formulate EEOI or EETI in terms of one another if a number of extra details about speed, cargo and the loaded/ballast voyages are known. These are, as represented in the right hand side of (3):

$\frac{m_t^L}{DWT}$= the average payload utilization

$\frac{d_t^L}{(d_t^L+d_t^B)}$= the allocative utilization or ratio of laden days to total operating days

$\frac{v_{ht}^L}{\left(\left(\sum_{i=1}^{p}\left(\frac{v_{ht}^{op,i}}{v_{ref}}\right)^n\left(\frac{T^{op,i}}{T^{ref}}\right)^{2/3}\right)/p\right)v_{ref}}$= the speed and draught factor

The average payload utilization is always less than 1, the allocative utilization is also always less than one, and the speed factor could be greater than, equal to, or less than 1. Although commonly, especially recently, it will be greater than 1 – demonstrating slow steaming.

In operation, a ship with a higher *EETI* value can offset this lower efficiency disadvantage by obtaining a higher average payload utilization, allocative utilization, speed factor, or some combination of these factors. As expected, this shows that the *EEOI* is highly influenced by how a ship is commercially operated, and only partially influenced by the technical efficiency of the ship. The derivation in this section of EETI and the connection between EEOI and EETI is used both to illustrate this point, and to introduce the concept of EETI which is calculated explicitly using the data in this study, with results presented in Section 6.

3. Description of the data

3.1 Ships covered in the dataset

Data for this paper comes from five companies who are members of the Royal Belgian Shipowners' Association (RBSA). RBSA has provided spreadsheets of data supplied by the ship owners. Where possible, other documentation such as noon report or arrival and departure report has also be provided by RBSA.

Table 1 describes the types of ships for which we are able to analyze the data, as for some ships the data provided is not consistent or complete so some ships had to be excluded. A filter has been applied that excluded every year of a ship for which more than 30% of voyages has not complete information. The majority of the ships analyzed are bulk carriers, accounting for 42% of the sample, followed by oil tankers (25%) and liquefied petroleum gas carriers (23%).

Table 1 Ships sample

Ship type/size	IMO size range	IMO size category	Original number of ships	Ships analyzed	% ships excluded
Bulk carrier	**(dwt)**		**58**	**43**	**26%**
	(10000-34999)	2		15	
	(35000-59999)	3		4	
	(60000-99999)	4		1	
	(100000-199999)	5		20	
	(200000-+)	6		3	
Chemical tanker	**(dwt)**		**2**	**2**	**0%**
	(10000-19999)	3		2	
Container	**(TEU)**		**10**	**10**	**0%**
	(1000-1999)	2		3	
	(2000-2999)	3		7	
Liquefied petroleum gas	**(cbm)**		**24**	**17**	**29%**
	(0-49999)	1		15	
	(50000-199999)	2		2	
Oil tanker	**(dwt)**		**30**	**22**	**27%**
	(120000-199999)	7		17	
	(200000-+)	8		5	
Grand Total				**94**	

The data is an unbalanced panel of individual ships over time because not all ships are reported in each year over the period 2008-2014.

Table 2 shows the representation of ships by year in the sample. There is data for bulk carriers in years 2008-2013, while data was not available for several years for each of the other ship types in the dataset.

Table 2 Number of ships in the data sample by year

Ship type	2008	2009	2010	2011	2012	2013	2014
Bulk carrier	11	13	21	33	41	37	0
Chemical tanker	0	0	0	2	2	0	0
Container	0	0	6	9	8	9	0
LPG	4	10	12	12	4	0	0
Oil tanker	0	0	4	12	7	9	13

In order to obtain additional information on each ship's technical specifications (deadweight, age, installed power, Specific Fuel Oil Consumption and reference speed) data was taken from Clarkson Research Services, by matching the IMO number provided by each company's data. This information allowed us to estimate the ships' Energy Efficiency Design Index (EEDI) using the formula provided in Germanischer Lloyd SE (2013). The estimate is similar to an EIV (Estimated Index Value) used in the calculation of EEDI baselines, but uses SFOC as reported in Clarksons. It is an estimate because there is no validation of the calculation's input data.

Table 3 provides the summary statistics of the average technical specifications. There is a strong relationship between the technical efficiency of a ship, represented by the EEDI, and the size of the ship (in deadweight tonnes or DWT). For all ship types, EEDI is decreasing with size, meaning that the energy efficiency is higher.

Table 3 Average technical specifications. Source: Clarkson Research

Ship type /IMO size	**Size range**	**No. of ships**	**Mean age**	**Mean DWT**	**Mean design speed**	**Mean EEDI**
Bulk carrier	**(dwt)**	**43**	**6**	**109,372**	**14.48**	**5.44**
2	(10000-34999)	15	4	33368.93	14.03	9.15
3	(35000-59999)	4	7	54997.5	14.73	5.53
4	(60000-99999)	1	8	76588	14.40	3.98
5	(100000-199999)	20	8	176760.7	14.78	3.11
6	(200000-+)	3	3	205143.3	-	-

Chemical tanker	**(dwt)**	**2**	**13**	**14582.5**	**13**	**16.309**
3	(10000-19999)	2	13	14582.5	13.00	16.31
Container	**(TEU)**	**10**	**8**	**25141.8**	**20.52**	**14.88**
2	(1000-1999)	3	10	16701.67	19.53	16.37
3	(2000-2999)	7	6	33582	21.50	13.39
LPG	**(cbm)**	**17**	**15**	**35952.8**	**15.53**	**12.66**
1	(0-49999)	15	10	12718	14.82	18.11
2	(50000-199999)	2	21	59187.5	16.25	7.21
Oil tanker	**(dwt)**	**22**	**11**	**230798**	**15.48**	**2.73**
7	(120000-199999)	17	12	154202.8	14.98	3.29
8	(200000-+)	5	10	307393.6	15.98	2.16
Grand Total		**94**	**11**	**82,169**	**16**	**10**

3.2 Data used to estimate the EEOI and subindices

We calculate the annual EEOI using detailed data on the fuel consumption of a ship and revenue tonne-miles per sea passage. As also identified in the VITO study (VITO, 2009), the format for reporting this detail varies by company; a sea passage could be defined as starting from one port and ending in another port or starting at sea and ending at sea. In some cases, the sea passage is not specified. In this case, we derive the passage from two temporal consecutive records.

While each company has its own internal procedure and format for collecting this data, each company collects data on fuel consumption separately from cargo information. Therefore, the data had to be merged together. An overview of the procedure and data checking is described in Appendix A.2. Each company's data was checked for consistency of the parameters required for the calculation (distance sailed, speed, hours of operation) and processed to obtain a standardized dataset that was uniform for all ships. This involved extensive filtering, cleaning and checking of the data.

There are a number of missing fields in the unprocessed data. We therefore estimate speed, distance or hours when at least two of the variables are provided. When all variables are known, we verified the hours of service using the distance/speed relationship to ensure that the triple is consistent. We also checked for outliers, described in Appendix A.2.

There are a number of cases in which we could not calculate the EEOI for a specific voyage. For example, if the fuel consumption per laden voyage is known, but the distance for these voyages is missing and speed is nonzero, then we excluded this voyage from the analysis to avoid overestimating the numerator without a corresponding tonne-miles statistic. These exclusion cases are described in Appendix A.2. Finally, the annual EEOI was calculated by aggregating the sea passages for which we have both valid fuel consumption and revenue tonne-miles data.

4. EEOI results

4.1 Aggregated annual EEOI for all ships (grouped by ship type and size)

We calculated annual EEOI for all ships in the database for each year (2008-2012) for which there was valid data. Figure 1 shows an overview of the annual EEOI in relation with the DWT for each ship type[4].

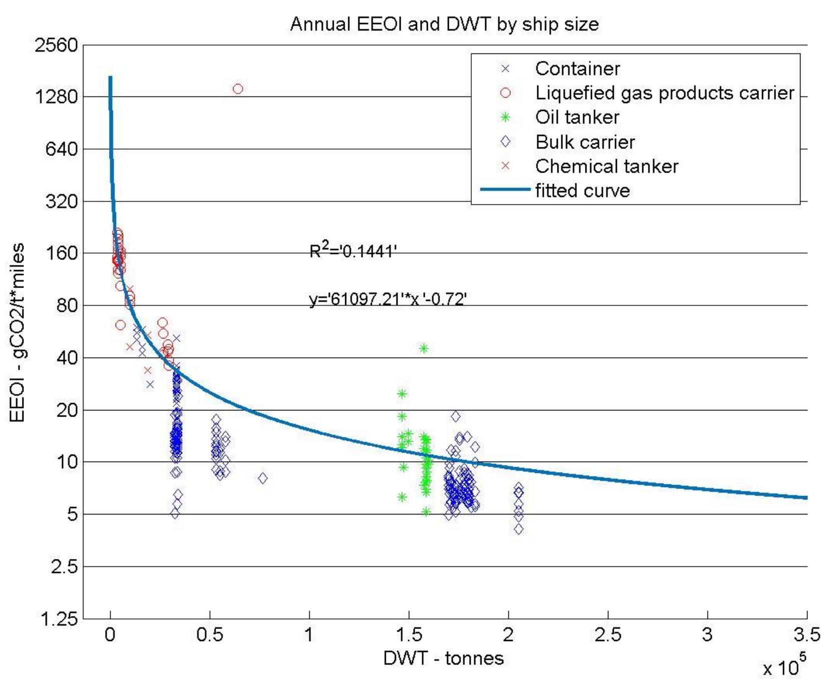


Figure 1 Annual EEOI and DWT grouped by ship type

The variation in annual EEOI for each ship type varies. For example, for large bulk carriers the annual EEOI varies between 5 and 20 gCO_2/t.km, while the variation in the EEOI for smaller bulk carriers is wider, between 5 and 40 gCO_2/t.km. The results are shown in Figure 1 for each ship grouped by ship type. Note that the same ship will appear multiple times if data is available on the ship for multiple years. It can be seen that the relationship between size (measured in DWT) and operational efficiency is not obvious given the wide dispersion of values for ships of a similar size (a higher EEOI means the ship is less efficient).

Figure 1 also shows there are several notable outliers. Generally, high EEOI values are often the result of a very low allocative utilization[5] and payload utilization. For example, the highest annual EEOI value (1428 gCO_2/t.km) was from the LPG ship type, which for the size class of 50,000-199,999, had an allocative utilization of about 5% and a payload utilization is about 22% in 2010. This is low compared to even the lower size class of LPG; in 2010, the allocative utilization for the 0-50,000 class size was 47% and had a payload utilization rate of 41%. The outlier values are affected by the availability of the data in that year. For example, the data with the highest EEOI values is only available for about 29 days in the year.

As the technical efficiency (EEDI) improves with size due to economies of scale, we also present the EEOI for each ship type and size (by IMO size categorization). Figure 2 shows the annual EEOI by DWT grouped by size for the bulk carriers in the sample. A non-linear curve fitted to the data shows that when outliers are excluded, DWT explains 46% of the total variation in the EEOI, as defined by the coefficient of determination or R^2. The R^2 produced from the model $EEOI = 815 DWT^{-.39} + \epsilon$ is an estimate of how much variation in EEOI is explained by DWT in the data sample and can be used as a measure of the goodness of fit to the data. A higher R^2 indicates a better fit, with 100% representing the regression line that perfectly fits the data. As predicted, DWT does not explain even half of the variation in the EEOI. This highlights the importance of examining the operational or logistics factors driving variation in EEOI values.

[5] Allocative utilization is the ratio of days laden to total sailing days.

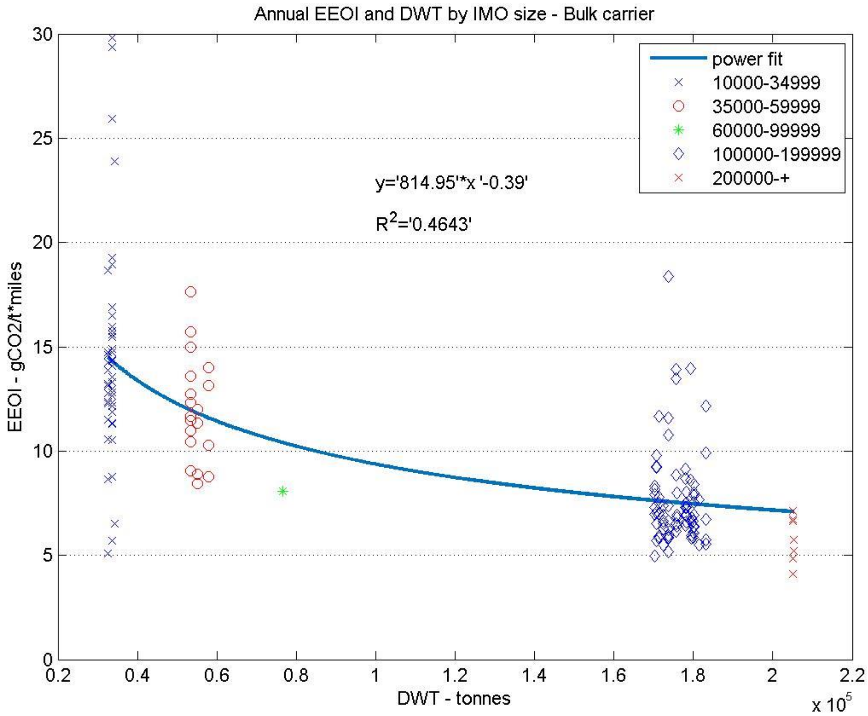


Figure 2 Annual EEOI and DWT for Bulk carrier by size

Figure 3 shows the distribution of annual EEOI for bulk carriers by size class between 2008-2013. This data was the most complete of the ship types in the study and will therefore be highlighted more in the report to explain the drivers of EEOI. The figure shows that the EEOI is monotonically decreasing in size, ranging between 5.74 for the largest size class (200,000+ DWT) and 13.42 (10,000-34,999) $gCO_2/t.nm$. Although size clearly does influence the EEOI values, the boxplots[6] show that there is variation within each size class. Section 6 will decompose the EEOI into sub-indices in order to explain the factors driving variation in these values.

[6] On each boxplot, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually. For example, the median value for carriers of 200,000+ DWT is 5.74. The mean is also plotted as a green diamond.

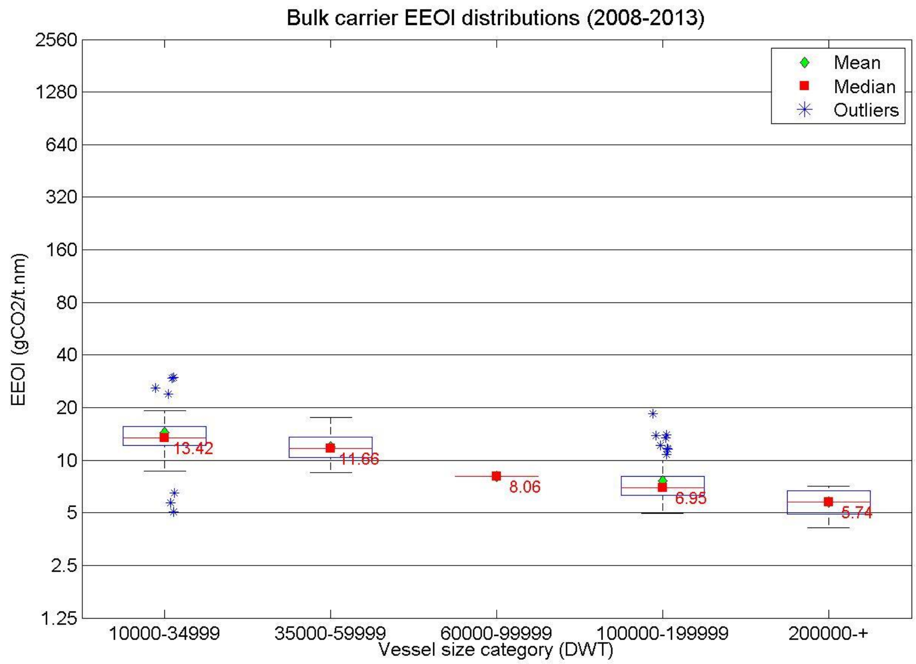


Figure 3 Annual EEOI bulk carrier by size

4.2 Variants of annual EEOI

Variants of the annual EEOI are also calculated for all ships in the database and all years, on a 'per-ship' basis. These variants include:

- The contribution of loaded, ballast and port EEOI per voyage
- The laden voyage EEOI presented as a rolling average alongside the annual EEOI

Figure 4 shows the annual, voyage, and rolling average EEOI for a bulk carrier ship of size 5 (100,000-199,999). Appendix A.5 shows the same type of plot for all ships. The laden and ballast EEOI are of similar magnitude, with the exception of 2012, when the ship incurred a higher laden EEOI than ballast EEOI, reaching a value of nearly 6 gCO_2/t.nm. This is driven by a lower payload utilization of about 42%.

Section 2 showed that the EEOI can be broken into sea EEOI, consisting of the fuel consumption when a ship is sailing divided by transport work, and port EEOI, which is the fuel consumption when a ship is in port divided by transport work. The data shows that port EEOI represents a significantly smaller share, only accounting for 7% of EEOI because a ship is relatively stationary when in port and thus consumes a small proportion of total annual fuel consumption.

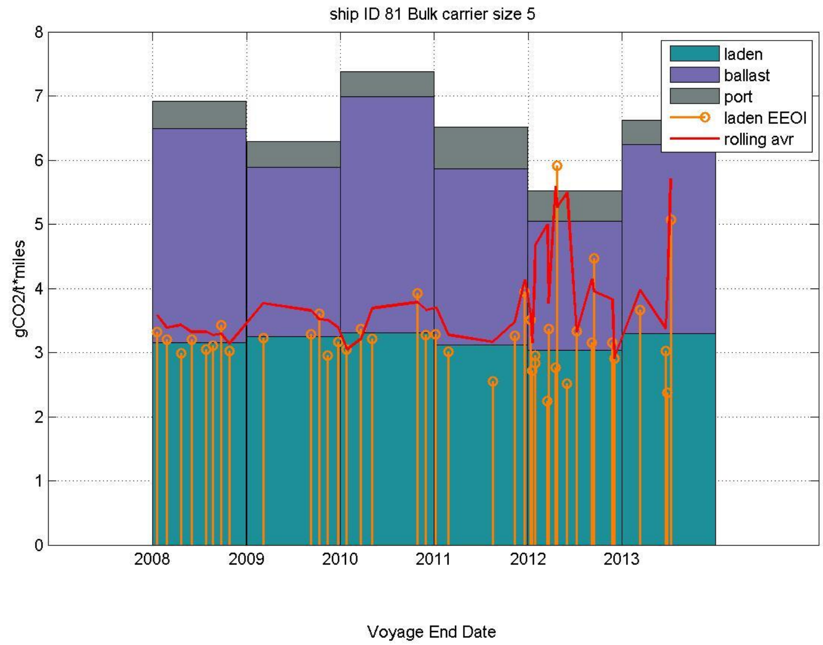


Figure 4 Variations of EEOI, voyage EEOI and rolling average for bulk carrier ship

Also presented in Figure 4 is the laden EEOI of individual voyages, which measures the fuel consumption on an individual voyage divided by the transport work performed for that voyage. The rolling average takes the average of 3 consecutive voyages. These numbers can be volatile, especially notable in 2012. The points which show high increases in the laden EEOI can be explained by a low cargo value compared to other observations. In particular, for the highest value of laden EEOI in 2012 (5.91 gCO_2/t.km), the payload utilization for that specific voyage is about 42%, a low value compared to an average of 91%. In addition, there are more laden voyages in 2012 which explains why the annual EEOI is lower compared to the other years.

