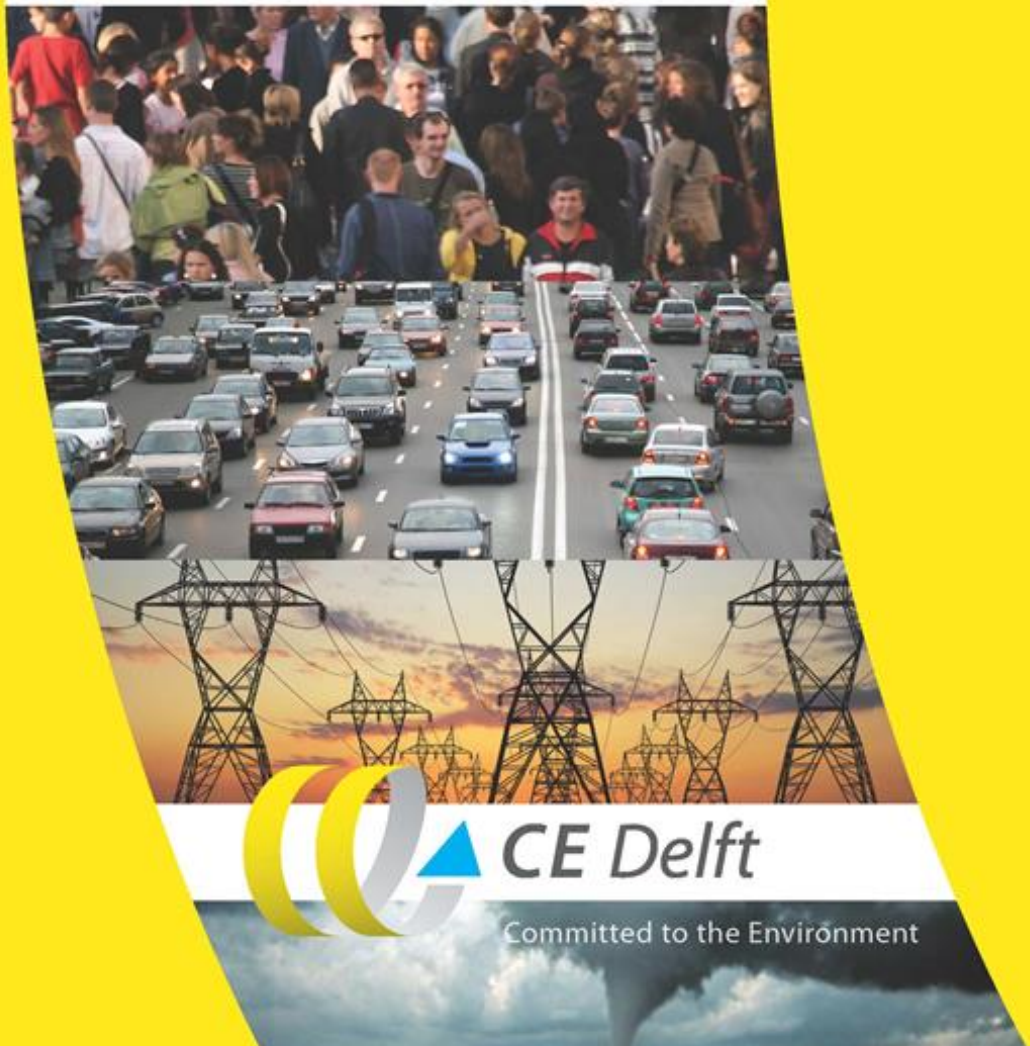
# Historical Trends in Ship Design Efficiency

## The Impact of Hull Form on Efficiency



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# Historical Trends in Ship Design Efficiency

## The Impact of Hull Form on Efficiency

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# Content

# Summary

There is a growing interest in the fuel efficiency of ships because of fuel prices, climate change and energy security issues. This has resulted in, amongst other things, a regulation governing the design efficiency of new ships called the Energy Efficiency Design Index (or EEDI for short). As of 2013, new ships are required to have an EEDI that meets or exceeds a target. The required EEDI is set as a percentage efficiency improvement relative to a baseline constructed from the average design efficiency of ships that have entered the fleet in the period 1999-2008. The percentage improvement will increase from 0% in 2013 (all ships have to be as efficient as the average of ships built between 1999 and 2008) to 30% from 2025 onwards.

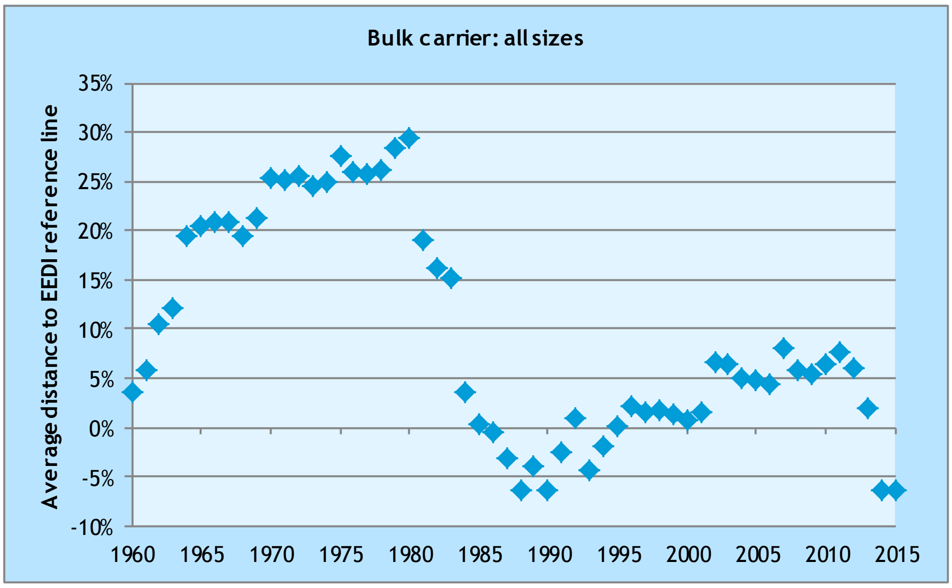
The Marine Environment Protection Committee (MEPC) of the International Maritime Organization (IMO) is currently engaged in a review of the 2020 target. One of the main questions being addressed is whether the stringency of the regulation should be retained or amended. Another issue of general interest is the effectiveness of existing EEDI targets in driving design efficiency improvements.

This study analyses which factor or factors have contributed to changes in the average design efficiency over time and what their relative importance has been.

### Key findings
The key findings of this study are:
- All ship types analysed here show a clear pattern of design efficiency changes, in which the average design efficiency of new ships improved considerably in the 1980s, deteriorated after 1990 and improved in recent years.
- Changes in ships design speeds, and in the power required to overcome the main component of resistance, viz. the frictional resistance, can only explain a fraction of the changes in the design efficiency.
- Other elements of ship design have historically been more important, such as hull, propeller and rudder design.
- Historically, fuel price and freight rates have been major drivers of fuel efficiency.
- The efficiency changes witnessed in recent years appear to be the result of high fuel prices rather than of regulation. The impact of the EEDI regulation may become more important in the coming years as a result of the lower fuel prices and the increased stringency.

### Historical development of design efficiency
The design efficiency of new ships improved significantly in the 1980s before peaking in the 1990s and then deteriorating after that. Figure 1 shows how the average design efficiency of new ships has changed over time for bulk carriers. A similar pattern can be observed for tankers and container ships.