4.3 Emissions, distance, service hours

We calculated the emissions, fuel consumption by type, distance travelled, and service hours per ship. Figure 5 illustrates the CO_2 emissions, fuel consumption, distance travelled, and hours of service for the same bulk carrier represented in Figure 4. Appendix B provides a similar plot for all ships. This ship has sufficient data coverage, as seen by the minimal “out” area or data that was excluded from the EEOI calculation. The average annual proportion of emissions in laden is 49%, compared to 44% for ballast, and 7% in port. HFO contributes the most to fuel consumption compared to MDO, averaging annually 94% over 2008-2013 period.

The hours spent in port are much higher than the emissions in port because of the low amount of fuel consumption burned in port due to their relatively stationary position. A similar result can be seen for the other ships in the sample[7], which justifies our focus on EEOI at sea as the main contributor to total carbon emissions.

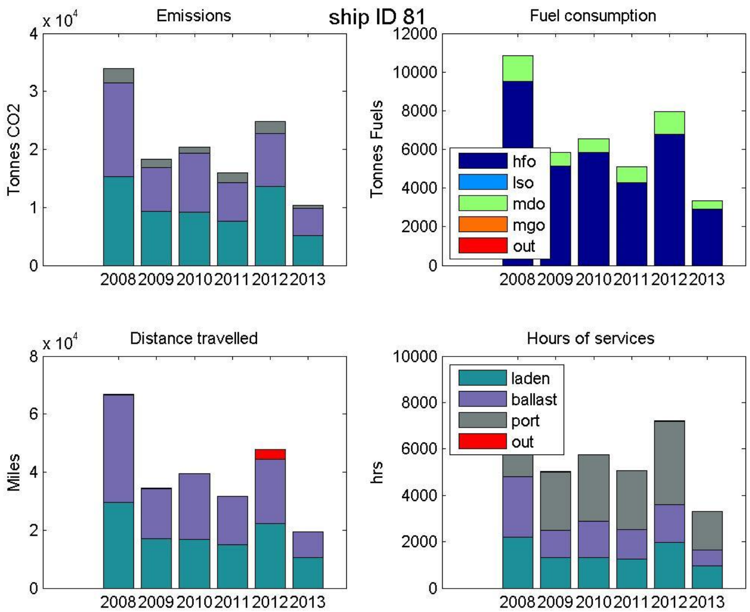


Figure 5 Emissions, fuel consumptions, distance travelled and hours of services for ship ID 81

7 The annual average proportion of port emissions for ships in the sample is about 9%

4.5 Tabular results per year for all ship types and sizes

Table 4 Results year 2008

Type	Size	Size sample	Mean dwt	Mean days at sea	Mean at sea speed	EEOI (gCO2/t.nm)			Median allocative utilization	Median payload utilization	Mean transport work per ship
			(tonnes)		(knots)	Median	Lower quartile	Upper quartile	(%)	(%)	billion t.nm
Bulk carrier	35000-59999	1	53505	118	13.75	11.66	11.66	11.66	57.4	86.4	1.04
Bulk carrier	60000-99999	1	76588	98	19.30	8.06	8.06	8.06	43.4	87.6	1.32
Bulk carrier	100000-199999	9	174843	118	14.21	8.30	7.25	9.86	41.0	95.4	2.68
LPG	0-49999	4	18135	112	14.63	65.41	44.20	107.76	41.9	62.9	0.19

Table 5 Results year 2009

Type	Size	Size sample	Mean dwt	Mean days at sea	Mean at sea speed	EEOI (gCO2/t.nm)			Median allocative utilization	Median payload utilization	Mean transport work per ship
			(tonnes)		(knots)	Median	Lower quartile	Upper quartile	(%)	(%)	billion t.nm
Bulk carrier	35000-59999	2	53459	75	13.65	11.644	10.9804	12.3068	58.16	92.13	.70
Bulk carrier	100000-199999	11	175625	89	14.02	7.50	6.58	8.11	49.00	97.50	2.28
LPG	0-49999	10	11910	91	13.95	115.58	63.98	144.38	46.44	43.81	0.08

Table 6 Results year 2010

Type	Size	Sample size	Mean dwt	Mean days at sea	Mean at sea speed	EEOI (gCO2/t.nm)			Median allocative utilization	Median payload utilization	Mean transport work per ship
			(tonnes)		(knots)	Median	Lower quartile	Upper quartile	(%)	(%)	billion t.nm
Bulk carrier	10000-34999	3	33353	44	13.45	14.36	13.50	18.04	71.6	93.2	0.3
Bulk carrier	35000-59999	4	54998	86	13.71	13.36	10.59	14.85	55.3	91.3	0.8
Bulk carrier	100000-199999	13	175649	112	14.22	7.65	7.12	8.59	47.3	93.1	2.6
Bulk carrier	200000-+	1	205097	88	14.36	7.12	7.12	7.12	49.5	86.6	2.7
Container	2000-2999	6	33607	235	17.47	30.22	27.04	33.73	100.0	70.0	2.3
LPG	0-49999	11	9157	115	13.65	146.57	96.42	157.40	47.0	40.6	0.1
LPG	50000-199999	1	64220	29	12.94	1428.24	1428.24	1428.24	5.8	22.7	0.0
Oil tanker	120000-199999	3	154784	81	11.22	11.99	10.32	16.71	52.6	82.9	1.5
Oil tanker	200000-+	1	315981	215	2.70				0.0		0.0

Table 7 Results year 2011

Type	Size	Sample size	Mean dwt	Mean days at sea	Mean at sea speed	EEOI (gCO2/t.nm)			Median allocative utilization	Median payload utilization	Mean transport work per ship
			(tonnes)		(knots)	Median	Lower quartile	Upper quartile	(%)	(%)	billion t.nm
Bulk carrier	10000-34999	13	33355	74	13.24	14.22	12.93	16.64	79.5	77.6	0.5
Bulk carrier	35000-59999	4	54998	135	13.33	12.80	11.14	15.62	57.8	81.1	1.1
Bulk carrier	100000-199999	15	176128	105	12.81	6.63	6.17	7.43	48.4	95.4	2.5
Bulk carrier	200000-+	1	205097	230	13.05	6.63	6.63	6.63	49.8	86.4	6.4
Chemical tanker	10000-19999	2	14583	160	10.07	50.07	46.16	53.98	79.0	51.2	0.2
Container	1000-1999	2	15016	150	15.00	56.99	55.86	58.12	100.0	70.0	0.6
Container	2000-2999	7	33582	249	16.97	29.44	26.46	32.64	100.0	70.0	2.4
LPG	0-49999	11	9134	120	13.28	145.47	98.92	160.74	47.0	41.5	0.1
LPG	50000-199999	1	64220	3	11.74				0.0		NaN
Oil tanker	120000-199999	11	155606	141	11.68	10.27	9.24	13.10	41.5	84.3	2.1
Oil tanker	200000-+	1	298969	91	10.02	413.48	413.48	413.48	1.2	39.7	0.0

Table 8 Results year 2012

Type	Size	Sample size	Mean dwt	Mean days at sea	Mean at sea speed	EEOI (gCO2/t.nm)			Median allocative utilization	Median payload utilization	Mean transport work per ship
			(tonnes)		(knots)	Median	Lower quartile	Upper quartile	(%)	(%)	billion t.nm
Bulk carrier	10000-34999	15	33369	119	12.38	12.33	10.80	14.86	79.5	72.5	0.7
Bulk carrier	35000-59999	4	54998	130	13.01	12.32	11.41	14.06	75.1	69.6	1.1
Bulk carrier	100000-199999	19	176692	112	12.51	6.44	5.84	7.46	47.3	93.9	2.1
Bulk carrier	200000-+	3	205143	122	11.66	5.74	4.51	6.46	51.8	97.7	3.4
Chemical tanker	10000-19999	2	14583	120	8.95	66.83	33.68	99.99	70.2	58.5	0.2
Container	1000-1999	3	16702	128	15.19	46.21	32.64	49.67	100.0	70.0	0.5
Container	2000-29999	5	33641	231	15.60	23.10	21.37	31.14	100.0	70.0	2.0
LPG	0-49999	3	12044	1	12.98	61.66	61.66	61.66	0.0	47.0	0.0
LPG	50000-199999	1	54155	3	15.67				0.0		NaN
Oil tanker	120000-199999	7	155693	141	11.84	8.22	7.72	14.46	41.9	83.4	2.0

Table 9 Results year 2013

Type	Size	Sample size	Mean dwt	Mean days at sea	Mean at sea speed	EEOI (gCO2/t.nm)			Median allocative utilization	Median payload utilization	Mean transport work per ship
			(tonnes)		(knots)	Median	Lower quartile	Upper quartile	(%)	(%)	billion t.nm
Bulk carrier	10000-34999	15	33369	66	11.59	13.15	11.59	16.06	72.6	81.1	0.4
Bulk carrier	35000-59999	4	54998	74	11.78	8.97	8.83	9.75	80.3	76.2	0.7
Bulk carrier	100000-199999	16	176248	82	11.95	6.62	5.86	7.23	42.9	93.3	1.6
Bulk carrier	200000-+	2	205167	152	11.06	5.03	4.84	5.21	46.4	97.8	3.8
Container	1000-1999	2	15016	86	14.07	51.02	42.35	59.69	100.0	70.0	0.3
Container	20000-2999	7	33582	139	15.76	25.94	24.15	27.66	100.0	70.0	1.2
Oil tanker	120000-199999	9	155562	114	10.29	11.53	8.48	12.77	43.1	77.2	1.1

Table 10 Results year 2014

Type	Size	Sample size	Mean dwt	Mean days at sea	Mean at sea speed	EEOI (gCO2/t.nm)			Median allocative utilization	Median payload utilization	Mean transport work per ship
			(tonnes)		(knots)	Median	Lower quartile	Upper quartile	(%)	(%)	billion t.nm
Oil tanker	120000-199999	10	154063	9	11	6.27	5.43	35.66	0	89.97	0.10
Oil tanker	200000-+	3	307339	6	10				0		0.00

5. Comparison studies analysis

To prepare for the imminent EU MRV legislation, a number of studies have been undertaken to measure operational energy efficiency using ship owner or vessel tracking data. In this section, we compare our results to the following studies that had comparable ship types[8]:

- Marin, 2014: Towards a realistic CO2-MRV model for merchant shipping. MRV study performed for the Dutch merchant fleet
- Intertanko, 2013: Report from the ISTEC/Environmental committee joint working group on MRV (JWG/MRV).
- Kristensen, 2013: Experience with Energy Efficiency Operational Indicators (EEOI) Seen in the Light of MRV. Danish Shipowners' Association.
- MEPC 68/INF.29. (2015): Empirical comparative analysis of energy efficiency indicators for ships.
- MEPC 68/INF.24. (2015): The Existing Shipping Fleet's CO2 Efficiency.

Figure 6 shows a comparison of fuel consumption/nautical miles for a container ship as reported in Marin (2014). In 2013, this indicator decreased to approximately 40% of its 2012 value (decreasing even further into 2014). In addition, the standard deviation as a percentage of the mean is plotted. The large standard deviations indicate that the mean values have little statistical meaning (Marin, 2014) and high variability on a day-by-day basis. We compare the results of the Marin study of a single containership to our data from this study. We plot a single container (bottom-left Figure 6) and all containerships in the data sample at top of Figure 6. The data from this study for both the single containership and the average for all containerships show very little change in fuel consumption per unit distance over the period (2010 through to mid 2013), which contrasts with the Marin study's data's steady decrease. The explanation is likely to be that the ship which the Marin study is describing experienced significant changes to its technology or operation (e.g. slow steaming) between 2012 and late 2014, whereas this study's containerships did not. The standard deviation for the individual ships studied (both in the Marin study and the sample used from this study) is less than the standard deviation of the combined containership fleet's data, which implies that the variability of one ship's operation is greater than the variability across the fleet of ships in this study.

[8] In some studies, the EEOI was not calculated for the ship types in our study. In these cases, we compared our data with the metric used in the published study.

In combination, these comparisons indicate that the global fleet of a given ship type/size was not modified in the same way over the period (there is some variation from one owner/operator to another), as well as showcasing the efficacy of the fuel/dist indicator for detecting basic trends in performance.

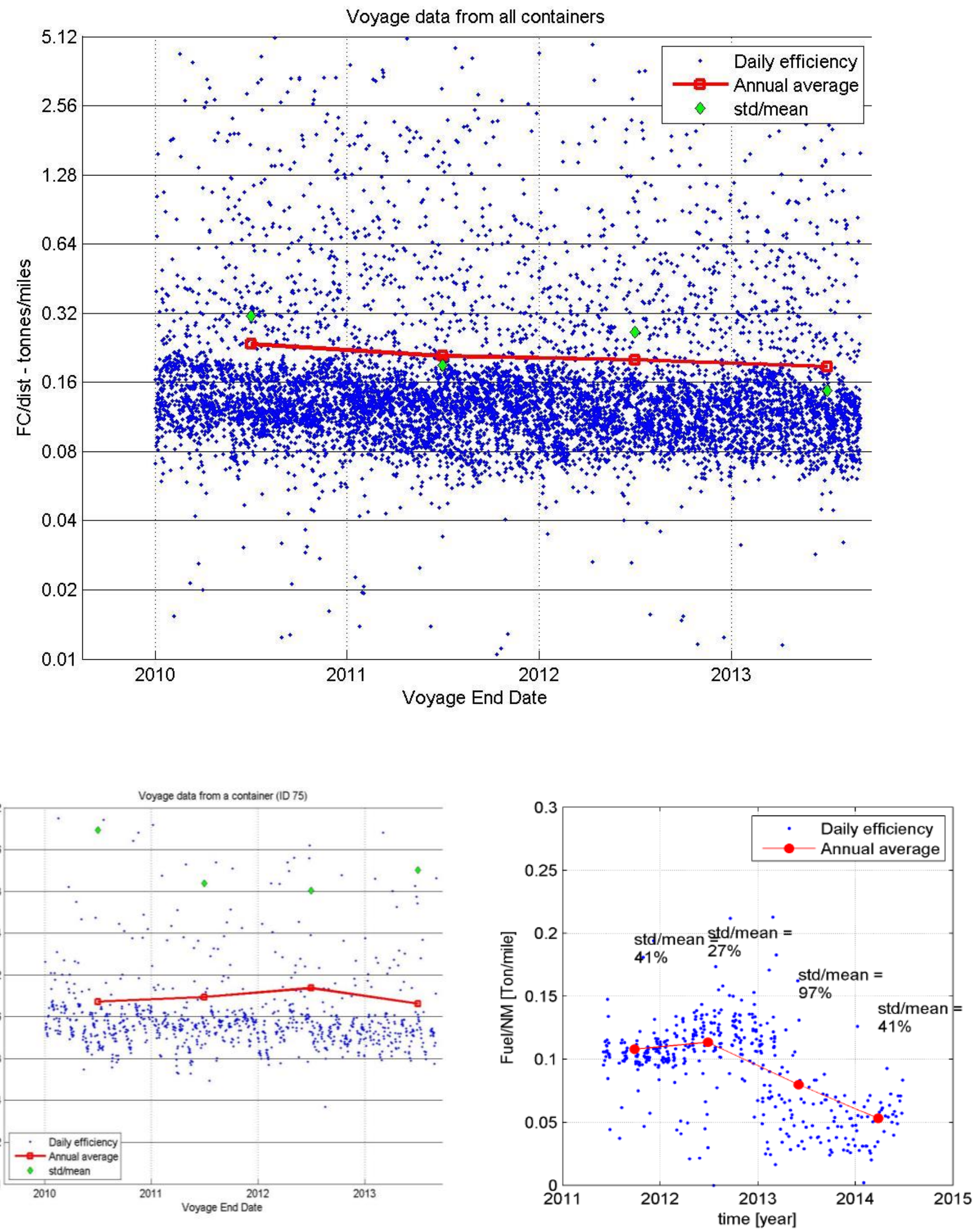
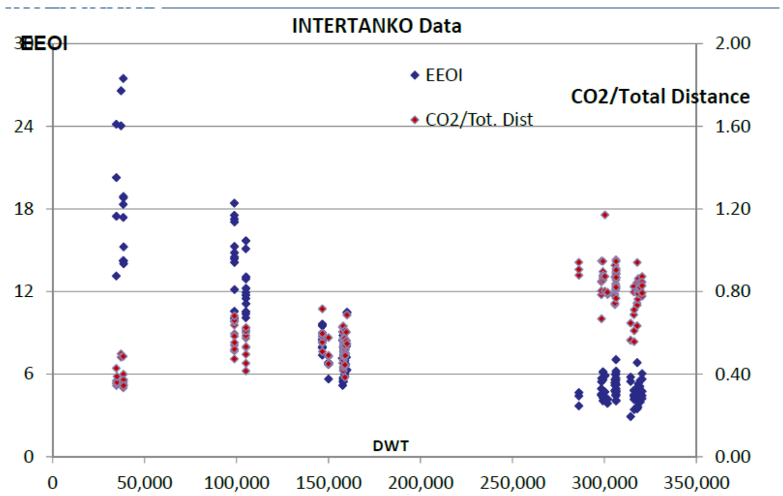


Figure 6 Comparison with MARIN study. Top: All containership data in the RBSA sample; bottom left a containership in the sample; bottom right Marin study fig.7 data from a container

Figure 7 compares the data in our study for oil tankers to data provided by Intertanko members (Intertanko, 2013). While the EEOI decreases as DWT increases, CO_2/distance increases as DWT increases.



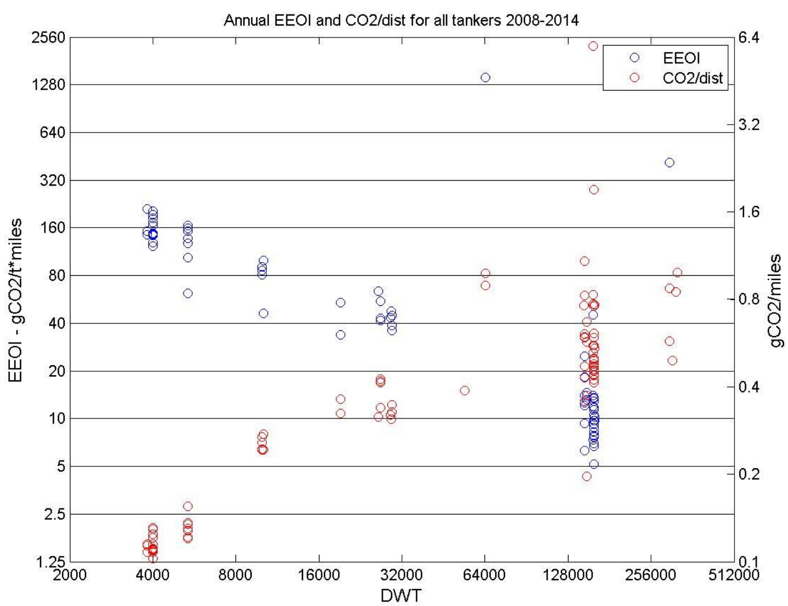
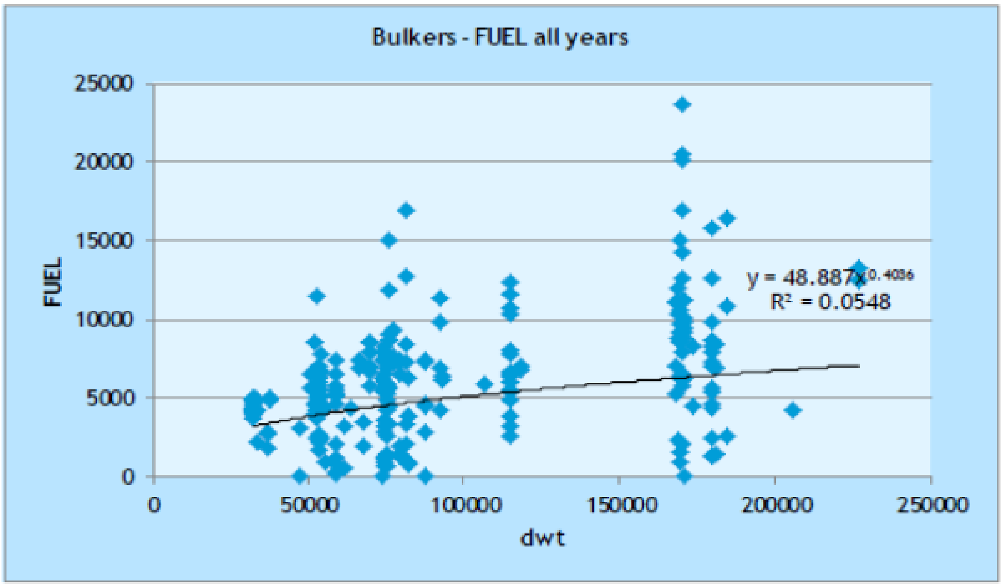


Figure 7 Comparison with INTERTANKO study. Top EEOI and CO2/distance from INTERTANKO presentation JWG/MRV at Hellenic Mediterranean Panel 2013; bottom EEOI and CO2/distance from our data sample for all tankers.