Figure 1 Design efficiency of bulk carriers, 1960s-2000s




Source: CE Delft.

Note: A negative value indicates a relatively efficient fleet, a positive value a relatively inefficient fleet.

In order to establish which factors have contributed to the development in energy efficiency, this study has analysed the contribution of:
- changes in average size of ships;
- changes in design speed;
- changes in the main engine power that is required to overcome the frictional resistance of the ship;
- changes in the difference between the actual main engine power and the power required to overcome the frictional resistance.

The latter factor is shown to have the largest contribution to changes in design efficiency. In periods with relatively poor design efficiencies, ships had more powerful engines relative to their size, design speed and frictional resistance, while in periods in which relatively efficient ships entered the fleet, the engines had less power than the long term average relation between power, speed, and size would predict.

Since the excess power (or lower than expected power) was not used to sail faster (slower), or transport more (less) cargo, a higher than expected power must mean that other elements of resistance were lower. So the development of the efficiency of new ship depends to a large extent on the hull efficiency (i.e. how the water flows around the hull and into the propeller), propeller efficiency, interaction with the rudder, transmission efficiency, et cetera.

## Drivers of efficiency improvements

The changes in design efficiency were found to reflect changes in market circumstances. Higher fuel prices make fuel-efficient ships more attractive, because efficiency reduces the total cost of ownership. Because in general fuel-efficient hull designs are more expensive to build, the payback period of the additional capital expenditure is shorter when fuel prices are high.

Fuel prices are not the only relevant factor: freight rates are also an important influence on ship design efficiency. When freight rates are high, new ships are in high demand and yards can build standard designs with a low risk of cost overruns and a high profit margin. In these circumstances, it may not be rational for yards to build higher risk innovative designs. Conversely, when freight rates are low, shipyards compete for clients and may be willing to build more efficient ships.

The analysis also shows that the design efficiency of new ships has improved significantly since 2012. In just a few years, the average ship has approached its historical efficiency maximum, previously reached in the 90s. It is clear that high fuel prices have played a key role in this improvement, as well as low freight rates. Since the design efficiency of ships that have a mandatory EEDI is not much better than the average design efficiency of ships that entered the fleet in the same period but were not covered by the EEDI and not required to meet an EEDI efficiency target, it appears that the stringency of the current EEDI design efficiency targets has had little impact to date.

The current low fuel prices and low freight rates provide a driver for a deterioration of the design efficiency of ships. The EEDI can prevent that from happening, especially when the stringency is increased.

# 1 Introduction

## 1.1 The relevance of an historical analysis of design efficiency

A growing interest in the fuel efficiency of maritime transport has been discernible in the last decade, driven by relatively high fuel prices (at least until mid-2014), climate change policies, corporate social responsibility policies of shipping companies and shippers, concerns about energy security and the costs of oil imports. Shipping companies, shippers, ports and other organisations have taken voluntary action, and regulation has been introduced.

### 1.1.1 Policy context

At a global level, Member States of the International Maritime Organisation (IMO) have taken action by including energy efficiency regulations in Annex VI of the MARPOL Convention. New ships need to meet a minimum Energy Efficiency Design Index (EEDI) value and all ships have to have a ship energy efficiency management plan, specifying how they monitor and control operational efficiency.

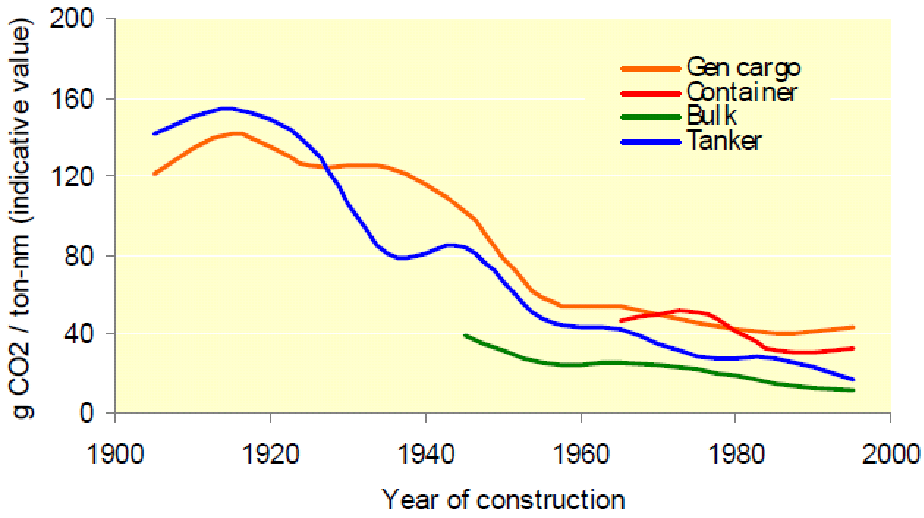
As of 2013, new ships are required to have an Energy Efficiency Design Index (EEDI) and to prove that the ship is more efficient than a minimum standard. Over time, the standard is set to become more stringent. In the first phase, the design efficiency of most new ships needs to be better than a reference line that is based on the average efficiency of ships that entered the fleet in the period 1999-2008. From 2015, ships have to be 10% better, five years later 20% better and starting 2025, the EEDI has to be 30% better than the reference line. Currently, the IMO is reviewing the stringency of the second phase.

Since the EEDI requirements are based on a historical average efficiency, it is instructive to be able to assess the efficiency in this period. This can be done by comparing the efficiency of new ships in the period 1999-2008 with the efficiency of ships in other periods.

### 1.1.2 Fuel efficiency of ships and other transport equipment

The historical design efficiency of new ships has not received much attention in the literature. The Second IMO GHG Study 2009 (Buhaug, et al., 2009) contains a brief analysis of average design efficiency over time, which suggests that the efficiency has generally improved considerably, but also that the design efficiency of general cargo ships and container ships deteriorated in the early 1990s (see Figure 2). The study does not present an analysis of the factors that contributed to these trends.

**Figure 2** Indicative development in average ship design transport efficiency

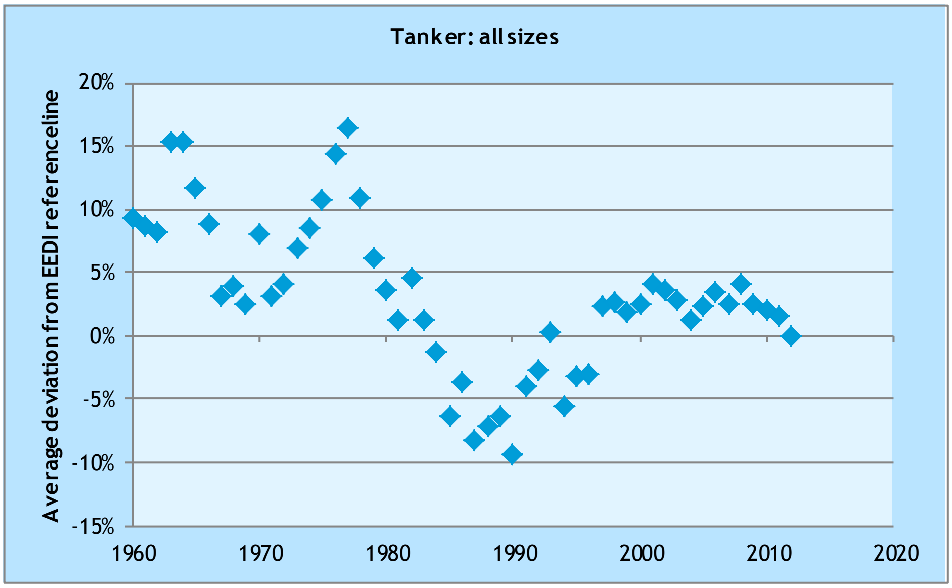



Source: (Buhaug, et al., 2009).
Note that the design efficiency is expressed in a different metric than used in this report.

Mortenson (2009) confirmed the general trend but showed that the efficiency of specific ship types follows different trends (Mortensen, 2009). The article showed that while the design efficiency of 1,800 TEU and 4,500 TEU containerships improved between 1990 and 2000 and remained more or less constant until 2009, the design efficiency of VLCC tankers improved between 1995 and 2000, but deteriorated in the next period. The efficiency of handysize bulkers does not show any trend.

CE Delft (CE Delft, 2015) analysed the design efficiency of ships that have entered the fleet since 1960 and found a similar pattern for bulk carriers, tankers and containerships. In general, the design efficiency of new ships improved significantly in the 1980s, was at its best in the 1990s and deteriorated after that. Figure 3 shows how the design efficiency of tankers has developed: a decrease in the deviation from the reference line indicates an improvement in efficiency, whereas an increase indicates a deterioration.

Figure 3 Development of the design efficiency of new tankers, 1960-2012




Source: IHS Maritime World Register of Ships, Clarkson World Fleet Register, calculation CE Delft.

Note: Design efficiency is defined as the EIV divided by the EEDI reference line, averaged across all ships built in a certain year.

Whilst CE Delft (CE Delft, 2015) clearly showed that the design efficiency of new ships had varied over time and how, and also pointed to the influence of fuel prices, building costs and freight rates, the study did not show what had caused the efficiency changes. This is nevertheless relevant to know when regulating design efficiency. It is also especially relevant for the ongoing review of the EEDI.

## 1.2 Objectives

The main aim of this study is to identify the factor or factors that have contributed to changes in the average design efficiency and analyse their relative importance.

Specifically, this study sets out to answer the following questions:
- How has the design efficiency of new ships changed over time for containerships, tankers and bulkers?
- Which changes in the design parameters speed, main engine power, and hull shape have contributed to the changes in efficiency and to what extent?
- Which drivers and barriers have resulted in design changes?

## 1.3 Methodology

This study has analysed the design efficiency of new ships that have entered the fleet in three steps. First, the design efficiency is calculated for each ship in the database for which sufficient data are available. Second, the power required to overcome the frictional resistance of the ship at the design speed is calculated and compared with the actual main engine power of the ship.

Third, the relation between the design efficiency on the one hand and the difference between the actual and expected main engine power is analysed. Each of these steps is described below in more detail.

### Analysis of design efficiency

This report defines the design efficiency as the Estimated Index Value (EIV), which is a simplified form of the EEDI. In contrast to the EEDI, the EIV can be calculated on the basis of publicly available data. The EIV was also used to set the EEDI reference lines.

The EIV is given by the formula (MEPC.215(63)):

$$EIV = 3.1144 \cdot \frac{190 \cdot \sum_{i=1}^{NME} P_{MEi} + 215 \cdot P_{AE}}{Capacity \cdot V_{ref}}$$

With:

3.1144 = The $CO_2$ emission factor of fuel (g/g).
190 = The specific fuel consumption of main engines (g/kWh).
215 = The specific fuel consumption of auxiliary engines (g/kWh).
$P_{ME(i)}$ = 75% of the total installed main power ($MCR_{ME}$) (kW).
$P_{AE}$ = The auxiliary power calculated according to paragraphs 2.5.6.1 and 2.5.6.2 of the annex to MEPC.212(63) (kW).
Capacity is defined as 70% of dead weight tonnage (dwt) for containerships and 100% of dwt for other ship types (tonnes).
$V_{ref}$ = Speed as indicated in the database (knots).

We have compiled a database of all ships that have entered the fleet since 1960 that contains their speed, deadweight tonnage, main engine power and dimensions based on the Clarksons World Fleet Register (for ships in the current fleet) and on the IHS Maritime World Register of Ships (for ships that were scrapped before 2015).

Next to the EIV of each ship in the database, the relative design efficiency is calculated and defined as the EIV of the ship divided by the EEDI reference line value of that ship.

The reference lines are set by IMO (MEPC, 2011). Table 1 shows the reference line values for the ship types analysed in this study.

**Table 1 Reference line formula for different ship types**

| Ship type | Reference line value |
|---|---:|
| Bulker | $961.79*(dwt)^{-0.477}$ |
| Tanker | $1218.8*(dwt)^{-0.488}$ |
| Container ship | $174.22*(0.7*dwt)^{-0.201}$ |

Source: (MEPC, 2011).

### Analysis of engine power

Based on more than 10,000 ships in our sample, we calculated the relationship between main engine power, speed and displacement for each ship type, using a relationship between engine power and frictional resistance of the ship.[1]

$$ln(P_{ME}) = c * ln(V * frictional\ resistance)$$

With:
$P_{ME}$ = Main engine power.
$c$ = A constant.
$V$ = Speed.
And $frictional\ resistance$ calculated as in Annex D.

The frictional resistance of a ship is the most important component of a ship's resistance, accounting for 70% of more of the total resistance of bulk carriers and tankers and somewhat less for container ships, which have a higher design speed.

This approach for calculating the expected main engine power does not account for wave-making resistance, nor does it account for the hull efficiency, propeller efficiency, relative rotative efficiency and other elements that determine the efficiency of a ship.

On the basis of this relation, we calculated for each ship in the database, which power it would need to provide the service to society in terms of capacity and speed if it was an average ship. We compared this $P_{ME,\ expected}$ with the actual main engine power to determine whether the ship had a more or less powerful engine than the average similar ship. The difference between the actual $P_{ME}$ and $P_{ME,\ expected}$ is labelled $P_{ME,\ deviation}$.

### Relation between engine power and design efficiency

Finally, the impact of the $P_{ME,\ deviation}$ on the relative design efficiency is determined.

## 1.4 Scope of the study

The study analyses the design efficiency of bulkers, tankers and containerships and its development between 1958 and 2015. In 2012, these ship types collectively emitted approximately 60% of the shipping $CO_2$ emissions (Third IMO Greenhouse Gas Study, 2014). The database includes ships above the threshold at which an EEDI is mandatory (see Table 2).

**Table 2 Minimum size threshold for inclusion in the analysis**

| Type | Minimum dwt |
|---|---:|
| Bulk carrier | 10,000 |
| Containership | 10,000 |
| Tanker | 4,000 |

Source: (MEPC, 2011).

[1] We calculated this relationship by running a series of regressions, see Annex C.

The focus of the study is the design efficiency of the ship. Note that because design efficiency is expressed as the EIV, changes in engine efficiency are not reflected in the design efficiency, rather the design efficiency reflects changes in hull shape, propulsion and rudder efficiency.

## 1.5 Outline of the report

The next chapter presents the development in design efficiency of ships that have entered the market between 1960 and 2015 and analyses the contribution of changes in speed, size and frictional resistance. Chapter 3 analyses drivers of changes in design efficiency. Chapter 4 presents the conclusions of the study.