Generally, this study's fleet contains a number of small tankers (below 32,000 DWT) for which there are no equivalents in the INTERTANKO sample. There is only one size class

(150,000 DWT) for which the data can be reasonably compared. For that size, the INTERTANKO data is on average lower in value and tightly clustered with EEOI's ranging from approx. 4-7 gCO2/t.nm. This contrasts with this study's data which covers a range of 6-15 gCO2/t,nm, and includes a number of outliers of significantly higher values. The same is true of the CO2/total distance data, the INTERTANKO study fleet has on average lower and more tightly clustered values than this study's data. This implies that overall, the fleet in the INTERTANKO study were on average either technically more efficient, operationally more efficient, or both technically and operationally more efficient. However, the presence of the outliers (particularly the high outliers) in this study's data suggests that another possible explanation is that the data used in the calculations for this fleet's EEOI and CO2/total distance contained some unreliable or spurious values, which is consistent with comments made in Section 1 about data quality.

We compare our data on bulk carriers to two studies. Figure 8 (top) plots the relationship between fuel consumption and DWT as reported in MEPC 68/INF.29 (2015), a study which compares the indicators that are currently under discussion at MEPC, namely the Annual Efficiency Ratio, the Individual Ship Performance Indicator, the Fuel Oil Reduction Strategy and the unnamed United States proposal. A logarithmic curve is fitted to the data, providing a low R^2 of 0.0548 and there is a considerable spread in the observations that cannot be explained by DWT. We compare this representation to our data for the bulk carriers in our sample (bottom plot). Although there is still considerable variation that cannot be explained by DWT, both curves (logarithmic and power) have a higher R^2 (0.29) than the MEPC 68/INF.29. (2015) study, which cannot be explained by the different curve fit. There is also a lower standard deviation in the comparison study for ships with lower DWT than in our data sample, which shows a fairly consistent standard deviation across different ship sizes of bulk carriers.



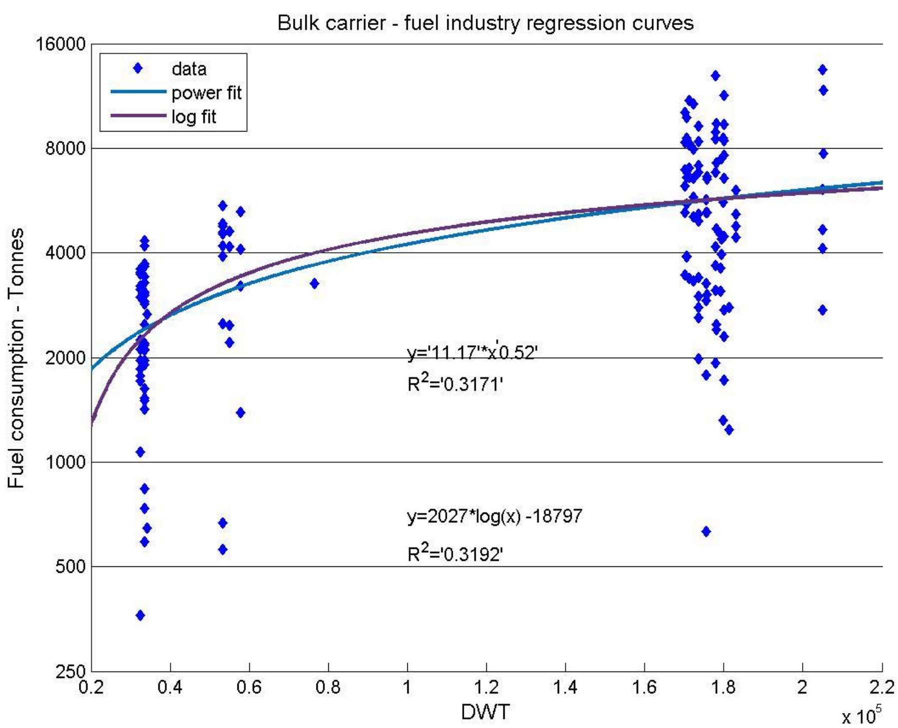


Figure 8 Comparison with MEPC 68/INF.29. (2015) study.

Another study by Kristensen (2013) provides curves of EEOI derived from model calculations and EEOI data reported by ship owners (Figure 9 top). The ship owner reported data is calculated in two ways, some data (the red dots) are for annual aggregates of EEOI and the yellow dots are for a single month's data. Both correspond to the year 2013. The ship owner data is reported as the average EEOI for a number of ships in a certain size range, so there is no indication of the variability in the EEOI's between similar ships. The data from Kristensen (2013) can be compared with a presentation of the data from this study (all years) for bulk carriers (Figure 9 bottom). Across the range of sizes this study's data shows, average EEOI's higher than the data presented in Kristensen (2013). For example, for ships around 50,000 DWT, the point estimates from the Kristensen (2013) study show values of approximately 4-10 gCO_2/t.nm, whereas this study's data provides values in the lower quartile of greater than 8 gCO_2/t.nm. However, inspecting the tabular results (Table 9) for the year 2013 shows that considering this year in isolation, this study's data has median values much closer to the average values in Kristensen (2013) (for example median capsize EEOIs are 5-6.6 gCO2/t.nm, median EEOI for 55,000 DWT fleet is 9gCO2/t.nm). Even on 2013 data only, this study's data still appear slightly higher than the Kristensen (2013) data, but now more credibly to do with differences between operation specifics and specialization rather than a fundamental difference between the fleets.

This comparison therefore shows the importance of drawing comparisons on a year-by-year basis, particularly during the period for which this study's data has been collected (2007-2013). In particular, this is because of the increasing prevalence of slow-steaming (seen clearly in the tabular data) that contributed to important increases in efficiency over the period.

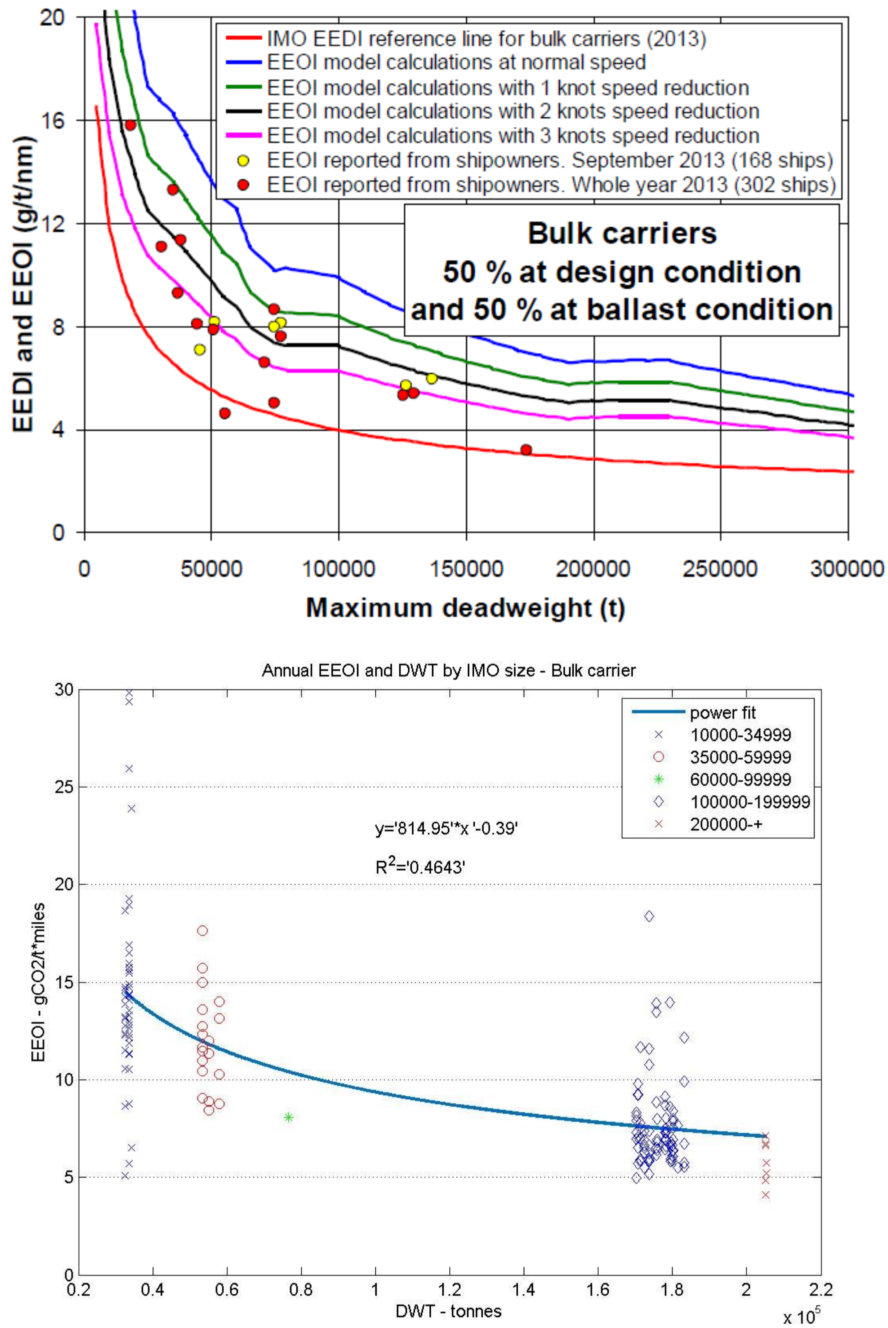


Figure 9 Comparison with Kristensen, 2013 (top) study to RBSA data (bottom)

A study using vessel tracking (AIS) data to estimate the EEOI is MEPC 68/INF.24. (2015). This study was a follow-on to the IMO Third GHG Study 2014, and deployed AIS derived estimations of fuel consumption in combination with AIS derived estimates of cargo mass and transport work to calculate EEOI. The cargo mass is obtained from the

AIS reported instantaneous draught and a series of algorithms filters the results to remove spurious data. The results present the statistics of transport work and EEOI broken down by ship type and size category (defined by dwt size). The filtering to remove spurious data leaves approximately 10-20% of the fleet that is assumed to be a representative sample of the global fleet (the representativeness is tested as part of the study).

MEPC 68/INF.24 is used as a source for point estimates of the median EEOIs of all ship types and sizes as reported in Table 11 for the same ship types and sizes in this study. There is no reason that the sample of RBSA ships that were included in this study should be representative of the overall fleet median, but similarity between the two numbers in a given year provides some indicative reassurance on the quality of the data.

Table 11 Comparison of EEOI tabular results with MEPC 68/INF.24. (2015)

		MEPC 68/INF.24. (2015).				**This study**		
Type	Size	2010	2011	2012		2010	2011	2012
Bulk carrier	10000-34999	13.4	14.4	15.4		14.36	14.22	12.33
Bulk carrier	35000-59999	10.6	11.5	11.7		13.36	12.80	12.32
Bulk carrier	100000-199999	12	6.34	5.83		7.65	6.63	6.44
Bulk carrier	200000-+	8.85	5.41	5.13		7.12	6.63	5.74
Chemical tanker	10000-19999	22.1	23.2	23.7		-	50.07	66.83
Container	1000-1999	28.1	31	31.6		-	55.86	50.82
Container	2000-2999	21.1	24.6	24.7		30.22	30.52	28.11
LPG	0-49999	24.7	27.9	30.4		146.57	145.47	61.66
LPG	50000-199999	13.9	15.3	16.3		1428.24	-	-
Oil tanker	120000-199999	14.3	9.12	10.8		11.99	10.27	8.22
Oil tanker	200000-+	4.89	6.47	6.57		-	413.48	-

There is generally reasonable agreement in the magnitudes between MEPC 68/IINF.24 and this study with some notable exceptions:

- In INF. 24, chemical tankers have lower EEOIs than those estimated in this study. This could be attributable either to the quality of the data used in this study, or the quality of data in INF. 24. Chemical tankers present a particular challenge for AIS derived estimates of EEOI since there is often fuel consumed for cargo heating and operations which AIS data can only estimate. They are also ships that operate often part-loaded with cargo which makes them more challenging with respect to the accuracy of AIS derived cargo mass. Inspecting the data further, INF 24 estimated utilization (the combination of payload and allocative utilization) is nearly twice (1.75 times, in 2011 and similar in 2012) the magnitude of the utilization estimate for the ships in this study. This goes some way to explaining the difference observed, but even taking this into account the EEOI's calculated for this study are approximately 20% higher than the INF. 24 values if like for like utilization had been measured. This implies that there is also a difference in the fuel consumption – with this study's ships reporting higher fuel consumption than that estimated in the Third IMO GHG Study 2014. INF. 24 estimates that the average speed and days at sea for this size category of chemical tankers are both higher than the speed and days at sea for this study's ships. Therefore the probable explanation is a difference in the auxiliary fuel consumption. Without further analysis it is not possible to say whether this is because the ships in this study have some unique features and operation that require higher auxiliary fuel consumption, whether the data quality is the source of the discrepancy, or whether deficiencies in the method and assumptions in INF. 24 are the explanation.
- Container ships appear to have lower EEOIs in INF. 24 than in this study. However, in this study as no cargo data was available a single size-generic assumption was applied for payload and allocative utilization. INF. 24 observes that smaller container ships have higher utilization than larger container ships which if applied to this study's data would have the effect of lowering the EEOI's calculated for the two size categories for which time-series data was available. This may resolve the observed discrepancy.
- Liquid gas carriers have very large discrepancies between this study's estimated values and those from INF.24. The likely explanation is the cargo data used in this study for this ship type - there were many inconsistencies and null values reported in the raw data describing the cargo mass for this ship type, and no means to estimate or validate or correct. The consequence of a shortage of cargo data is unreliability in the calculation of transport work and a likely under-calculation of

transport work and this would result in an overestimation of EEOI, which is consistent with the tabular results in Table 11.

- There is reasonable agreement for the Suezmax tanker size class (120000-199999 DWT), however poor agreement for the VLCC tanker size class (200000 + DWT). The explanation is likely to be the quality of the cargo data available in this study for this size category of tanker.

Other than these specific larger discrepancies, there are a few discrepancies in trends over the time period. For example some ship type and size categories in this study show improving EEOIs with time when the INF. 24 results imply deteriorating EEOIs over the same time period. This could be the result of a comparison between a single operator, instilling operation efficiency optimization practices in their specific fleet, and the median performance of the wider fleet in which that operator was based.

6. Decomposition analysis of EEOI

As discussed in Section 2, the EEOI can be decomposed into logistic and technical factors. Logistic factors include the ship's average payload utilization, allocative utilization, and a factor reflecting operating speed and draught. The variables influence both the numerator and denominator of the EEOI equation in different ways, making interpretation of the index not completely straightforward.

A ship's payload utilization affects both fuel consumption and transport work. A ship that is carrying cargo requires more energy for propulsion at a given speed, compared to a ship that is carrying less cargo or ballasting empty (fuel consumption). The cargo carried over a time period also determines the tonnes component of transport work over the same time period. Allocative utilization, or days in laden divided by the total sailing days, affects the transport work or revenue miles through the distance component.

The operational speed affects the fuel consumption, and the transport work achieved within a given period of time. It is a common error to assume that a ship that slow-steams will always obtain a higher operational efficiency compared to an equivalent ship sailing at a faster speed. Any differences in payload and allocative utilization also need to be taken into account. In Figures 10-18, we examine these relationships for bulk carriers to understand the main drivers of EEOI. Note that the allocative utilization shown in the figures is the ratio of distance laden to total sailing distance. This metric will be the same as the days laden to total sailing days (the allocative utilization) if the average operating speed is the same as the average laden speed, and approximate if the two speeds are similar. The laden distance to total sailing distance ratio is used in order to be consistent with other studies.

We first describe the EEOI in terms of the logistics factors by ship type and size, alongside the same information with the estimated EETI (see Appendix A.1). Viewing the data by size class allows for some control over the influence of technical efficiency that increases with size. We then compare the EEOI to some alternative indicators proposed in the IMO.

The decomposition analysis results are presented as time-series for each ship type. In some instances, the composition of the fleet of ships (within a given type and size) changes over time (ships are scrapped or new ships are added). These changes to the fleet can influence the observed trends and so the results included in the plots shown in Section 6 are limited to a subset of the ships that are consistently operating for the duration of the time-series.

For the comparison against some alternative indicators, the following are considered: the Annual Efficiency Ratio or the carbon emissions divided by the product of deadweight and distance sailed (proposed by Japan and denoted as AER), carbon emissions divided by total hours of operation (proposed by the US but with joules of energy rather than carbon emissions and denoted as EEUSI), and fuel consumption over distance (proposed in MEPC-66/4/6, 2013).

6.1 Decomposition analysis for bulk carriers

Figures 10-15 show the EEOI, EETI and logistics factors for three size classes of bulk carriers for which there was a sufficient sample size of ships per year to justify a time-series and trend analysis.

For bulk carriers in size 2 (DWT range 10,000-34,999), Figure 10, the EEOI decreases between 2008 and 2009 and then slightly increases between 2009 and 2010. The logistics factors can be used to explain this trend, as the decrease in EEOI can be explained by a lower speed, which counteracts the decrease in payload utilization and flat allocative utilization between 2008 and 2009. An opposite trend occurred between 2009 and 2010 with payload utilization improving and allocative utilization deteriorating, while speed continues to decrease. Therefore the allocative utilization overrides the positive impacts of changes in payload utilization and speed on efficiency.

For the same size category, Figure 11 presents the logistics factors alongside the estimated EETI. The resulting EETI trend is a gradual deterioration over time – increasing by an average of approximately 10% over a 2-year period.

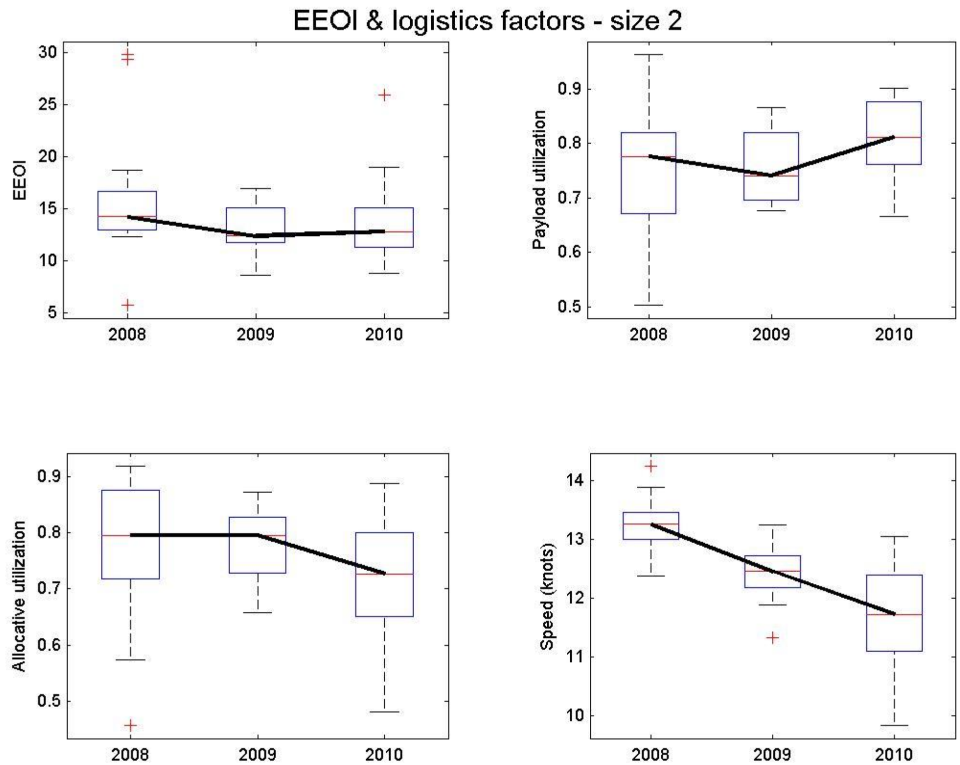


Figure 10 EEOI and logistics factors for bulk carriers size range 10,000-34,999 dwt; size sample: 13 ships.

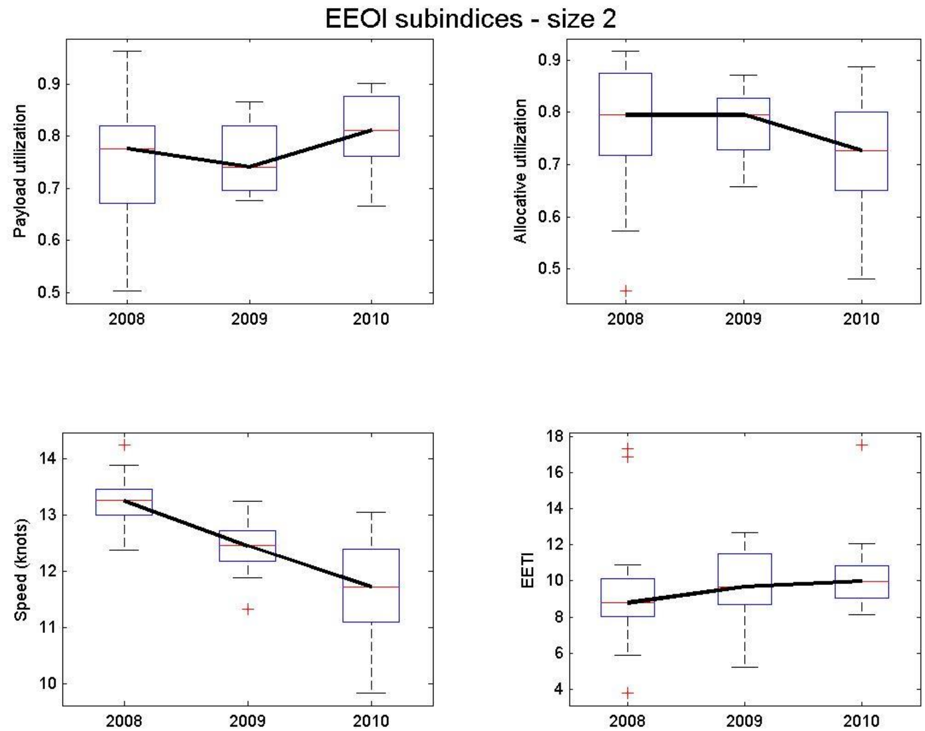


Figure 11 EETI and logistics factors for bulk carriers size range 10,000-34,999 dwt; sample size: 13 ships.

Figure 12 and Figure 13 present results for bulk carriers in the size class 3 (DWT range 35,000-59,999). Over the four years for which consistent data is available, the EEOI consistently decreases (energy efficiency improves). The logistic factors contributing to this trend include significant increases in allocative utilization and slower speed. These factors offset the decreasing trend in payload utilization during 2008-2010. However the increase in payload utilization, in combination with increasing allocative utilization and reducing speed, can clearly be seen as contributing to a more precipitous decline in EEOI during 2010-2011. On average, over the period studied, the EETI increases (again by approximately 10%), with a slight decrease between 2010 and 2011.

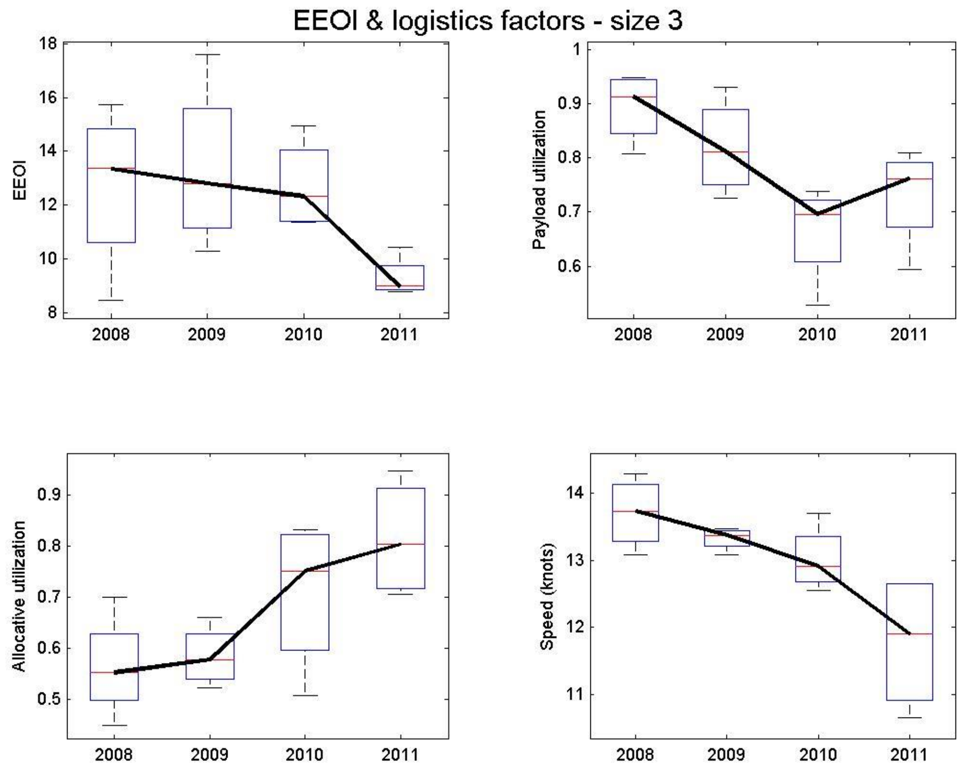


Figure 2 EEOI and logistics factors for bulk carriers size range 35,000-59,999 dwt; size sample: 4 ships.

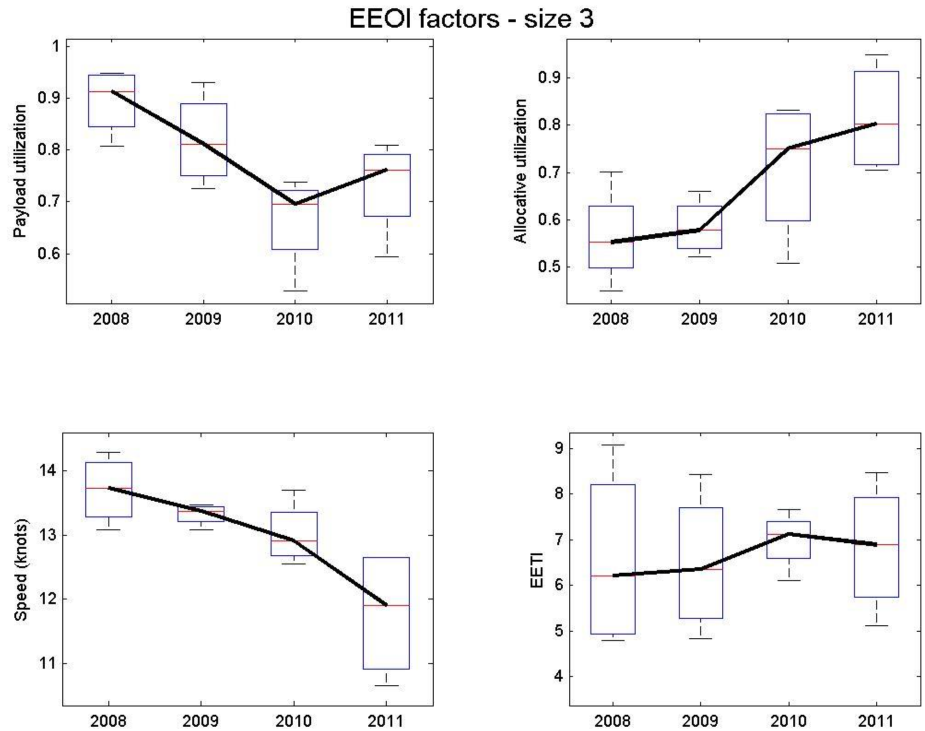


Figure 13 EETI and logistics factors for bulk carriers size range 35,000-59,999 dwt; size sample: 4 ships.

As shown in Figure 14 and Figure 15, for the larger size class 5 (100,000-199,999), the EEOI reduces over the period 2008-2010, before increasing in 2011. Again, this can be explained by the interaction of the variations in allocative utilization, along with a declining payload utilization and decreasing speed. The EETI over the same period steadily increases with time, this time by approximately 15% over the four-year period of the study.

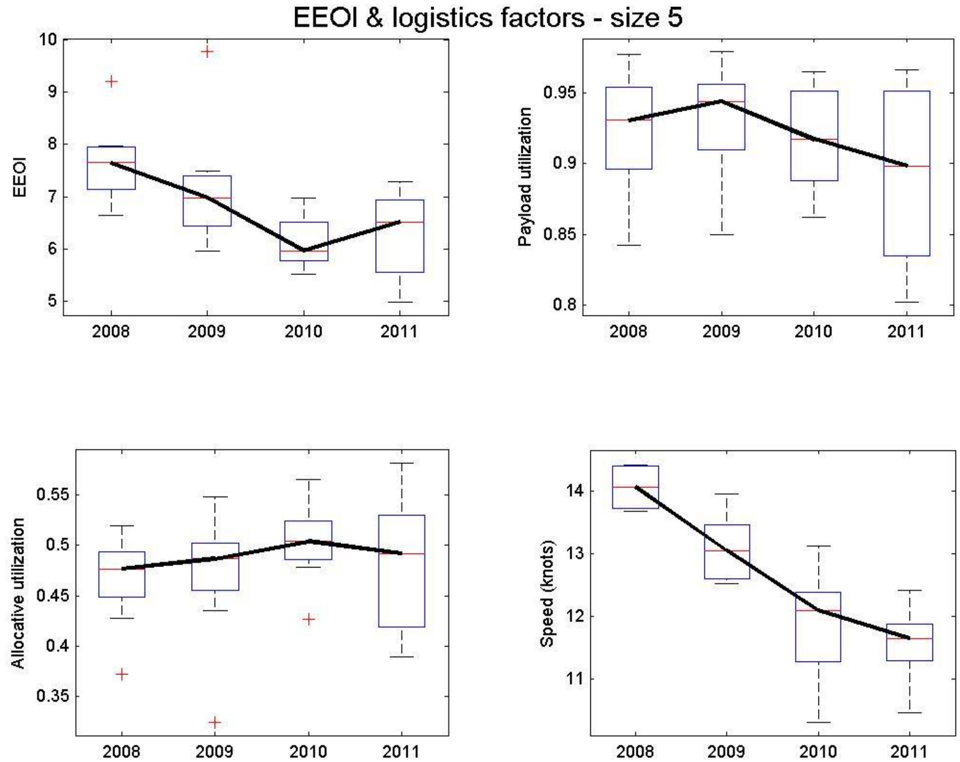


Figure 14 EEOI and logistics factors for bulk carriers size range 100,000-199,999 dwt; size sample: 8 ships.

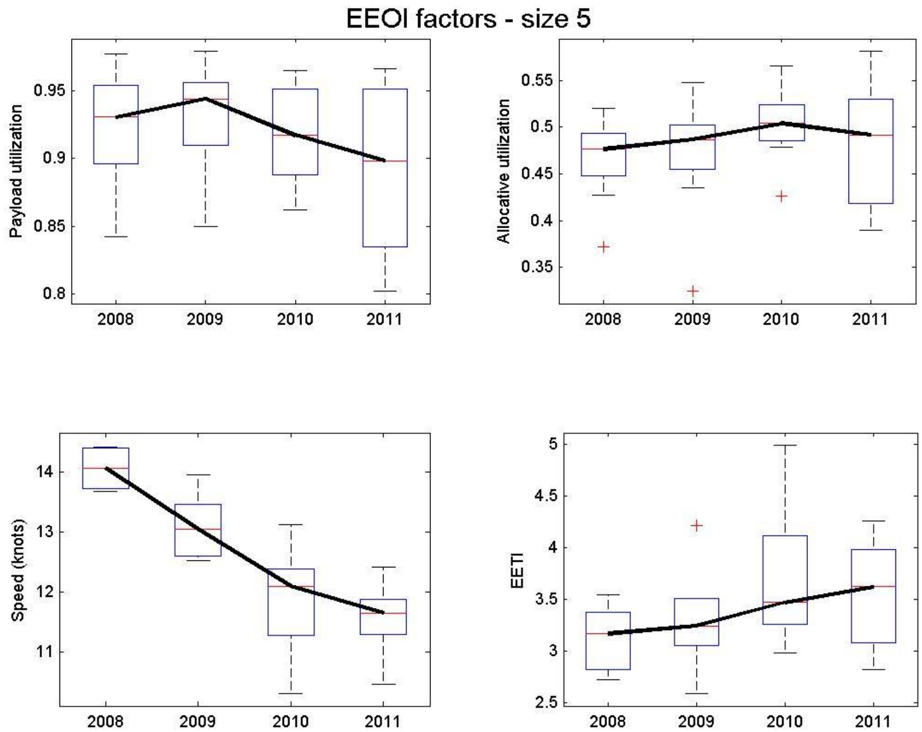


Figure 15 EETI and logistics factors for bulk carriers size range 100,000-199,999 dwt; size sample: 8 ships.

6.1.2 Comparison to alternative indicators

Figures 16-26 present the calculation of energy efficiency indices for three of the ship size categories of bulk carrier (size 2, 3 and 5), for which a year-on-year consistent sample of ships could be identified. The results show that whilst similar trends are apparent in the AER, fuel consumption/distance and EEUSI, these are not always consistent with the trend in EEOI. This appears to be particularly the case for size 2 and size 5 which see reductions in operational efficiency between 2009 and 2010, and between 2010 and 2011 respectively, whilst the alternative indices were showing continued improvements.

This difference between the EEOI trend and the trends of the alternative indices can be explained by the fact that the alternative indices have no means to capture the influences of varying payload or allocative utilization – logistics factors that in Section 6.1 were shown to produce important variations in the EEOI.

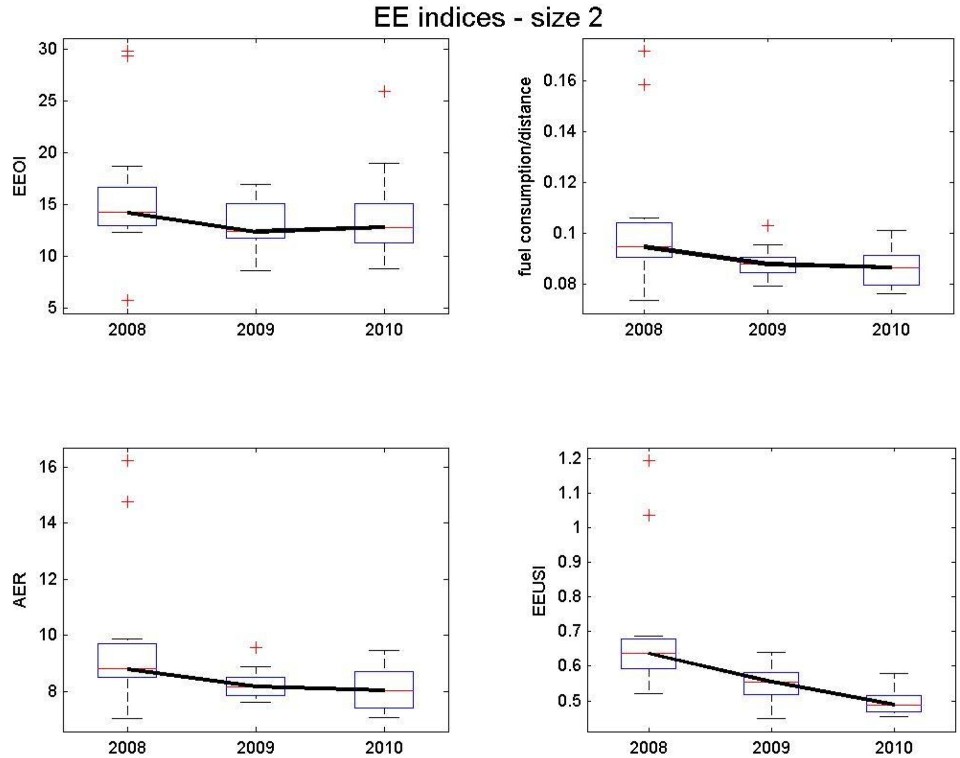


Figure 16 EEOI and alternative indicators for bulk carriers size range 10,000-34,999 dwt; size sample: 13 ships.

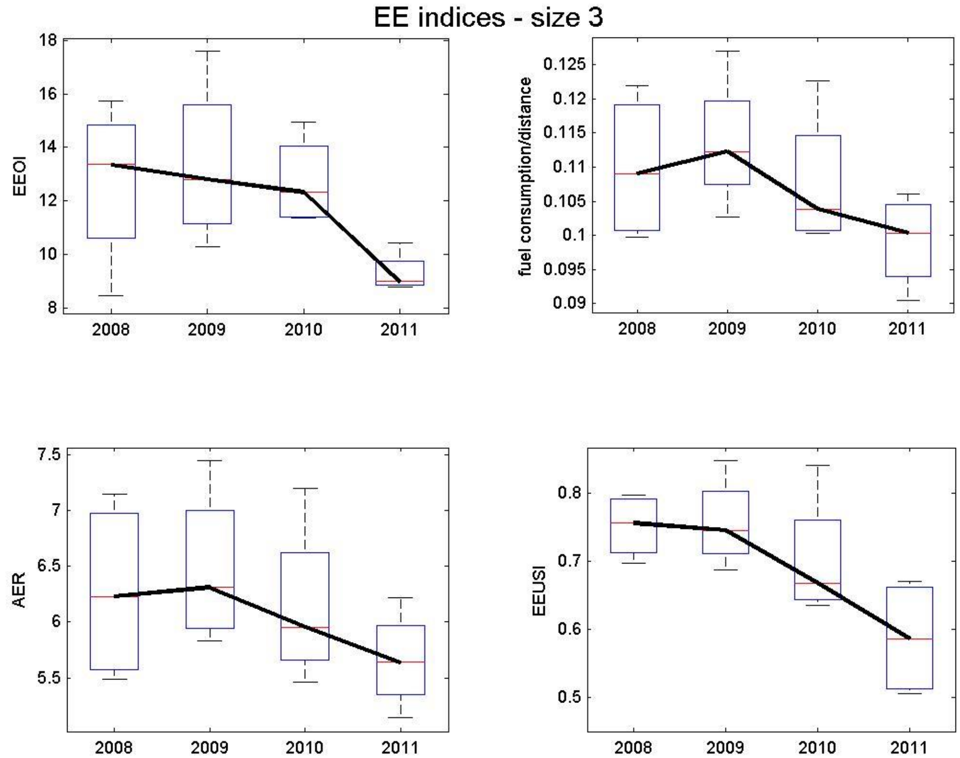


Figure 17 EEOI and alternative indicators for bulk carriers size 35,000-59,999 dwt; size sample: 4 ships.