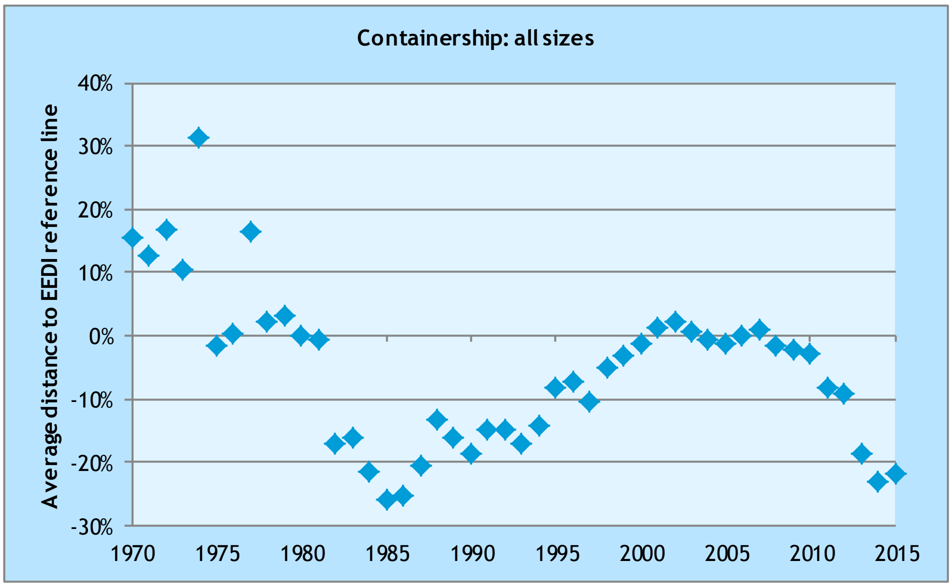
# 2 The development of design efficiency 1960–2015

## 2.1 Container ships

### 2.1.1 Changes in design efficiency and deviations from expected engine power

Our database has data on a sufficient number of containerships from about 1970 onwards. For ships built in the 1960s, only a few records per year have the required data to calculate the EIV, so the average is not very reliable. Figure 4 shows how the deviation of the EIV from the reference line has changed since 1970. The graph shows large swings in the average efficiency of new builds in the 1970s, and a marked decline until the mid-1980s. The period until 2000 saw a steady deterioration of the design efficiency of new container ships, followed by an improvement after around 2006, the year in which some of the fastest container ships ever built entered the fleet.

Figure 4 **Development of the design efficiency of new container ships, 1970-2012**

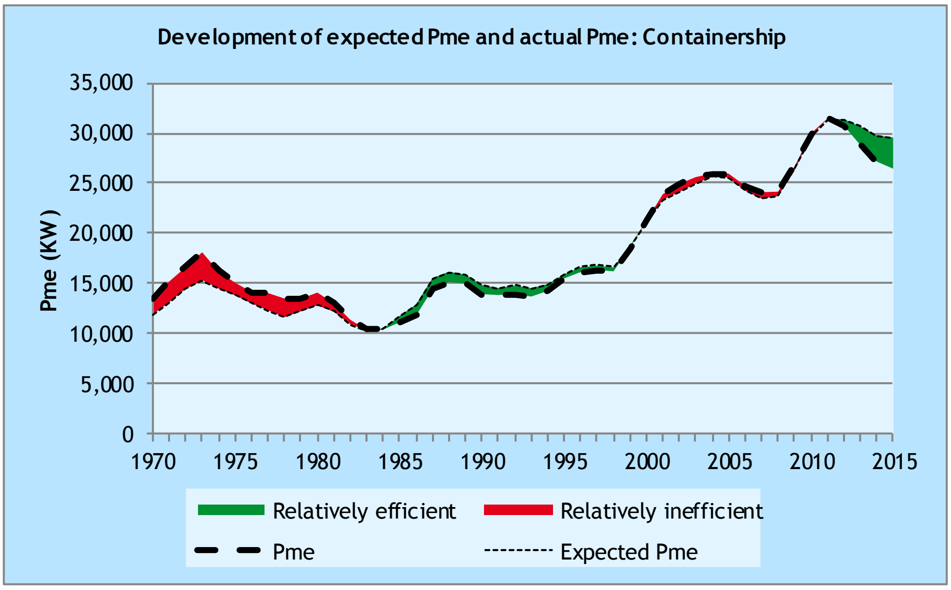



Source: IHS Maritime World Register of Ships, Clarkson World Fleet Register, calculation CE Delft.

Note: Design efficiency is defined as average distance of the EIV divided to the EEDI reference line for all ships built in a certain year.

As explained in Section 1.3 and Annex A we calculated the expected engine power based on the developments over time of the design speed and the frictional resistance. The expected engine power and the actual development of the engine power are plotted in Figure 5. When the actual engine power is higher than the expected engine power this suggests a relatively inefficient technical ship design (marked in red). However a negative deviation from the expected engine power, i.e. the actual engine power is lower, suggests a relatively efficient technical ship design (marked in green).

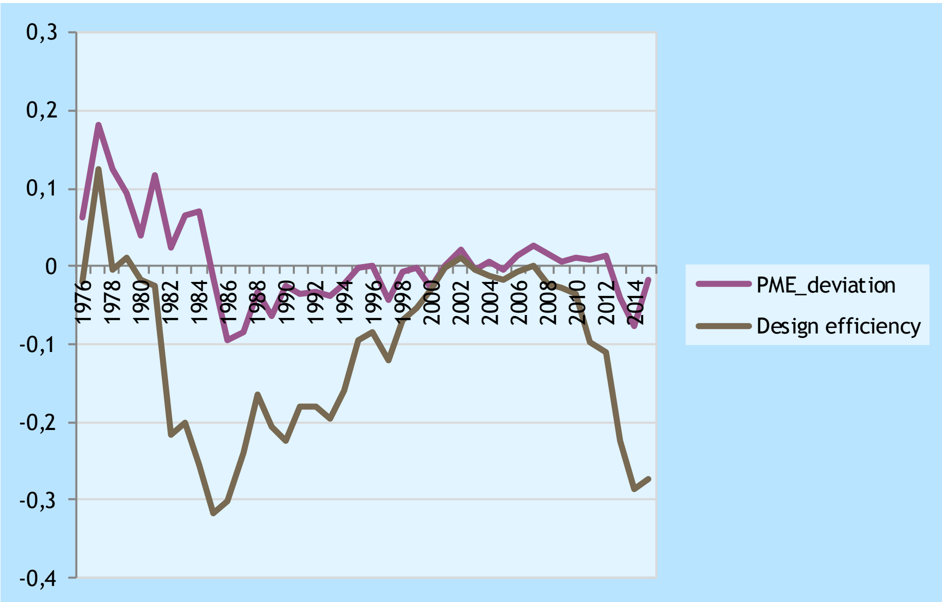
Figure 5 **Development of expected Pme and actual Pme for Containerships**




Source: CE Delft.

The relation between the design efficiency and the deviation from the expected main engine power is shown in Figure 6, which plots the development of design efficiency ($log\,\frac{EIV}{EIV_{ref}}$) and deviations from expected engine power ($\log(PME_{deviation})$) over time.

Figure 6 **The development of design efficiency and deviations from expected power over time, for container ships**




Source: CE Delft.

From Figure 6, we note that the patterns of development over time of design efficiency and deviation from the expected main engine power are rather similar. They have the same peaks and troughs in the pattern.

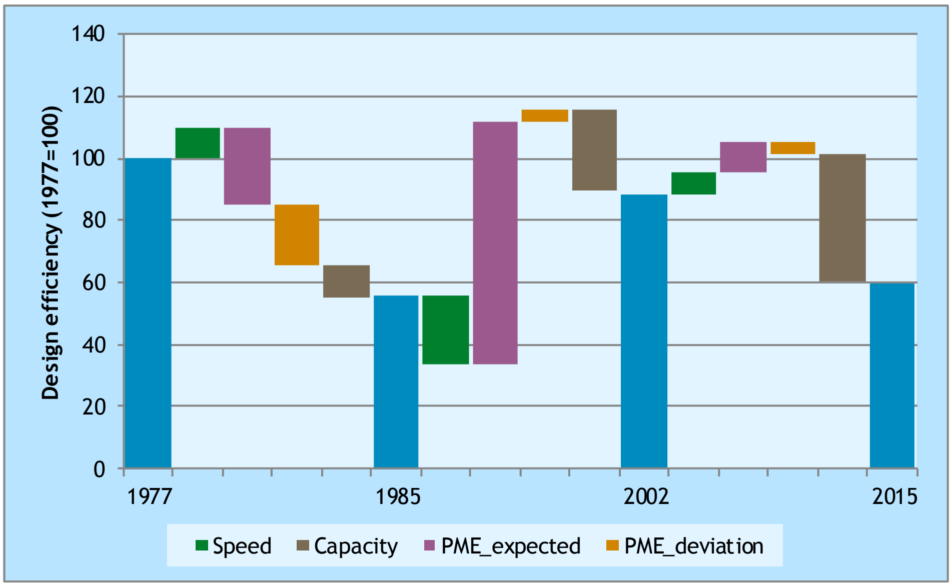
This is confirmed by the correlation between the two patterns over time, which equals 61%. So deviations from expected main engine power are an important factor in the design efficiency for container ships.

With regard to the development of design efficiency, we observe that there are distinguishable time periods in which design efficiency is rising and in which it is falling. This pattern is analysed in more detail in Section 2.1.2.

### 2.1.2 Changes in design efficiency as a consequence of design speed, capacity, expected engine power and deviations from expected engine power

Figure 6 shows that the design efficiency of container ships was at a peak (least efficient) in 1977, improved until 1985, deteriorated until 2002 and improved in the period since. These developments can be explained on the basis of changes in the average speed of new vessels, average size, changes in $P_{ME\_expected}$ which is a result of a change in frictional resistance caused by changes in speed and wetted surface area, and changes in $P_{ME\_deviation}$.
Figure 7 shows the contribution of each of these factors to the changes in the design efficiency.

**Figure 7** **% change of design efficiency due to % changes in speed, capacity, expected main engine power and deviations from expected main engine power, for container ships**




Source: CE Delft.

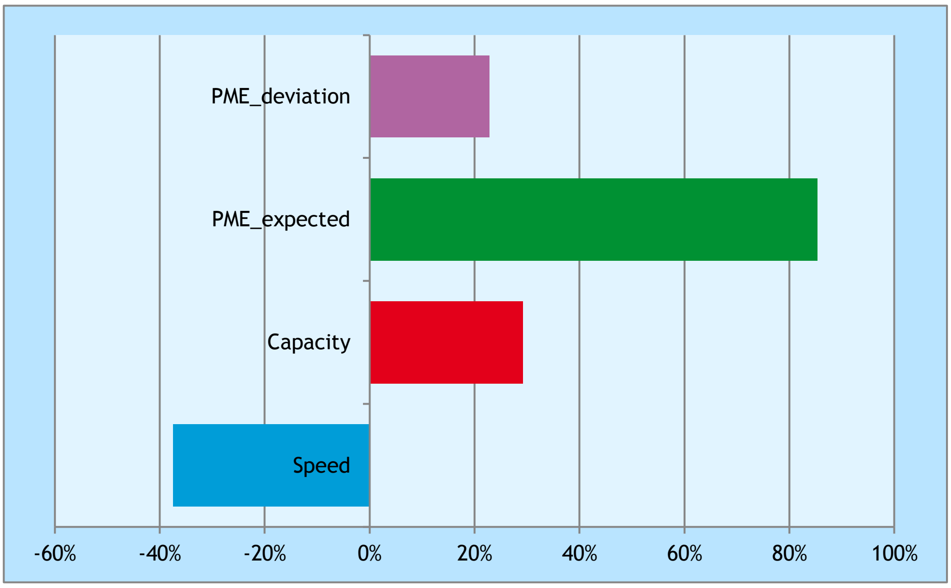
Figure 7 should be interpreted as follows:

- The design efficiency of newly built containerships was at its peak (worst) in 1977 and improved until 1985 (blue columns labelled 1977 and 1985).
- Between 1977 and 1985, the average speed of the new builds decreased, which caused the design efficiency to deteriorate (the green column moves upward).
- In the same period, there was a decrease of the expected $P_{ME}$, i.e. the power required to overcome the frictional resistance at the design speed. This caused the design efficiency to improve (the purple column moves downward).

- Moreover, the reduction of the average engine power was larger than what would be expected on the basis of changes in the average frictional resistance and speed alone. The difference, $P_{ME\_deviation}$ resulted in a further improvement of the design efficiency (the yellow column).
- Finally, the average capacity of the ships increased, which led to a further improvement in the EIV efficiency (the downward brown column).
- The figure shows that the contribution of $P_{ME\_deviation}$ in this period was relatively large, accounting for over a third of the design efficiency improvement.

In the periods 1985–2002 and 2002-2015, deteriorations and improvements in design efficiency are almost entirely explained by changes in expected PME, design speed and capacity. Deviations from expected main engine power have a consistent contribution that fosters the movement of design efficiency, albeit in some periods this contribution is somewhat small.

**Figure 8 Relative contributions of four factors that explain the pattern in the % change of design efficiency for container ships**




Source: CE Delft.

Figure 8 summarises the relative contributions to % changes of design efficiency because of changes in speed, capacity, expected main engine power and the deviation from expected main engine power[2]. We note that the largest contribution came from changes in expected engine power. This explains 85% of the changes in design efficiency. Capacity and the deviation from main engine power have a smaller but non-negligible contribution: respectively 29% and 23%. Changes in speed had a counteracting influence of -37%.