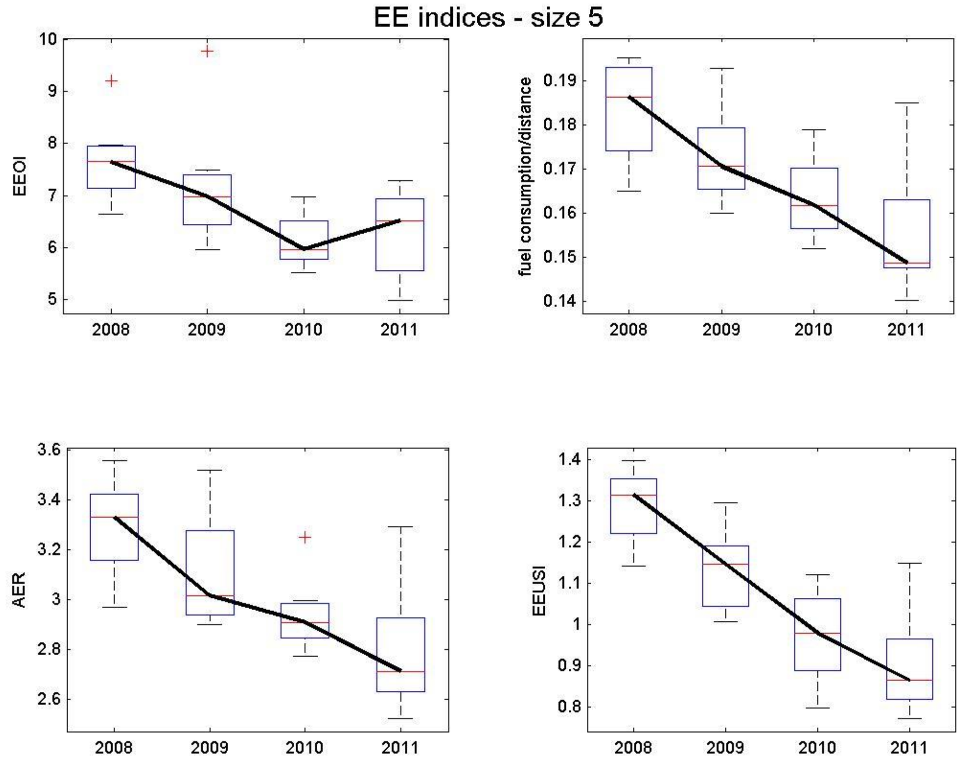


Figure 18 EEOI and alternative indicators for bulk carriers size range 100,000-199,999 dwt; size sample: 8 ships.

6.2 Decomposition analysis for container ships

Figure 19 presents results for the container ships in size category 3, a small sample of 5 ships. Information on the ships' design/reference speeds was not available and therefore EETI calculations were not possible. Furthermore, there was no data describing the specifics of the ship's cargo, and so the allocative utilization was set to 1 and the payload utilization set to 0.7 as default assumptions for all ships.

Over the four year time period for which a consistent time-series was possible, the EEOI gradually improved, reducing by approximately 15%. This is driven by a reduction in operating speed – in this instance with assumptions for cargo, no other logistics factors could possibly induce variability in EEOI.

Figure 20 presents results comparing the different energy efficiency indices. As there is no variation in the cargo over time or between ships, it is not surprising that unlike the case for the bulk carrier fleet, all four indices display the same trend over time. This at least demonstrates that each of the indices has a similar ability to detect variations in operational efficiency due to changes in operating speed. This is because the numerator, fuel consumption, is the same across all indices, and is affected by speed.

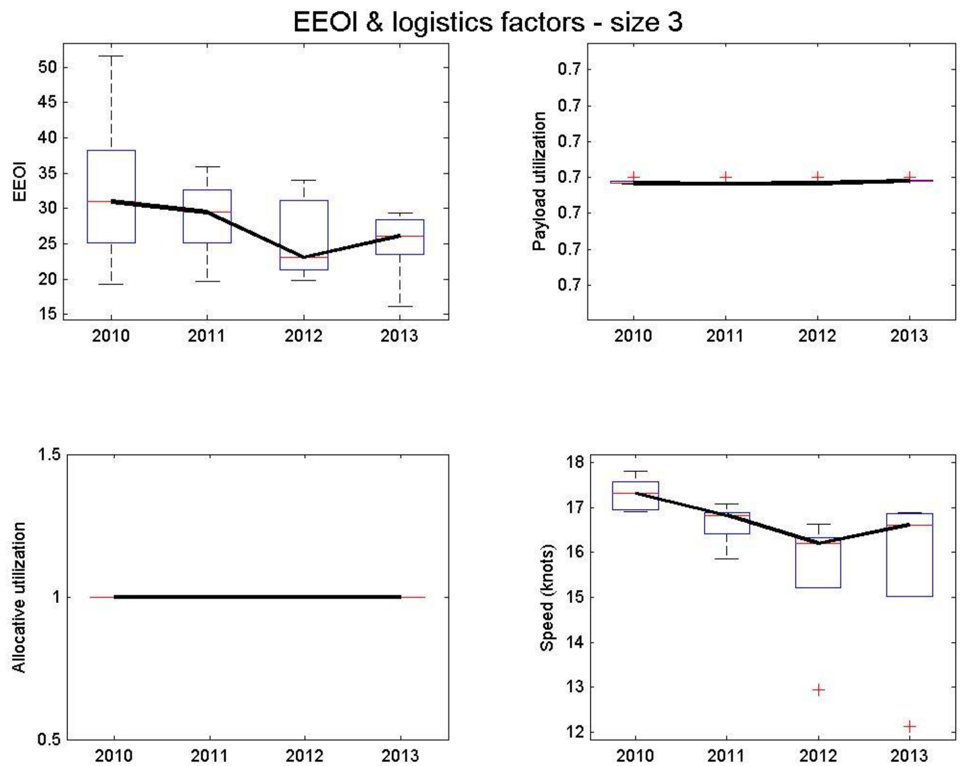


Figure 19 EEOI and logistics factors for containers size range 2000-2999 TEU size sample: 5 ships.

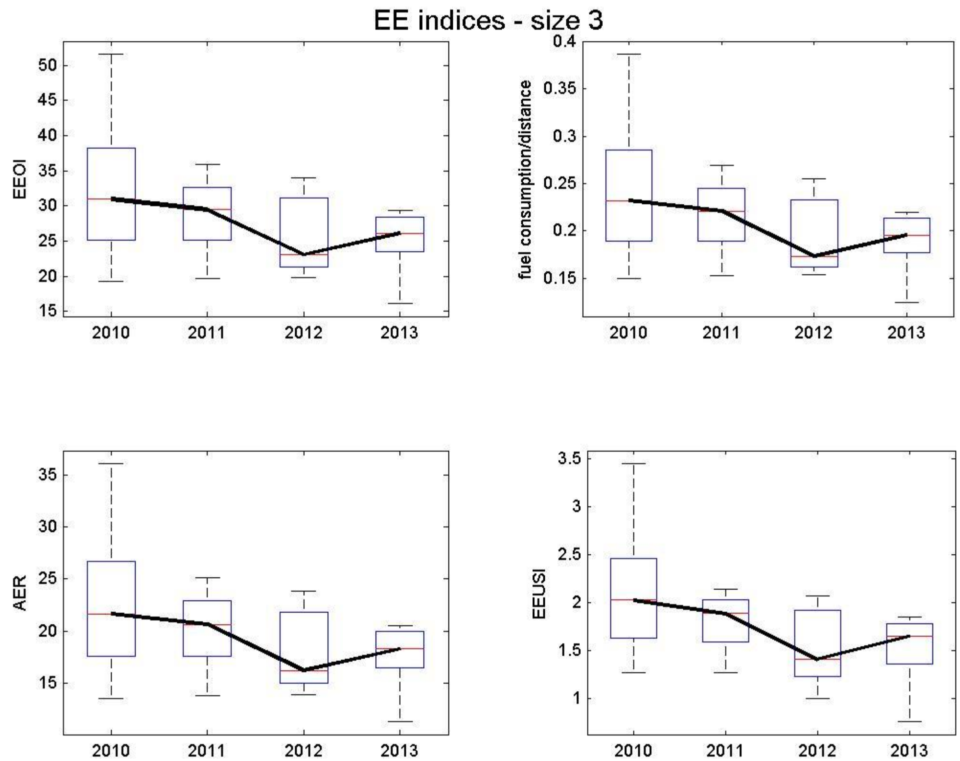


Figure 20 EEOI and alternative indicators for containers, size range 2000-2999 TEU; size sample: 5 ships.

6.3 Decomposition analysis for Liquefied Petroleum Gas (LPG) carriers

Figure 21 and Figure 22 present trends in EEOI, EETI and logistics factors for a subset of the LPG carrier's fleet (size 1, 0-49,999 CBM capacity) over the period 2008-2010. There is a wide variability in the EEOI of the fleet (between ships), which appears to be largely driven by the variability in the fleet's payload utilization – some ships carry, on average, half as much cargo as other similar ships in the same fleet.

Consistent with other ship types and sizes, the fleet shows a steady improvement in EEOI over the period of the study, driven both by a lowering of operating speed, and an increase in allocative utilization (the median payload utilization stays approximately constant with time).

The trend in EETI is for a steady increase, again consistent with the other ship types and sizes – in this instance a deterioration of approximately 10% over the period 2008-2010.

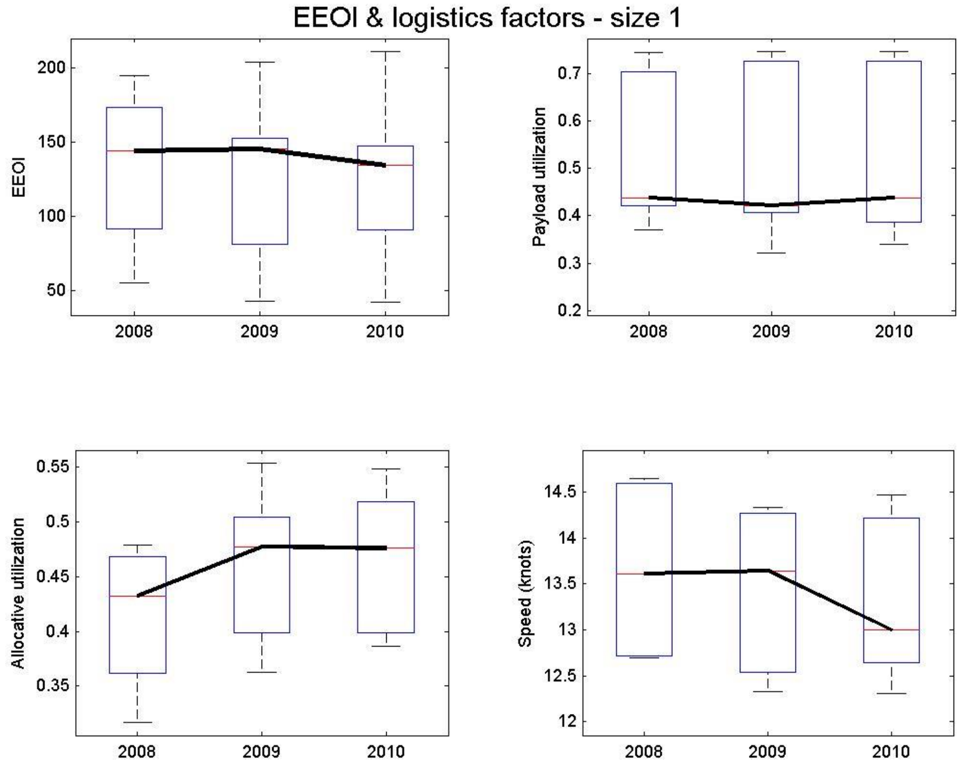


Figure 21 EEOI and logistics factors for LPG carriers, size range 0-49999 cbm; size sample: 6 ships.

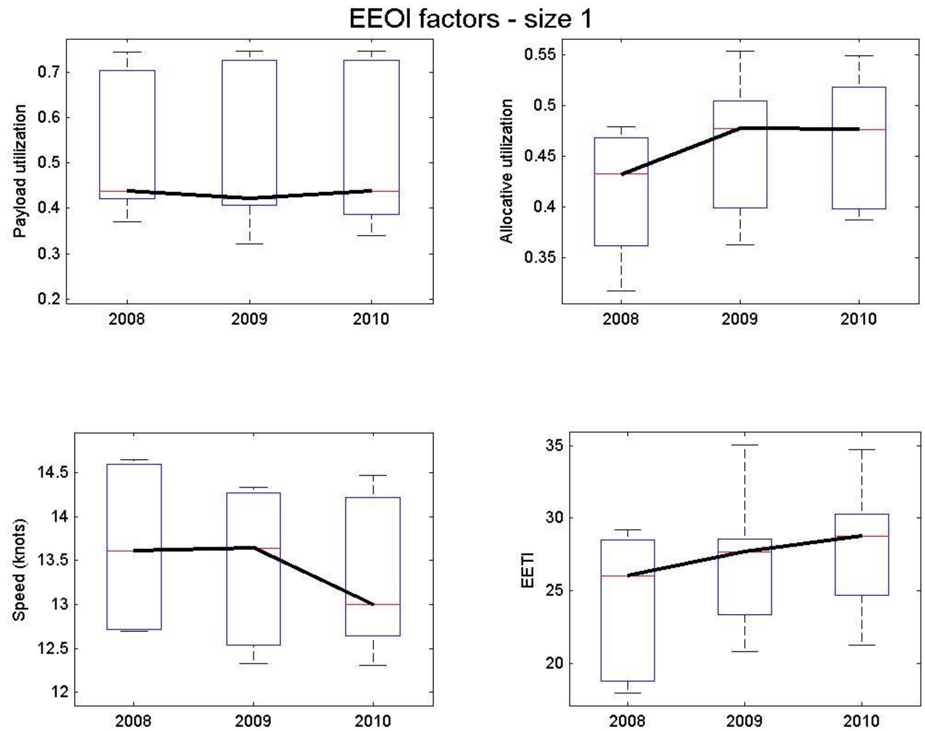


Figure 22 EETI and logistics factors for LPG carriers size range 0-49999 cbm; size sample: 6 ships.

Figure 22 shows that in this instance, the different energy efficiency indices give slightly different trends. EEOI improves over the period of the study (by a small amount), whereas the other three indices either deteriorate or stay approximately constant. As with other ship types, this can be explained as the result of the EEOI capturing variations in logistics factors that are not considered in the other three indices.

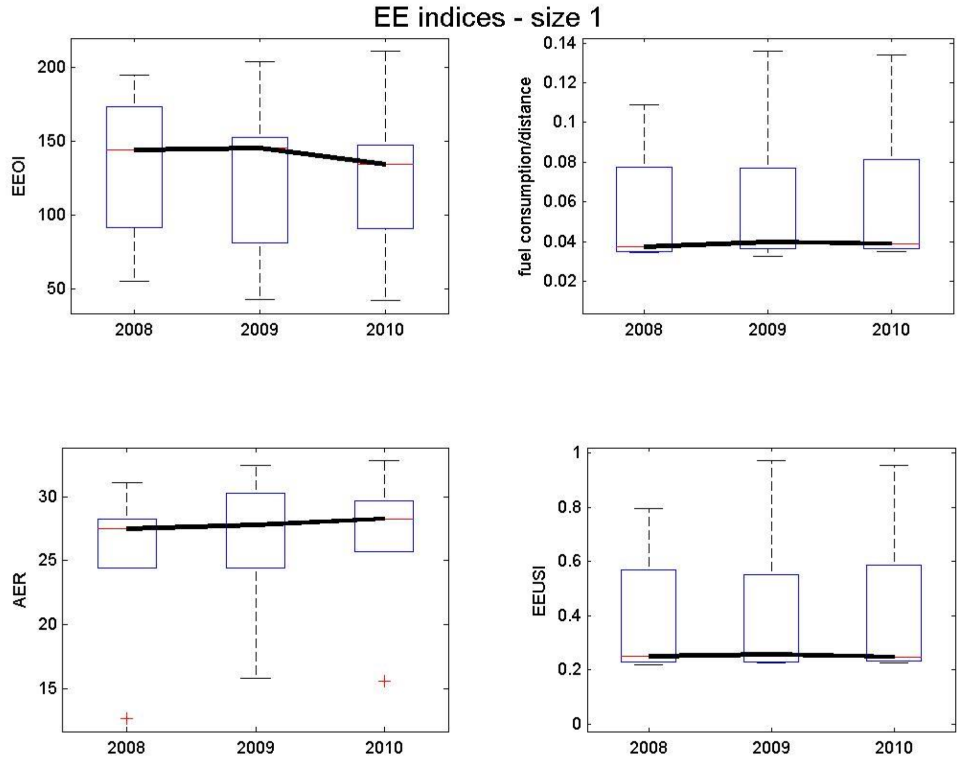


Figure 23 EEOI and alternative indicators for LPG carriers size range 0-49999 cbm; size sample: 6 ships.

6.4 Decomposition analysis for oil tanker

Figure 24 and Figure 25 present results for the fleet of size 7 (DWT range of 120,000 – 199,999) tankers, a fleet of three ships with consistent data year on year during 2010 – 2012. Reducing average speeds, increasing allocative utilization and reducing payload utilization all trade off to create an initial improvement in EEOI (2010-2011), followed by a deterioration (2011-2012) and a net deterioration over the period 2010-2012.

Over the same period, the EETI deteriorates initially, and then improves so that in 2012 it is similar in magnitude to its value in 2010.

For the energy efficiency metrics (Figure 26), in this instance, both fuel consumption/distance and EEJI provide similar trends, whereas the EEUSI shows a consistent downward trend. Only the EEOI shows a net deterioration during 2010 to 2012, which is driven by the significant reduction in payload utilization between 2011 and 2012.

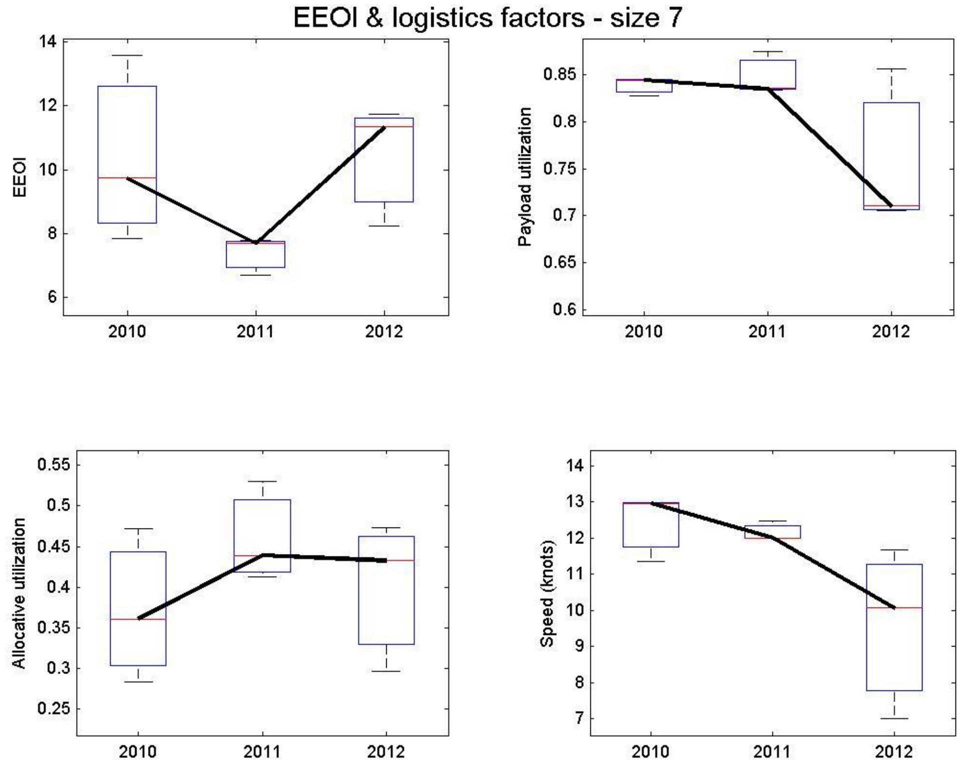


Figure 24 EEOI and logistics factors for oil tankers size range 120000-199999 dwt; size sample: 3 ships.