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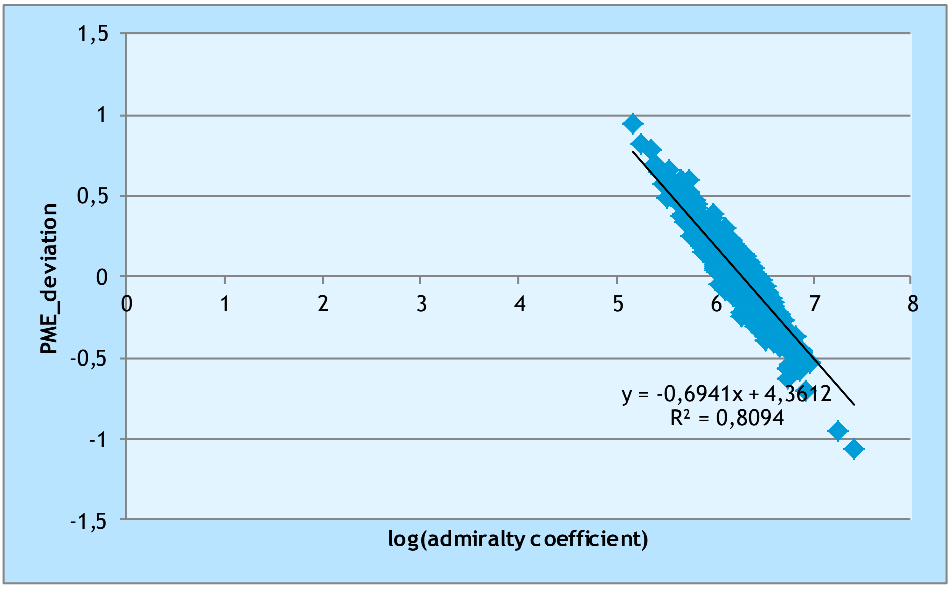
[2] The relative contribution is the average of % change of the factor divided by the % change of design efficiency, over the three periods considered. A negative number should be interpreted as a counteracting contribution of that factor to the movement of design efficiency. Numbers at up to 100% of changes in design efficiency explained.

### 2.1.3 The interpretation of the deviation from main engine power

In this section, we focus on the interpretation of $PME_{deviation}$. We analyse its relation with the admiralty coefficient. On top of this, we have also analysed whether the development in $PME_{deviation}$ over time could be explained by changes in design speed and/or capacity. There are no marked differences in the development over time for ships of different speed and/or weight classes.

Figure 9 shows that the (log of the) admiralty coefficient and $PME_{deviation}$ are strongly related: the variation in $PME_{deviation}$ is explained for 81% by the variation in the admiralty coefficient. Moreover, the relation is in the direction one would expect[3].

**Figure 9 The relation between $PME_{deviation}$ and the Admiralty coefficient**




Source: CE Delft.

We conclude that the admiralty coefficient can provide a good explanation of $PME_{deviation}$. The admiralty coefficient is a holistic concept and captures the whole resistance of a ship and includes propeller efficiency. A higher admiralty coefficient indicates a more efficient ship.

There are many design options that can increase the admiralty coefficient and thus reduce the required engine power of a ship, including:
- improvement of the hull shape;
- installation of energy saving devices;
- more efficient propellers (larger diameters, optimal pitch, optimal number of blades); and
- better rudder designs.

[3] The admiralty coefficient is defined as the design speed^3 * displacement^(2/3) over the main engine power. Higher deviations from the expected engine power imply higher main engine power. A higher main engine power is associated with a lower admiralty coefficient. One would thus expect a negative relationship between the admiralty coefficient and $PME_{deviation}$.

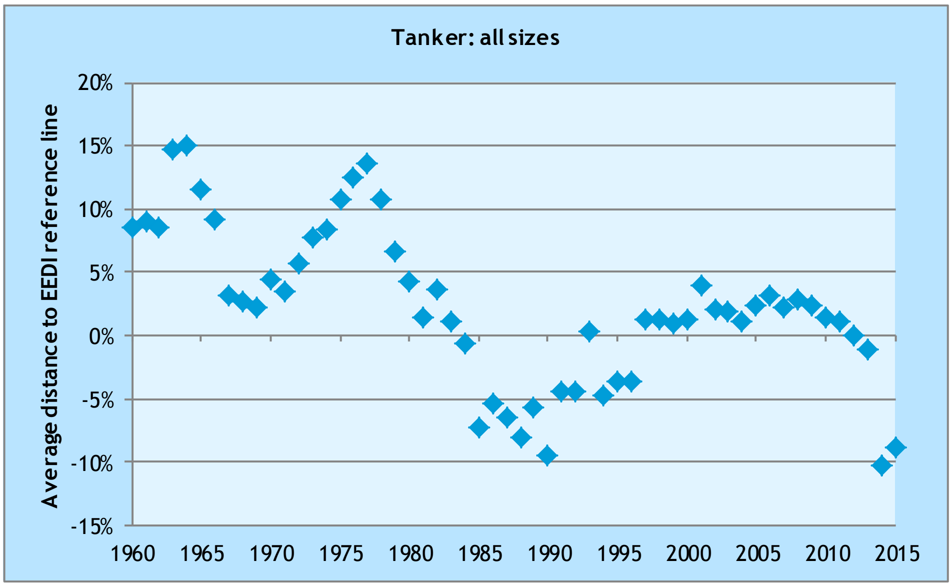
The database does not allow for proof of the use of any of these ways to improve the efficiency of ships because it only contains records on the engine power and dimensions of ships. However, it is clear that the efficiency of ships with a negative $PME_{deviation}$ is better.

## 2.2 Tankers

### 2.2.1 Changes in design efficiency and deviations from expected engine power

Our database contains sufficient data for tankers to calculate the EIV scores from 1960. Figure 10 shows how the deviation of the EIV from the reference line has changed over time. The graph shows large swings in the average efficiency of new builds in the 1960s and 1970s, with a peak in 1977. In that year, the EIV was on average 17% above the reference line. The design efficiency improved considerably until 1990 when it was 9% below the reference line. This means that there was an efficiency improvement of 22% in 10 years. After 1988, there has been a gradual deterioration in efficiency that lasted until around 2008, after which year efficiency improvements became apparent again.

**Figure 10 Development of the design efficiency of new tankers, 1960-2015**




Source: IHS Maritime World Register of Ships, Clarkson World Fleet Register, calculation CE Delft.

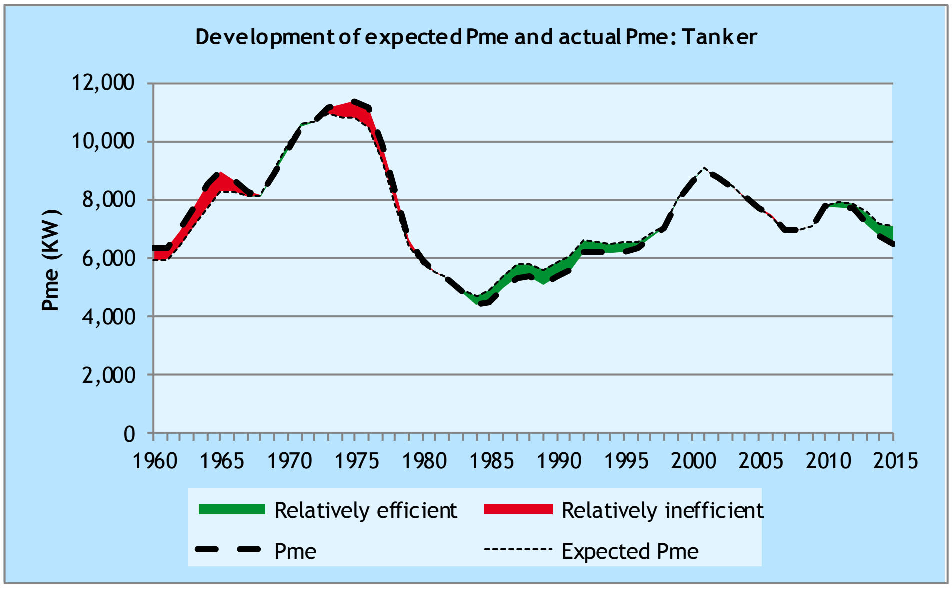
Note: Design efficiency is defined as average distance of the EIV divided to the EEDI reference line for all ships built in a certain year.