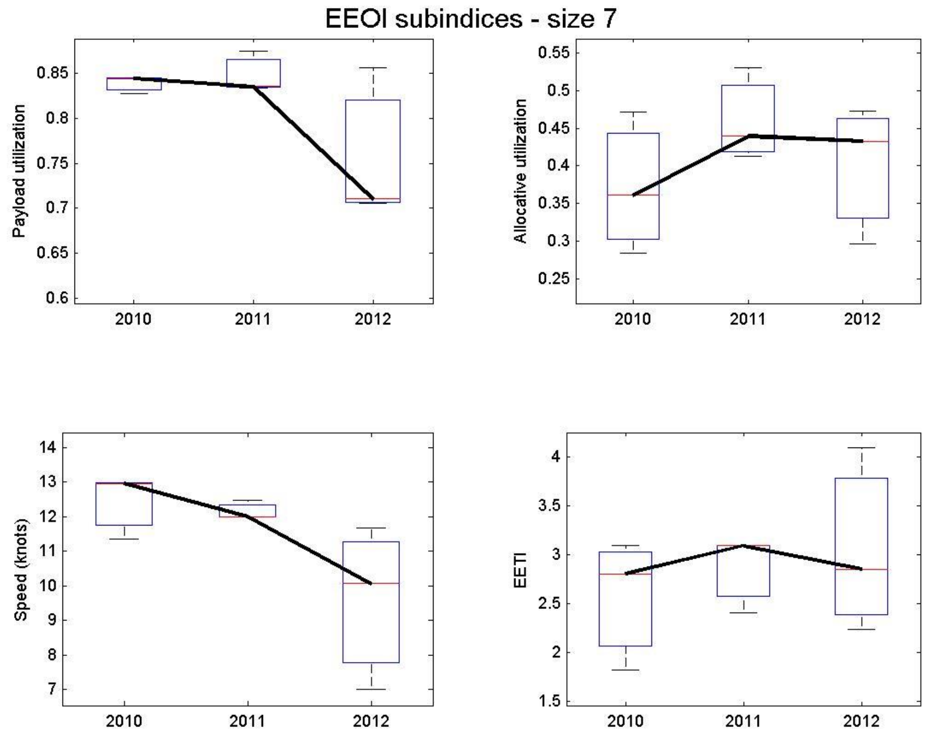


Figure 25 EETI and logistics factors for oil tankers size range 120000-199999 dwt; size sample: 3 ships.

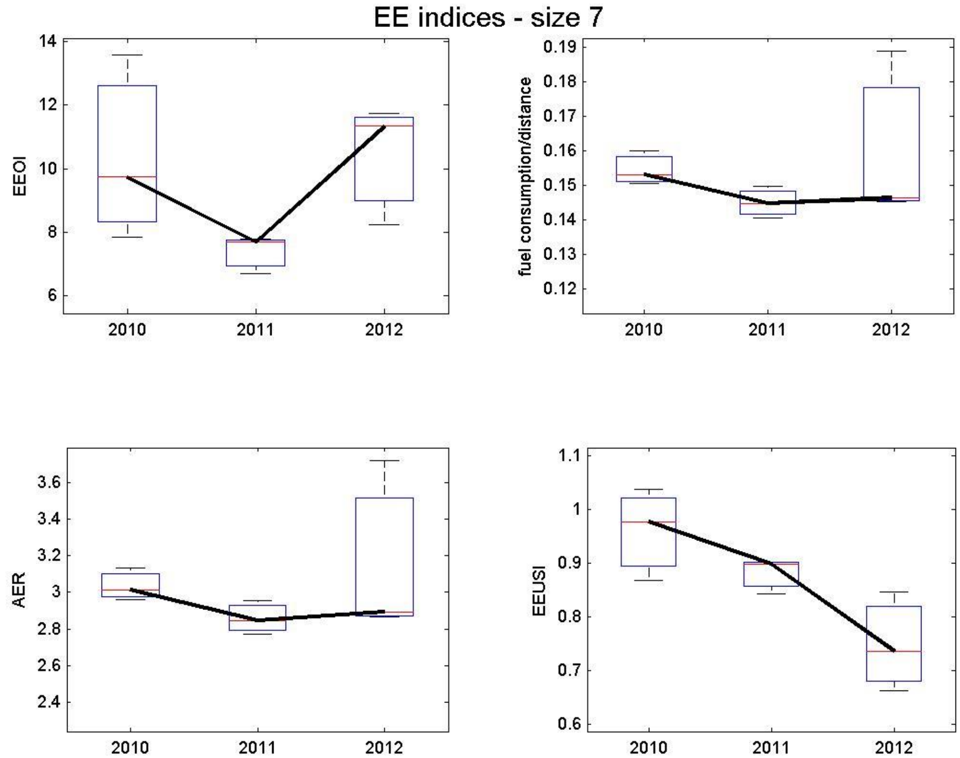


Figure 26 EEOI and alternative indicators for oil tankers size range 120000-199999 dwt; size sample: 3 ships.

6.5 Summary

In summary, taking the results for all different ship types and sizes:

- There is little evidence of correlation between EEOI and any one logistics factor, for all of the types and sizes considered, variations in EEOI can be explained only by considering contributions from a combination of the logistics factors.
- Consistently across all ship types and size categories, speed decreased during the period of this study, trends for both allocative and payload utilization differ and in many cases showed deterioration in utilization which counteracts operational efficiency improvements obtained by slow-steaming.
- On average, the trend is for moderate decreases (improvements) in EEOI during the period of the study.
- In general, the variability in EETI in any given year and ship size, appears smaller than the variability in EEOI. This appears particularly true for the larger ships (e.g. Capesize), which is to be expected since these ships are more likely to be technically homogenous to begin with. This is to be expected as the drivers of

EEOI should have greater variability than the drivers of EETI (hull, propulsion and machinery condition changes, and metocean variability).

- The estimated trend in EETI appears consistent with expectations that performance is likely to deteriorate over time (e.g. coating and fouling deterioration, propeller damage, engine wear), and implies that EEOI improvements are being obtained over the period of the study (reducing EEOI with time) in spite of this underlying technical efficiency deterioration – mainly due to extensive implementation of slow steaming.
- However, as there are some other trends that are well correlated with the EETI (e.g. reducing speed, increasing EETI) it is possible that the trend in EETI is the result of an inaccuracy in its estimation (e.g. due to an inadequacy in the power 3 used in the speed factor derivation). Further work would be needed with data controlling for the trend in speed in order to understand this better.
- For each of the different ship types and sizes, the alternative operational energy efficiency indices show varying levels of trend agreement/disagreement. Significantly, it is often the case that the three alternative indicators produce different trends to EEOI. This shows that a) no alternative energy efficiency metric is a reliable proxy to EEOI and b) the choice of energy efficiency metric is a function of what information is believed to be of greatest importance. Of the indicators considered, the EEOI is the only indicator that represents the carbon intensity of the actual transport work done (when measured in t.nm's), all other indicators approximate transport work done in some way.

7 Factors influencing the EEOI

7.1 Interviews with companies on technical and operational measures

The decomposition analysis from Section 6 highlighted that the EEOI is influenced by technical and logistics factors. Because we were unable to measure the technical efficiency of the ships in the data sample in their real operating conditions nor obtain data on any retrofits that might have occurred, we conducted interviews with some of the owners for the study to see if any technical interventions were undertaken during the sample period (2008-2012).

For the liquefied gas products (LPG), no intervention measures were undertaken during this period. However, a consultant working on the technical performance of the LPG fleet commented that investment in technical measures were implemented in 2012, therefore post 2012 it would be likely that a step change occurred in the technical efficiency of their LPG fleet which would not be seen in the data we analyzed.

For the bulk carrier ships in the sample, the ships have Propeller Boss Cap Fins, and two have Mewis ducts. The Supramax ships have trim optimization.

For container ships, the technical manager reported that they are not investing in energy efficiency improvements because the ships are time-chartered and they “don’t receive a higher time charter rate.” This split incentive arises in the time charter market because the fuel costs are borne by charterers (in addition to the daily charter rate) and capital and maintenance costs are borne by the ship owner or operator. This represents a type of principal-agent problem that also arises in the building sector between a tenant and landlord (see Blumstein et al. (1980), Scott (1997), Maruejols & Young (2011), Bird & Hernandez (2012)).

The degree of the split incentive in each market segment depends on the size of the time charter market, the length of the contracts and whether charterers are willing to reward owners for their investments in energy efficiency or clean technologies. Estimates from an analysis of fixtures in 2011 (Rehmatulla, 2014) shows the size of the time charter market varies in each sector. In the tanker sector, the majority (around 90%) of ships are traded on the voyage charter (spot) market, while in the dry bulk sector time charter contracts could account for as much as 60% of the ships, suggesting that this type of barrier is a larger problem in the dry bulk sector.

The extent to which the fuel cost savings are passed back to the owner-operator through higher charter rates will create direct incentives for ship owners and operators to implement wind technology. Agnolucci, Smith & Rehmatulla (2014) show that on average only 40% of the financial savings delivered by energy efficiency accrue to the ship owner for the period 2008–2012 in the dry bulk Panamax sector. The incomplete pass-through of savings through higher rates has also been suggested in Smith et al. (2013a), Riise & Rødde (2014) and Parker & Prakash (Accepted) and has been referred anecdotally in Faber, Behrends & Nelissen (2011), Maddox Consulting (2012) and Lloyds List (2013).

In terms of operational measures, the companies interviewed are using voyage optimization in varying degrees. For the liquefied petroleum gas carriers in the sample, voyage optimization is used to optimize for current and weather due to the performance fuel claims. For example, mid-size LPG travel on long-haul routes (i.e., Arabian Gulf to India) so they can benefit more from interventions and are taking advantage of favorable currents. The company is starting to monitor and train captains to create awareness that fuel consumption can vary due to the crew’s handling of the ship and to collect consistent noon reports to track the fuel consumption on ships.

For the bulk carriers in the sample, super slow steaming was implemented from 2013, with ships sailing at economical speeds (45% of MCR) from 2008 and this was verified by the data presented in Section 6. Voyage optimization is only used if the masters ask for it, but “it is not always accurate, sending some ships on bad routes (to rocks, islands).”

The companies were receptive to understanding what data might be useful to collect in the future for the EEOI calculations so that they can optimize the collection process.

7.2 Time series of freight rates, bunker prices, and speed

The financial crisis of late 2007 lead to a recession in the United States in December 2007 and spread globally, impacting freight rates at the end of 2008. Figure 27 depicts the freight rates and bunker prices as moving in tandem until late 2008 as a result of the global recession, but the series diverge after 2009 when bunker prices continued to rise while freight rates were still dampened by the effects of an oversupplied market.

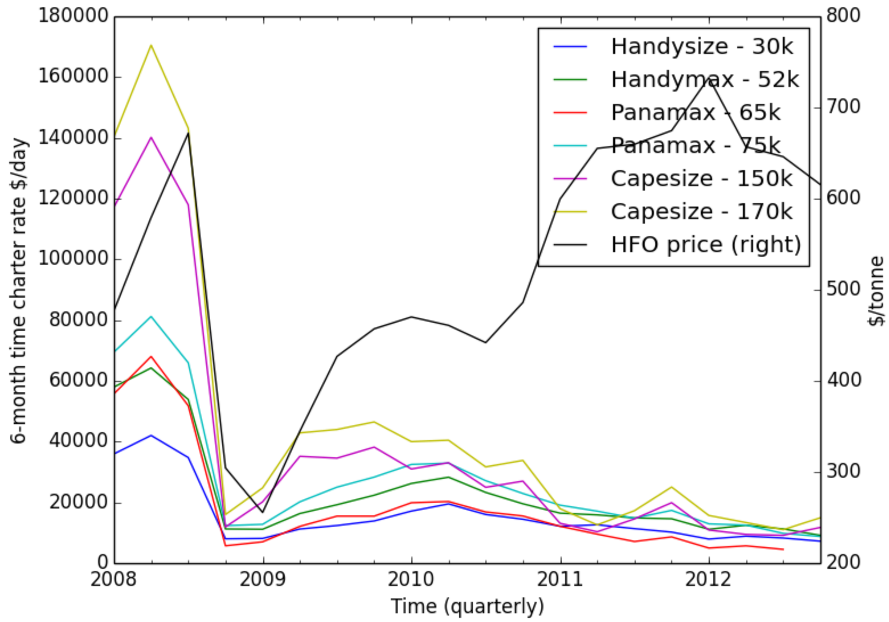


Figure 27: Dry bulk time charter rates and bunker prices (2008-2013). Source: Clarkson Research.

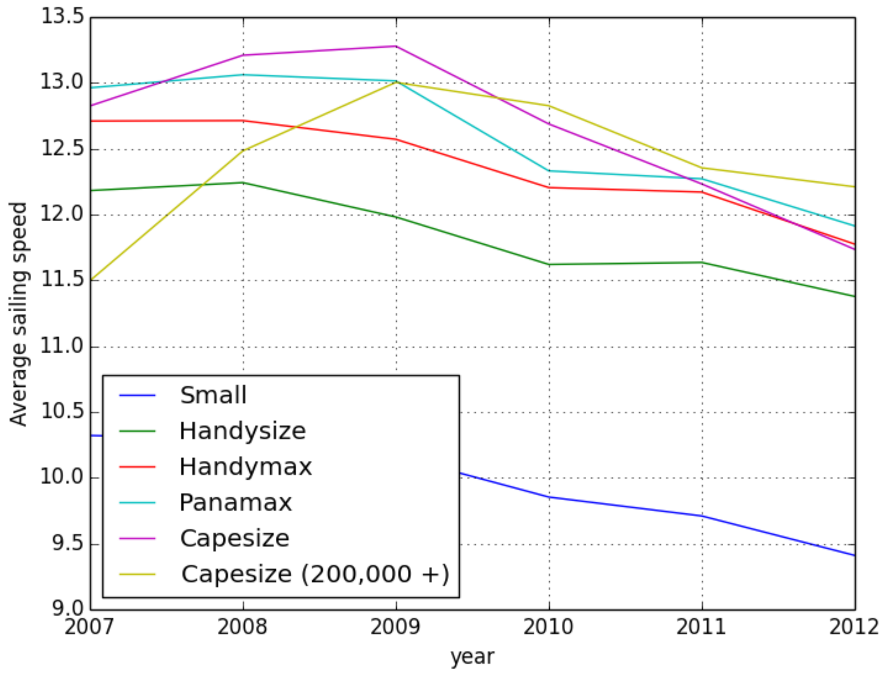


Figure 28: Average sailing speed of bulk carrier fleet 2007-2012. Source: Smith et al., 2013

Speed is related to market conditions, with vessel speeds increasing as market conditions improve and the value of time becomes more important relative to cost savings. This relationship can be seen from vessel tracking data (Smith et al., 2013) in Figure 28, which shows the average speeds for bulk carriers by size class. Average speeds peaked in 2008, with the exception of the Capesize segment which peaked in 2009. This largely reflects the trend in mean speeds of the bulk carriers in the RBSA sample, which dropped from 14.6 to 14.0 between 2008 and 2009, remaining flat in 2010, and then steadily decreasing from 14.1 to 11.7 knots between 2010 to 2013.

Poor market conditions also mean that ships have a lower probability of obtaining cargo fixtures per time period, and may have to sail further in search of cargo. During a depressed market, ship owners do not have bargaining power and have to accept lower payloads in order to avoid ballasting empty to another destination. This can be seen in the overall bulk carrier data, which saw its median payload utilization drop each year starting in 2009, from 97% to 84%. Allocative utilization, which is size specific due to the fact that different ship sizes are optimized for specific bulk trades and thus will differ depending on the distance between load and discharge areas, varied across time and size. There was a decreasing or flat trend for size classes 2 and 5 and an improvement for size class 3.

An improvement in allocative utilization may signify that fuel costs dominate owner/operators' decisions about where to allocate their ships due to the low or negligible profit margin earned. However, it is also likely that owners had to ballast further in search of employment, thus leading to a decrease in the allocative utilization. We also did not consider changes in trade patterns during this period, which could also alter allocative utilization.

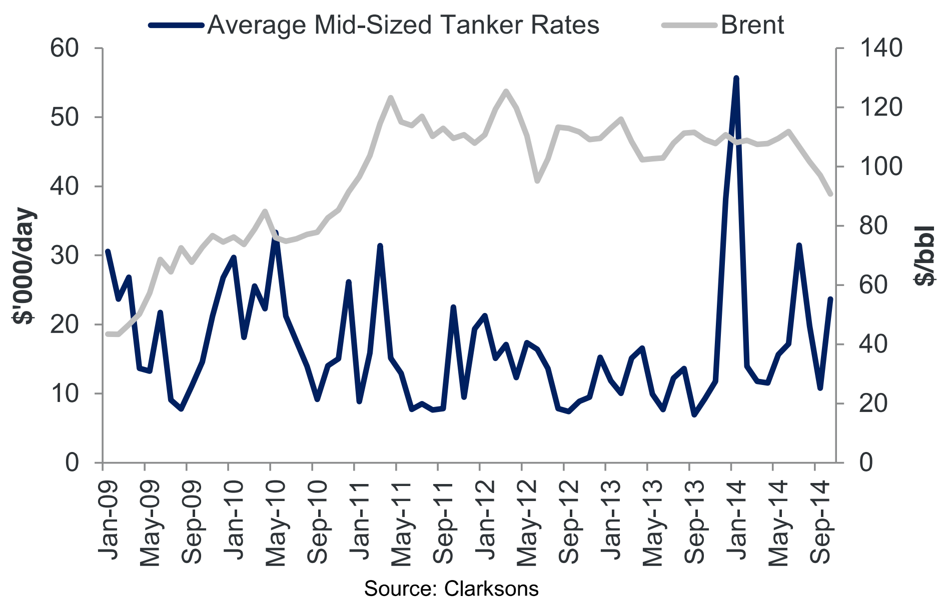


Figure 29: Tanker rates and oil prices (2009-2014)

The tanker sector has also experienced a depressed market during the study's period (2008-2014) due to oversupply, although conditions improved slightly in 2014 as can be seen in Figure 29 for oil tankers. For oil tankers in size class 7, the sample shows a decline in payload utilization between 2011 and 2013 and then an improvement in 2014, while the allocative utilization dropped after 2010, remaining moderately flat through to 2013 (there was no data available in 2014). Median speeds fluctuated around 11 knots between 2010 and 2013, increasing to 12 knots in 2014.

For the two chemical tankers analyzed in the dataset, the median speed decreased between 2011 and 2012 (10.1 to 9.0 knots), while payload utilization improved slightly and allocative utilization decreased.

For LPG, the general trend was a decrease in speeds from 14.8 in 2008 to 12.5 knots in 2012 and payload utilization decreasing during this time period. At the same time, allocative utilization improved slightly.

Figure 30: Container rates (2009-2015). Source: Shanghai Shipping Exchange; Economist.com

The economic picture for the container sector is mixed, with two peaks in rates in 2010 and 2012 as depicted in Figure 30 (there were no reliable price indices before the financial crisis (Economist, 2015)). Because of the rising price of fuel and low rates during the financial crisis, container operators made strides in improving the efficiency of their fleets, replacing old vessels for bigger, more fuel-efficient ones to be more resilient to poor market conditions (Economist, 2015).

For the container ships in the sample, the median speed decreased between 2010 to 2012 from 17.4 to 15.7 knots, increasing to 16 knots in 2013. As described in Section 6, data was not available on payload utilization or allocative utilization.

7.3 Laden EEOI and contract type

Ship type	IMO size	Contract type	Observations	Median laden EEOI
Bulk carrier	all	0	180	3.21
Bulk carrier	all	1	2408	6.77
Bulk carrier	2	0	46	7.20
Bulk carrier	2	1	947	8.71
Bulk carrier	3	0	9	7.37
Bulk carrier	3	1	409	6.71
Bulk carrier	4	0	2	-
Bulk carrier	4	1	23	4.75
Bulk carrier	5	0	106	3.10
Bulk carrier	5	1	958	3.33
Bulk carrier	6	0	17	2.10
Bulk carrier	6	1	71	2.98
LPG	all	0	300	62.25
LPG	all	1	3210	49.95
LPG	1	0	300	62.25
LPG	1	1	3170	49.77
LPG	2	0	0	-
LPG	2	1	40	54.91

Table 12: Median laden EEOI by contract type where 0=SPOT and 1=Time charter, 2008-2013

We analyze the laden EEOI by contract type for a subset of the data as it was only available for bulk carriers and LPG carriers. Table 12 reports the median laden EEOI by contract type. For both ship types, over 90% of contracts were time charter.

By ship size, classes 2, 5, and 6 have a lower median laden EEOI for spot market contracts compared to their respective size classes in time charter, while class 3 has a higher laden EEOI in the spot market compared to the time charter market. The classes with a lower laden EEOI in the spot market can be partially explained by ships being operated at slower speeds over the time period; the median speed for all bulk carriers was 11.6 knots for ships operated on spot compared to 13.1 knots on time charter. Payload utilization was .04 percentage points higher for the spot market compared to time charter market.

In the LPG sector, the opposite trend occurred, with the laden EEOI higher for tankers on spot compared to time charter. This is attributed to a lower payload utilization in the spot market.

7.4 Summary

This section provided details on the possible technical and economic drivers of the sub-indices presented in Section 6. From interviews with the companies owning bulk, LPG, and container ships, there were no major technical interventions during the period of the study. However, the company owning bulk carriers was taking operational measures such as economical (slow) steaming and voyage optimization, while the LPG fleet was responding to fuel performance claims by better monitoring the ship's fuel performance and considering retrofits.

Given the bleak prospects for the shipping industry at the end of 2008 (the first year of the study's time period) and high fuel prices through to 2013, ships were slow steaming for all ship types in the study until at least 2013. Payload utilization also followed a similar declining trend, but there was no obvious pattern in allocative utilization. This could be due to different strategies for owners, with some owners minimizing ballast distance whereas other owners were forced to search for employment by ballasting farther. Furthermore, we did not investigate whether there were changing trade patterns which could also alter allocative utilization.

We found that there were significant differences in the laden EEOI by contract type for the ship types we could investigate. For bulk carriers, the median laden EEOI for the majority of size classes operated on spot contracts is lower than for ships operated on the time charter market. This can partly be explained by the lower speed of bulk ships operated in the spot market compared to time charter, and points to the fact that owners which leased their ships on time charter obtained higher (less efficient) EEOI ratings than owner-operated ships.

8 Conclusion

Technical and logistics factors are the key drivers of the Energy Efficiency Operational Index (EEOI). This paper has mathematically decomposed the EEOI into sub-indices in order to understand the drivers of the index. We find that there is a relationship between technical efficiency (EEDI) and EEOI across different ship sizes, but there is a wide dispersion of EEOI values within a ship size class. This can be explained by the variation in logistics factors, with little evidence of correlation between EEOI and any one logistics factor. For all of the types and sizes considered, variations in EEOI can be explained only by considering contributions from a combination of the logistics factors.

We find that consistently across all ship types and size categories, speed decreased during the period of this study, trends for both allocative and payload utilization differ and in many cases showed deterioration in utilization which counteracts operational efficiency improvements obtained by slow-steaming. We also found significant differences in the laden EEOI when a ship was operated on the spot market compared to time charter for a subset of the ships for which there was contract data, resulting in higher laden EEOI for ships on time charter. This points to the importance of principal agent problems in the shipping industry, in which the owner may not be in control of the operation and hence efficiency of the ship for the majority of the operation of a ship.

We compared the EEOI and alternative indicators proposed at the IMO. For each of the different ship types and sizes, the alternative operational energy efficiency indices show varying levels of trend agreement or disagreement. Significantly, it is often the case that the three alternative indicators produce different trends to EEOI. This shows that no alternative energy efficiency metric is a reliable proxy to EEOI and the choice of energy efficiency metric is a function of what information is believed to be of greatest importance. Of the indicators considered, the EEOI is the only indicator that represents the carbon intensity of the actual transport work done (when measured in t.nm's), all other indicators approximate transport work done in some way.

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Appendix

Appendix

A.1 Operational efficiency: the EEOI

The EEOI, or annual fuel consumption divided by transport work, can be considered as the annual average efficiency of a ship in its real operating condition, taking into account actual speeds, draughts, capacity utilization, distance travelled, and the effects of hull and machinery deterioration and weather.

The metric used for quantifying the operational efficiency of shipping is the EEOI (IMO MEPC.1/Circ.684, 2009):

(1)

$$\boxed{EEOI = \frac{\sum_i \sum_j F_{ij} C_j^F}{\sum_i m_i^L D_i^L}}$$

where:

- i = the voyage
- j = the fuel type
- F_{ij} = the amount of fuel consumed for the voyage *i* and fuel type *j*
- C_j^F = the carbon factor for fuel type *j*
- m_i^L = cargo mass of voyage *i*
- D_i^L = distance travelled in loaded voyage *i*
- v_i^L = average loaded speed of voyage *i* in nautical miles per hour

Each individual voyage *i* is summed over a time period *t*. Distance, D_i^L, equals the product of d_i^L, the duration in days of loaded voyage *i*, v_i^L the average speed during the loaded voyage (in knots) and 24. Substituting these terms in for D_i^L:

$$\boxed{EEOI = \frac{\sum_i \sum_j F_{ij} C_j^F}{\sum_i m_i^L d_i^L v_i^L 24}}$$

Efficiency is increasing as *EEOI* decreases. Equivalently, instead of expressing the EEOI as summations of each voyage's parameters, it can be expressed using the average characteristics of a number of parameters during the course of a time period t (commonly 1 year) as:

(2)

$$\boxed{EEOI = \frac{C^F(F^L_{dt}d^L_t + F^B_{dt}d^B_t + F^P_{dt}d^P_t)}{m^L_t d^L_t v^L_{ht} 24}}$$

where:

- C^F = the average carbon factor[9]
- F^L_{dt} = the loaded average daily operating fuel consumption during period *t*
- F^B_{dt} = the ballast average daily operating fuel consumption during period *t*
- F^P_{dt} = the port average daily operating fuel consumption during period *t*
- d^L_t = the days a ship is sailing loaded during period *t*
- d^B_t = the days a ship is sailing ballast during period *t*
- d^P_t = the days a ship is in port during period *t*
- m^L_t = the average cargo mass during period *t*
- v^l_{ht} = the average loaded speed per hour *h* in time period *t*

Equation (2) can be further decomposed into the *EEOI* at sea and the *EEOI* in port:

$$\boxed{EEOI = \frac{C^F(F^L_{dt}d^L_t + F^B_{dt}d^B_t)}{m^L_t d^L_t v^L_{ht} 24} + \frac{C^F(F^P_{dt}d^P_t)}{m^L_t d^L_t v^L_{ht} 24}}$$

$$EEOI = EEOI^{sea} + EEOI^{port}$$

2.2 Technical efficiency in real operating conditions

Analogous to the use of the EEOI to estimate the operational efficiency of a ship, the technical efficiency of a ship or energy efficiency technical indicator (*EETI*) can be defined as the energy efficiency (gCO_2/tonne-nautical mile) of a ship in a reference operating condition (speed and draught):

(3)

$$\boxed{EETI = \frac{C^F F^{ref}_d}{v_{ref} DWT 24}}$$

where:

- C^F = the average carbon factor of the fuel used
- F^{ref}_d = the daily fuel consumption at a reference speed and draught
- v_{ref} = the reference speed[10]
- DWT = the deadweight tonnage of a ship

[9] We assume that C^F is the same for the loaded, ballast and port days.

[10] The reference speed may or may not equal the design speed.

The *EETI* is a ship's estimated technical efficiency in real operating conditions at a specific point in time, whereas the *EEDI* (gCO_2/t-nm), is the ship's design technical efficiency at the start of its life and under specific EEDI assessment conditions. Differences between a ship's EEDI and EETI could arise due to fouling, modification of technical specifications (such as retrofitting) or because the EEDI trial performance cannot be recreated in real operating conditions.

In order to estimate the fuel consumption in a reference condition, a correction factor can be applied to measurements of fuel consumption in a specific operating speed and draught, F_d^{op}.

(4)

$$\boxed{F_d^{ref} = \frac{F_d^{op}}{\left(\sum_{i=1}^{p}\left(\frac{v_{ht}^{op,i}}{v_{ref}}\right)^{n}\left(\frac{T^{op,i}}{T^{ref}}\right)^{2/3}\right)/p}}$$

where:

- $T^{op,i}$ = the operating draught at passage or passage segment *i*
- T^{ref} = the reference draught
- $v_{ht}^{op,i}$ = the average operating speed for a passage or passage segment *i* (nautical miles/hour).
- p = total number of passages or passage segments

Approximating fuel consumption in real operating conditions raises issues around: the accuracy of the correction factor formula (and its applicability to a specific design) and the allowance for the influence (or correction for) weather and metocean conditions (wind, waves, currents) on fuel consumption.

The former issue (applicability of the correction factor) could be addressed by using ship specific correction formulae derived from sea trials or model tests. These were not available for this study, and so standard assumptions were used (applicability of the Admiralty formula, and the use of n = 3, as justified to be generally applicable for most tankers and bulk carriers in Smith et al. 2014).

The latter issue (effect of weather and metocean) cannot easily be resolved. Either the data could be collected inclusive of any effects, or it could be filtered to contain only fuel consumption measurements obtained during a day with weather and current effects deemed to be sufficiently low as to be negligible. The inclusion of weather and current effects is more 'honest', but route and seasonal effects will influence the EETI. The route/season specificity will diminish if data is collected and averaged over a sufficiently long period of time.

Both of these issues are linked to long-running debates in the operation and regulation of ships and deserve greater attention than can be afforded here. For the purposes of this study, we take the EETI to be inclusive of all weather and metocean effects encountered by a ship in its day-to-day operation.

2.3 Decomposing EEOI into technical and logistics factors

The EEOI and the EETI, when estimated from measurements of a ship's daily fuel consumption and activity, are inextricably linked because they have overlaps in their input data. The mathematical derivation of the two formulae can be used to show how EEOI can be decomposed into a number of technical and logistics factors, one of which is the ship's EETI. This is useful as a means to break EEOI down into a series of drivers that each influence the overall value. As the only 'technical factor', the EETI indicates the technical efficiency contribution to the EEOI quantification, while three logistics factors indicate the contribution of the specifics determining the ship's commercial operation (speed and utilization).

An annual estimate of EEOI normally includes emissions when a ship is in port and at sea. Although the port emissions should be included in the total EEOI, for the purposes of decomposition analysis it is important to separate the port emissions from sea emissions, as they represent a source of variability in overall emissions which has little or no connection to technical efficiency or the main logistics drivers of changes in operational efficiency. Distinguishing between port-time emissions and sea emissions, also allows port emissions to be effectively monitored.

As port emissions represent only a small fraction (e.g. as shown in Figure 5, less than 10%), a simplifying assumption can be made in order to reduce the complexity of the computations:

$$EEOI^{sea} \sim EEOI$$

This assumption is applied whilst combining (4) with (2) and inserting (3) (under the assumption that n = 3), which enables the production of an expression that makes the link between EEOI and EETI:

(6)

$$EEOI \sim \frac{C^F F_d^{ref} \left(\left(\sum_{i=1}^{p} \left(\frac{v_{ht}^{op,i}}{v_{ref}} \right)^n \left(\frac{T^{op,i}}{T^{ref}} \right)^{2/3} \right) / p \right) (d_t^L + d_t^B)}{m_t^L d_t^L v_{ht}^L 24}$$

$$\sim \frac{C^F F_d^{ref}\left(\left(\sum_{i=1}^{p}\left(\frac{v_{ht}^{op,i}}{v_{ref}}\right)^n \left(\frac{T^{op,i}}{T^{ref}}\right)^{2/3}\right)/p\right)(d_t^L + d_t^B) v_{ref} DWT24}{v_{ref} DWT24 m_t^L d_t^L v_{ht}^L 24}$$

$$\sim EETI \frac{\left(\left(\sum_{i=1}^{p}\left(\frac{v_{ht}^{op,i}}{v_{ref}}\right)^n \left(\frac{T^{op,i}}{T^{ref}}\right)^{2/3}\right)/p\right) v_{ref}}{v_{ht}^L} \frac{(d_t^L + d_t^B)}{d_t^L} \frac{DWT}{m_t^L}$$

$$\sim \frac{EETI}{\frac{m_t^L}{DWT} \frac{d_t^L}{(d_t^L + d_t^B)} \frac{v_{ht}^L}{\left(\left(\sum_{i=1}^{p}\left(\frac{v_{ht}^{op,i}}{v_{ref}}\right)^n \left(\frac{T^{op,i}}{T^{ref}}\right)^{2/3}\right)/p\right) v_{ref}}}$$

Rearranging for $EETI$:

(7)

$$\boxed{EETI \sim EEOI \frac{m_t^L}{DWT} \frac{d_t^L}{(d_t^L + d_t^B)} \frac{v_{ht}^L}{\left(\left(\sum_{i=1}^{p}\left(\frac{v_{ht}^{op,i}}{v_{ref}}\right)^n \left(\frac{T^{op,i}}{T^{ref}}\right)^{2/3}\right)/p\right) v_{ref}}}$$

Equations (6) and (7) show that it is possible to formulate EEOI or EETI in terms of one another if a number of extra details about speed, cargo and the loaded/ballast voyages are known. These are, as represented in the right hand side of (6) and (7):

$\frac{m_t^L}{DWT}$= the average payload utilization

$\frac{d_t^L}{(d_t^L + d_t^B)}$= the allocative utilization or ratio of laden days to total operating days

$\frac{v_{ht}^L}{\left(\left(\sum_{i=1}^{p}\left(\frac{v_{ht}^{op,i}}{v_{ref}}\right)^n \left(\frac{T^{op,i}}{T^{ref}}\right)^{2/3}\right)/p\right) v_{ref}}$= the speed and draught factor

The speed and draught factor shows a moderate degree of complexity. That is because the correction of speed and draught incur non-linear relationships (speed to the power 3, and draught to the power 2/3). As a result of this non-linearity, simplifying to annualized averages of operating speed and draught would create inaccuracies. The significance of those inaccuracies will be a function of the variability in operating speed and draught from one voyage to the next. The variability in operating speed is more important than the variability in draught (as speed varies according to a higher power). For the purposes of monitoring and reporting, it is possible to calculate the speed factor term on a voyage-by-voyage basis that can be used to calculate a single annualized figure (e.g. there is no need for voyage-level data to be reported).

In this study, draught information was not consistently available. Furthermore, it can be seen that draught is of lower importance to the correction factor than speed. As a result the draught correction is omitted, and only operating speed corrections (calculated for each unique component sea passage) are included.

The average payload utilization is always less than 1, the allocative utilization is also always less than one, and the speed factor could be greater than, equal to, or less than 1. Although commonly, especially recently, it will be greater than 1 – demonstrating slow steaming.

In operation, a ship with a higher *EETI* value can offset this lower efficiency disadvantage by obtaining a higher average payload utilization, allocative utilization, speed factor, or some combination of these factors. **As expected, this shows that the *EEOI* is highly influenced by how a ship is commercially operated, and only partially influenced by the technical efficiency of the ship.**

A.2 Data collection processing by company

Figure 3 provides an overview of all scripts developed in order to process the data supplied by RBSA.

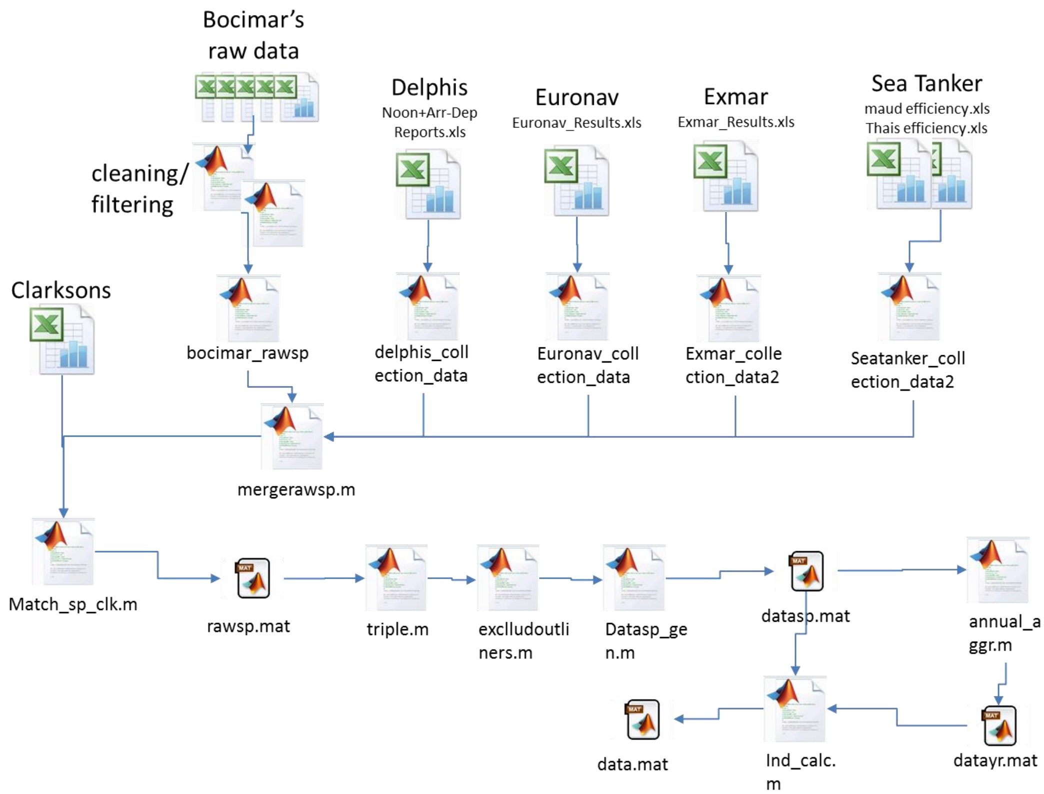

Figure 3 Matlab scripts structure

Company 1 (Bocimar) – script name: bocimar_rawsp

- Calculation of main engine and auxiliary engine fuel consumptions ware obtained using the formulas:

$$FC_{me} = FC_{me\_day} * AT_{days}$$

$$FC_{ax} = FC_{ax\_day} * AT_{days}$$

$$FC_{p} = FC_{p\_day} * AT_{p\_days}$$

where :

- AT are the actual time days per voyage
- ATp are the actual time days at port
- FCme is the fuel consumption ME_day per voyage
- FC ax is the fuel consumption Aux_day per voyage
- FCp is the fuel consumption at port

- Fuel type of the main engine is assumed to be HFO, while fuel type of auxiliary engine and fuel consumption at port is assumed type to be MDO.
- One single variable "distance" has been created merging three parameters: miles laden, miles ballast and sea miles. When one of the first two is missing then sea miles is used.