As explained in Section 1.3 we calculated the expected engine power based on the developments over time of the design speed and the frictional resistance. In the case of tankers, we analysed the impact of double hull tankers, which are mandatory from 1993 onwards. A reference from 1996 suggests that a double hull tanker costs about 16-18% more than a single hulled design primarily because of the increased steel requirements (Brown & Savage, 1996).

The increase in the actual amount of material that is required will be lower as some of these costs may also be attributed to welding costs rather than steel cost, so an additional increase in the lightweight of a ship of around 16% is sufficient to estimate the impact of the take up of double hull tankers. Because the lightweight of a ship constitutes, on average, 10% of the displacement, the impact of the double hull regulation on the displacement is not expected to exceed a few percent. For this reason, we have not taken this into account.

The expected engine power and the actual development of the engine power are plotted in Figure 11. When the actual engine power is higher than the expected engine power this suggests a relatively inefficient technical ship design (marked in red). However a negative deviation from the expected engine power, i.e. the actual engine power is lower, suggests a relatively efficient technical ship design (marked in green).

**Figure 11 Development of expected Pme and actual Pme for Tankers**

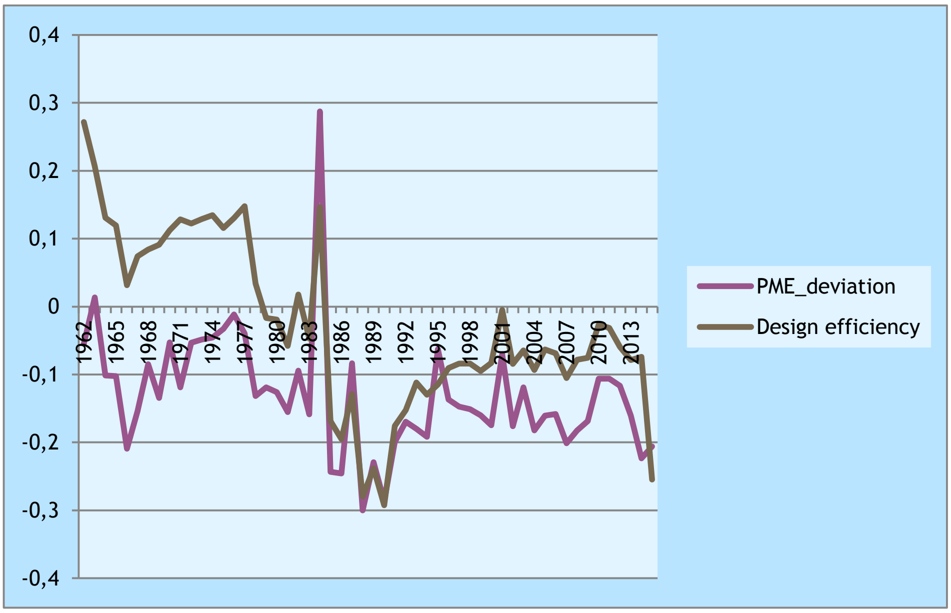



Source: CE Delft.

The general development of Figure 11 obscures the fact that the relation between the expected and actual main engine power of new tankers varies significantly for different tanker classes.

To obtain a clean analysis of the causes behind the development of design efficiency, we have limited the sample to ships of similar weight: 75,000 to 120,000 dwt. We have chosen this weight class because since the 1960's ships in this weight class were built in considerable numbers every year. In Annex G we show that the relation between design efficiency and deviation of expected main engine power is strong for ships of other weights as well: they show similar movements over time.

Figure 12 The development of design efficiency and deviations from expected power over time, for aframac tankers (75,000-120,000 dwt)



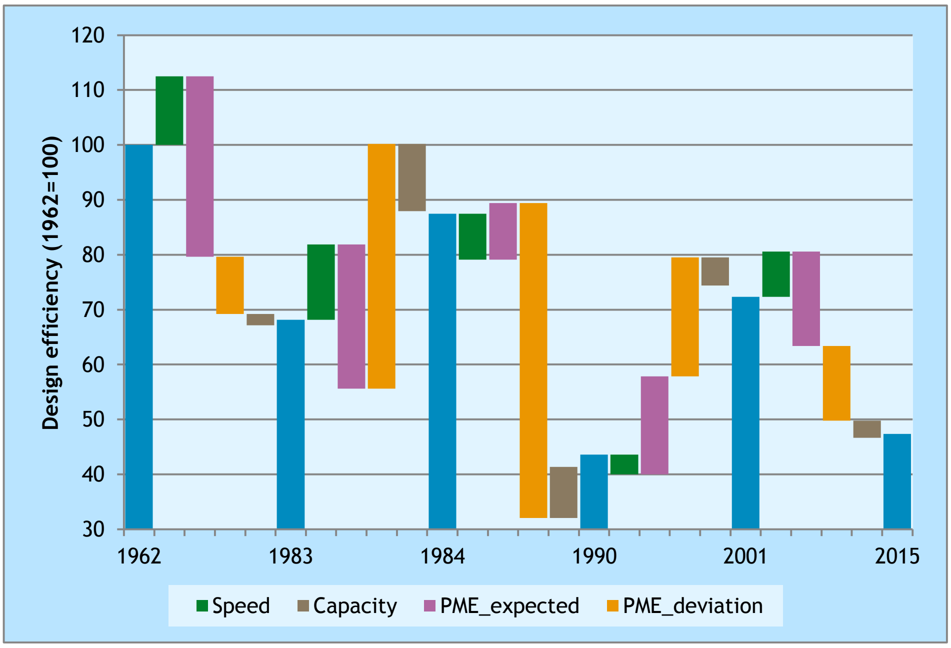

Source: CE Delft.

In Figure 12, we see that the pattern over time of deviations from expected main engine power shows similar peaks and troughs as that of the design efficiency. This is confirmed by the correlation between the two variables: the correlation between $PME_{deviation}$ and design efficiency is 73%.
Peaks in design efficiency – points where design efficiency is worst - are at the start of the series (1962), in 1984 and in 2001. Troughs –points where ships are most efficiency - are in 1983, 1990 and at the end of the series (2015). Below we will analyse how % changes in speed, capacity, expected main engine power and deviations from expected main engine power contributed to these peaks and troughs.

### 2.2.2 Changes in design efficiency as a consequence of design speed, capacity, expected engine power and deviations from expected engine power

The developments in the design efficiency can be explained on the basis of changes in the average speed of new vessels, average size, changes in $P_{ME\_expected}$ which are the result of a change in frictional resistance caused by changes in speed and wetted surface area, and changes in $P_{ME\_deviation}$.
Figure 13 shows the contribution of each of these factors to the changes in the design efficiency.