Company 2 (Delphis) – script name: delphis_collection_data

Data for this company are taken from noon report and arrival and departure report. The noon report contains per each record:

- the position of the ship (latitude and longitude) in a specific date,
- the average speed,
- the next port of call,
- the distance made in the last 24 hours,
- the miles to go to next port,
- the fuels quantity on board,
- the main engine RPM.

The arrival and departure report contains:

- the date,
- the port name,
- fuels quantity on board on arrival and on departure,
- the draft data on arrival and departure,
- the next port of call.

We combine the noon reports and the arrival and departure reports, and we use two temporal consecutive records to create a sea passage record. An algorithm is used to calculate per each sea passage the distance made, the fuels consumptions at sea and at port. We don't have times data (hrs at sea) which have been calculated using speed and distance.

The algorithm calculates the parameters for the EEOI calculation considering three different cases:

1. ship at port and next signal at sea
2. ship at sea and next signal at port
3. case ship at sea and next signal at sea

Company 3 (Euronav) – script name: euronav_collection_data

Data are taken from the aggregated spreadsheet file provided by RBSA. This spreadsheet doesn't contain data for time at port, and fuel consumed in port. However time port in hours is estimated using the dates of start and end of the sea passage assuming that each sea passage finishes at port.

$$Hrs_p = SSP_{(t+1)} - ESP_{(t)}$$

Where:

Hrs_p are the hours spent at port

$SSP_{(t+1)}$ is the date of start of sea passage including time ('dd/mm/yyyy HH:MM') in the observation (t+1)

$ESP_{(t)}$ is the date of start of sea passage including time in the observation (t)

We note that for these ships we still miss information about the fuel consumption at port.

Company 4 (Exmar) – script name: exmar_collection_data2

Data are taken from the aggregated spreadsheet file provided by RBSA.

Each row in this spreadsheet contains data per sea passage and data in adverse weather in separated columns. So, data in adverse weather has been aggregated in each sea passage and taken in account in the calculation of the indices.

Company 5 (Sea Tanker) – script name: seatanker_collection_data2

Data are taken from arrival and departure reports. This type of report contains per each record:

- port name,
- arrival date and time,
- departure date and time,
- fuels quantities on board on arrival and on departure times,
- cargo mass on board,
- speed
- distance

Two consecutive records are taken in account to create a sea passage record. The ESP is calculated as difference between time of arrival and times of departure of the two records. Similarly fuel consumptions at sea and at port is derived from fuels data at arrival and departure date of the two records.

Cargo, speed and distance of the sea passage is assumed to be equal to the ones reported in the latest record. Only when cargo is empty the sea passage is considered ballast.

A2. Outliners

The check of the consistency between the triple speed, distance and hours doesn't exclude outliners, which we define as "unrealistic data" (e.g negative values, very high value). The Figure 4 shows the distribution of these variables and their correlations.

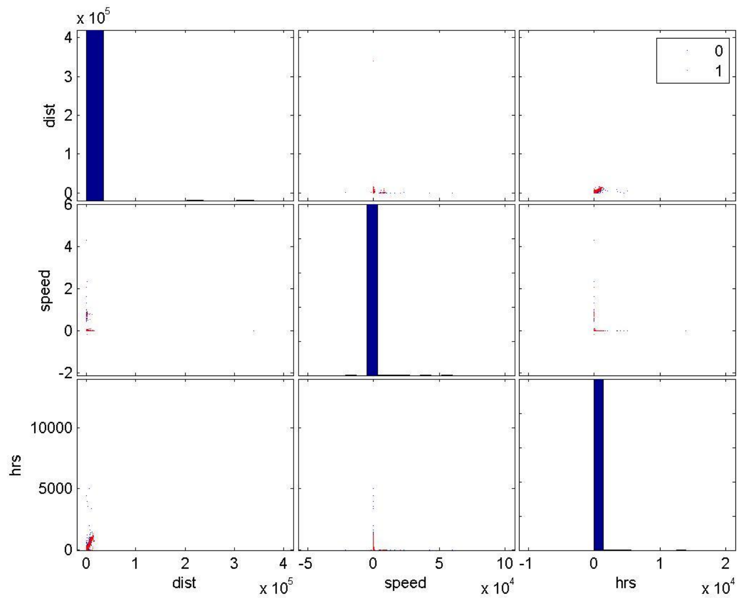

Figure 4 Distribution of speed, distance and time before excluding outliners

Then we remove the rows with all values that meet the following criteria:

- Speed >30 or <0 nmiles/hrs
- Distance >5000 or <0 miles
- Hours >5000 or <0 hr

Figure 5 shows the distribution after excluding outliners.

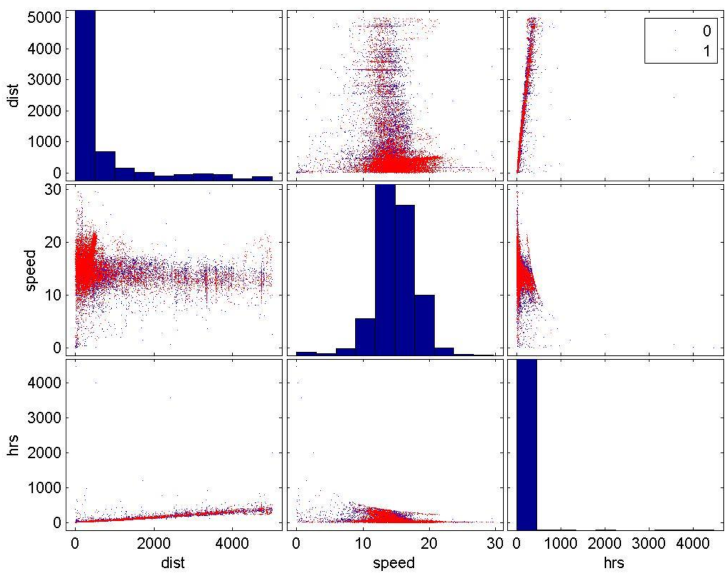

Figure 5 Distribution of speed, distance and time after excluding outliners

Similarly it has been applied for cargo. Every time cargo is bigger than the dwt, we remove the entire row.

Slightly different it has been applied for the variables: hours at port, fuel consumptions at ports, fuel consumptions at sea, and cargo. For these variables we set to NaN instead of removing the entire row. Figure 6, Figure 7, Figure 8, and Figure 9 provide the distribution of these variables before and after excluding the outliners. The criteria to select the outliners for these variables are:

- Hors at ports >1000 or <0
- HFO and LSO at port >50 or <0
- MDO and MGO at port >100 or <0
- HFO at sea >10000 or <0
- LSO at sea >2000 or <0
- MDO and MGO at sea >100 or <0

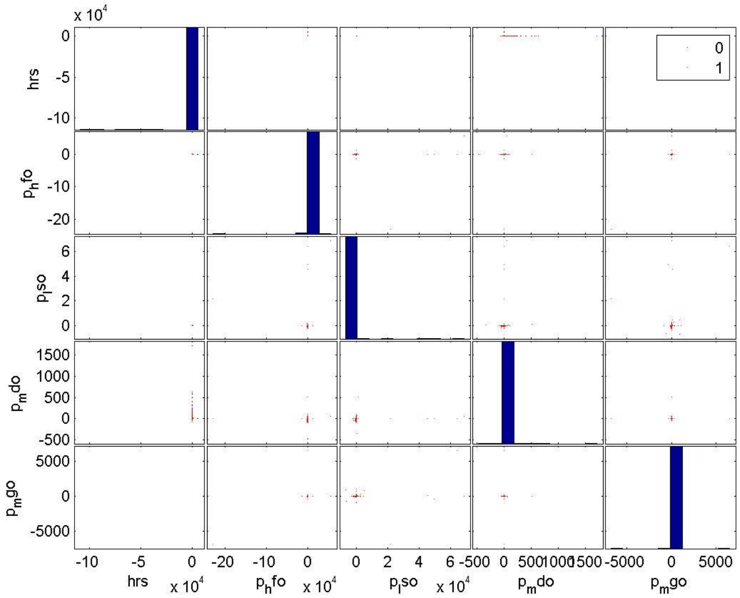

Figure 6 Distribution of time and fuel consumptions at port before excluding outliners

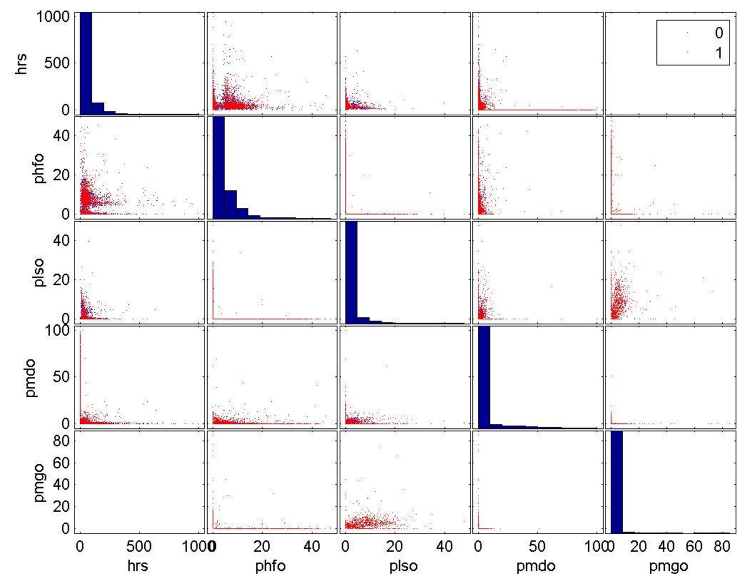

Figure 7 Distribution of time and fuel consumptions at port after excluding outliners

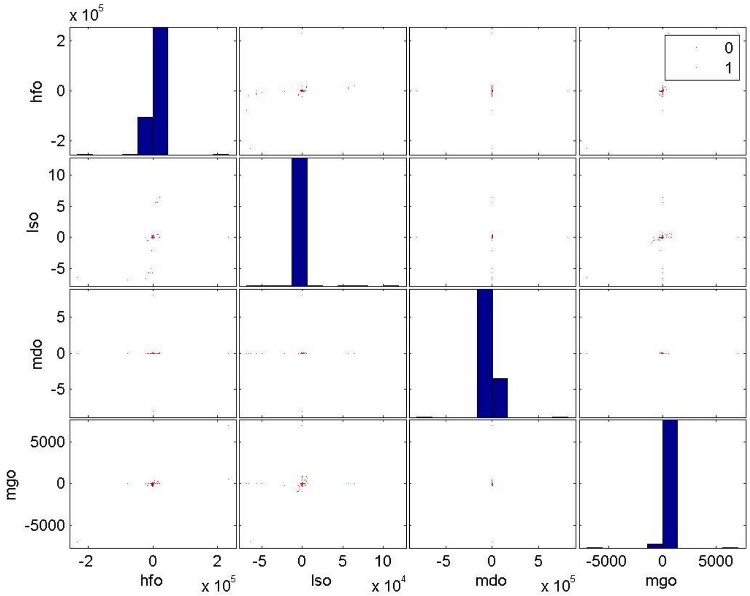

Figure 8 Distribution of fuel consumptions at sea before excluding outliners

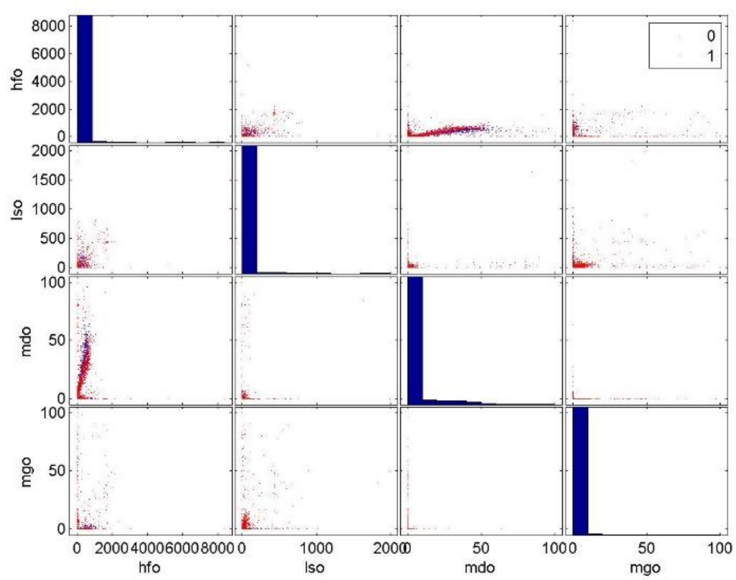

Figure 9 Distribution of fuel consumptions at sea after excluding outliners

A3. Excluded values.

In this step we generate "out" variables that are taken out from the calculation of the EEOI. Particularly we take in account 4 cases:

1. If fuel consumption per laden voyage are known, however distance for these voyages are missing and speed is different from zero. In this case for not overestimating the numerator of EEOI formula we take out the fuel

consumptions and all the variables by setting NaN and creating the variables "out".

2. Fuel consumptions per laden voyages are missing, however distance for these voyages are known and speed is different from zero. In this case for not overestimating the denominator of EEOI formula we take out the distance and all the variables by setting NaN and creating the variables "out".
3. Fuel consumptions per laden voyages are known, however cargo for these voyages are missing. In this case for not overestimating the numerator of EEOI formula we take out the fuel consumptions and all the variables by setting NaN and creating the variables "out". In this case containers are excluded.
4. Fuel consumptions per laden voyages are missing, however cargo for these voyages are known. In this case for not overestimating the denominator of EEOI formula we take out the cargo and all the variables by setting NaN and creating the variables "out". In this case containers are excluded.

Table 4 shows the number of ships in the sample for which we are able to calculate the EEOI per year.

A3. Population Distribution Statistics

The population statistics (with a log normal y-axis scale and kernel distribution fit) for categories of ship types is also calculated and represented in Figures 7-10.

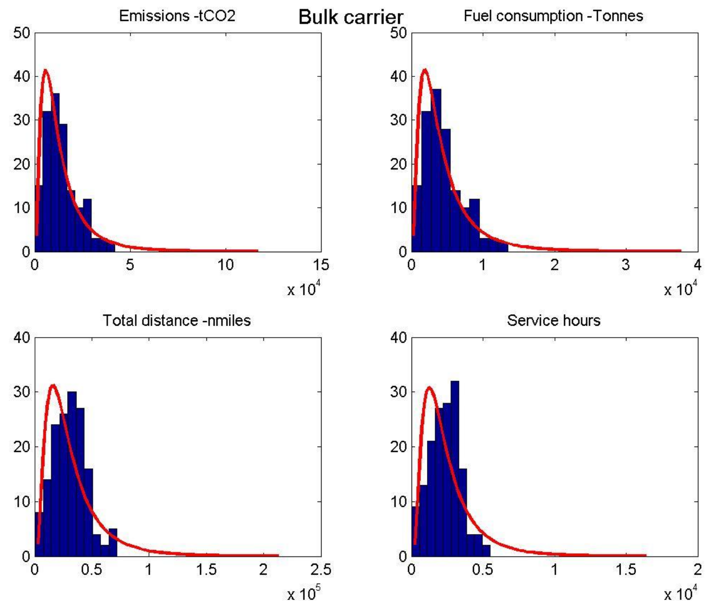

Figure 10 Population statistics for Bulk carrier

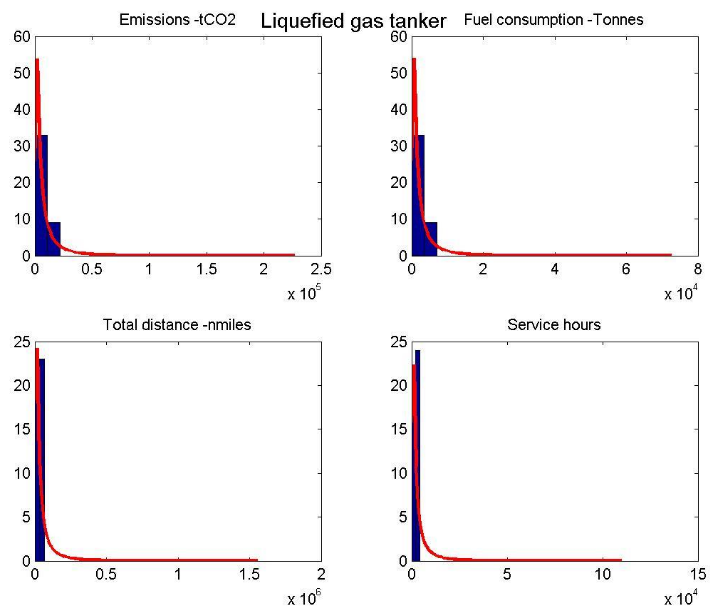

Figure 11 Populations statistics for liquefied petroleum gas

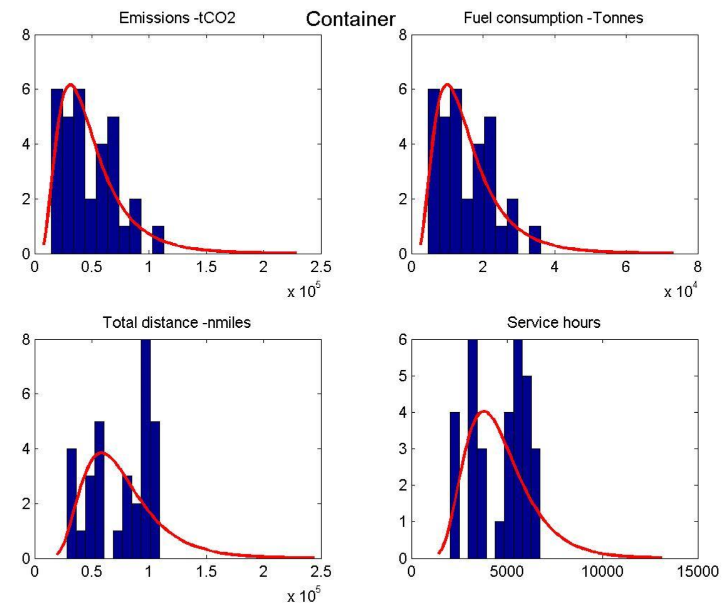

Figure 12 Population statistics for containers

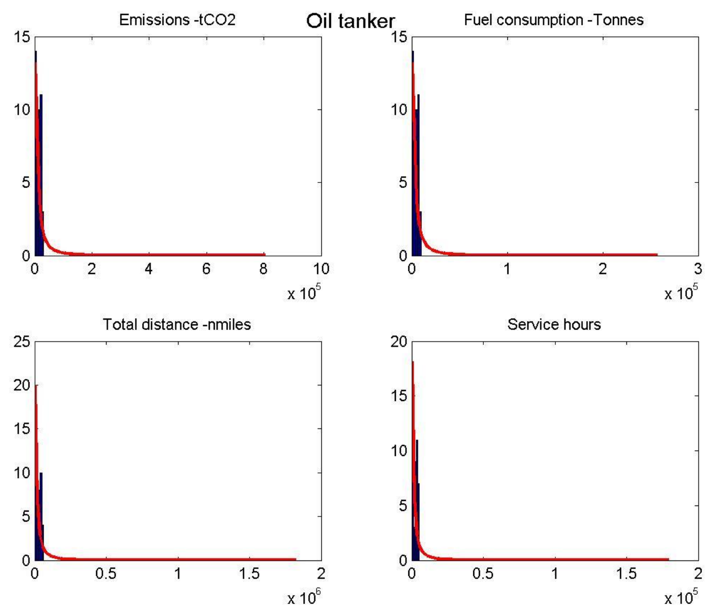

Figure 13 Population statistics for oil tankers