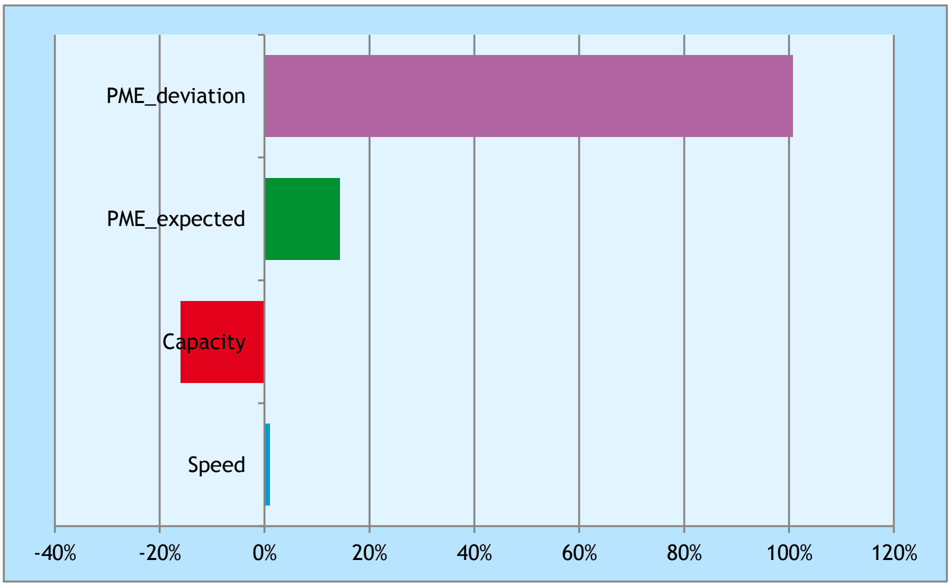
Figure 13 % change of design efficiency due to % changes in speed, capacity, expected main engine power and deviations from expected main engine power, for aframax tankers (75,000-120,000 dwt)




Source: CE Delft.

Figure 13 breaks down the % change of design efficiency in the contribution of speed, capacity, expected main engine power and deviations from expected main engine power. We note that the deviation from expected main engine power moves consistently in the same direction as design efficiency, with falling deviations associated with more efficient ships. Moreover, the contribution of the deviation from expected main engine power is larger than other factors. We conclude that the deviation from main engine power is an important factor in explaining improvements and deteriorations of design efficiency for tankers.

Figure 14 Relative contributions of four factors that explain the pattern in the % change of design efficiency for tankers of weight class 75,000-120,000, since 1962




Source: CE Delft.

Figure 14 summarises the contributions of the four factors to the historic development of design efficiency. We see that $PME_{deviation}$ is by far the most dominant factor, followed considerably behind by expected main engine power. Speed had a very small contribution, while the contribution of capacity moved generally in the opposite direction of efficiency (when efficiency improved, capacity fell and vice versa).

### 2.2.3 The interpretation of the deviation from main engine power

$PME_{deviation}$ is strongly linked to the admiralty coefficient ($r^2$ = 0.88), as was the case for container ships. It is not correlated with changes in design speed or ship size.

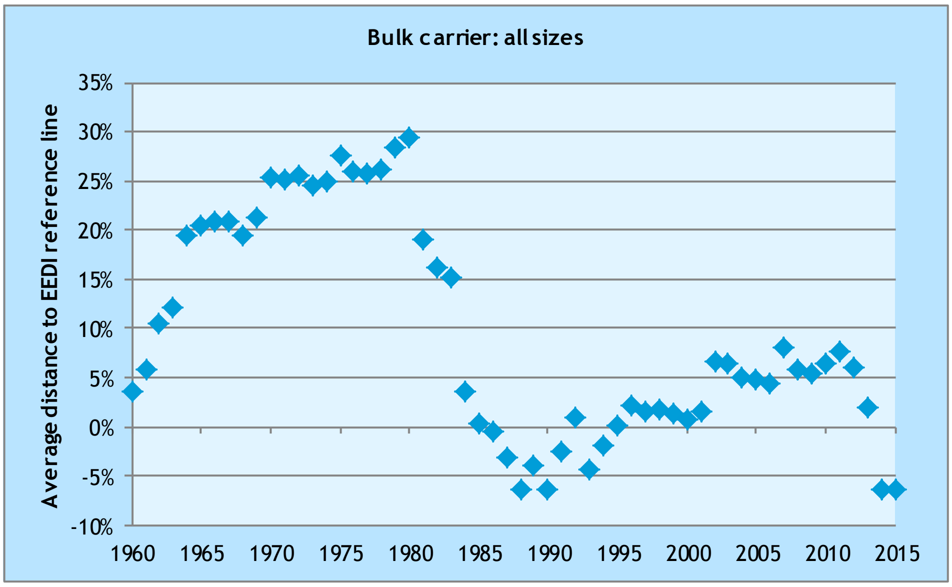
As discussed in Section 2.1.3, the strong correlation shows that ships with a lower than expected main engine power have been designed more efficiently.

## 2.3 Bulk carriers

### 2.3.1 Changes in design efficiency and deviations from expected engine power

For bulk carriers there was sufficient data to calculate the EIV scores from 1960. Figure 15 shows how the average deviation of the EIV from the reference line has changed over time. It indicates that the design efficiency of new ships deteriorated in the 1960s, increasing from the reference line to 29% above the reference line in 1980. The design efficiency improved considerably in the 1980s to 7% under the reference line around 1990. This means that there was an efficiency improvement of 28% in 10 years. After 1990, there has been a gradual deterioration in efficiency that lasted until 2013.

**Figure 15 Development of the design efficiency of new bulk carriers, 1960-2012**

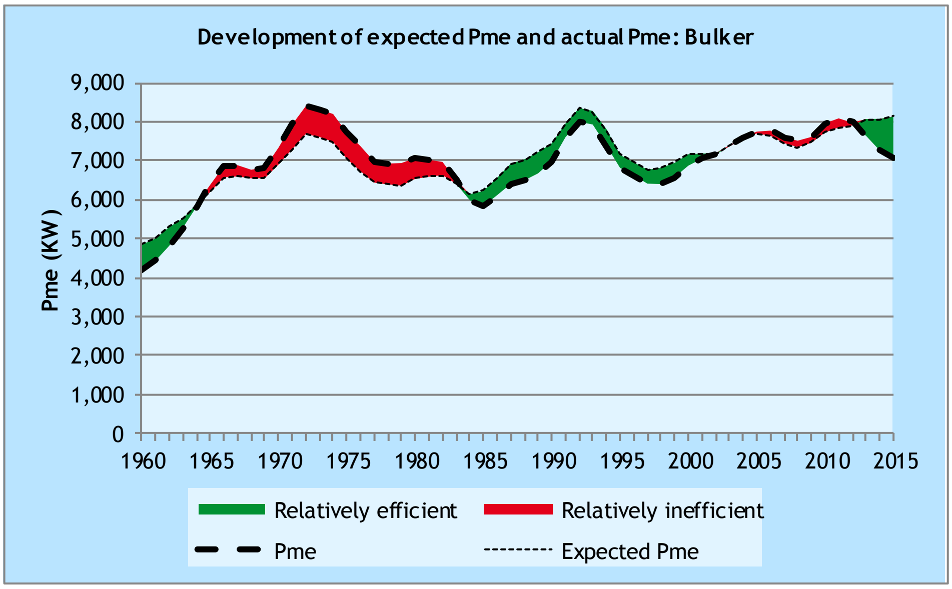



Source: IHS Maritime World Register of Ships, Clarkson World Fleet Register, calculation CE Delft.

Note: Design efficiency is defined as average distance of the EIV divided to the EEDI reference line for all ships built in a certain year.

As explained in Section 1.3 we calculated the expected engine power based on the developments over time of the design speed and the frictional resistance. The expected engine power and the actual development of the engine power are plotted in Figure 16. When the actual engine power is higher than the expected engine power this suggests a relatively inefficient technical ship design (marked in red). However a negative deviation from the expected engine power, i.e. the actual engine power is lower, suggests a relatively efficient technical ship design (marked in green).

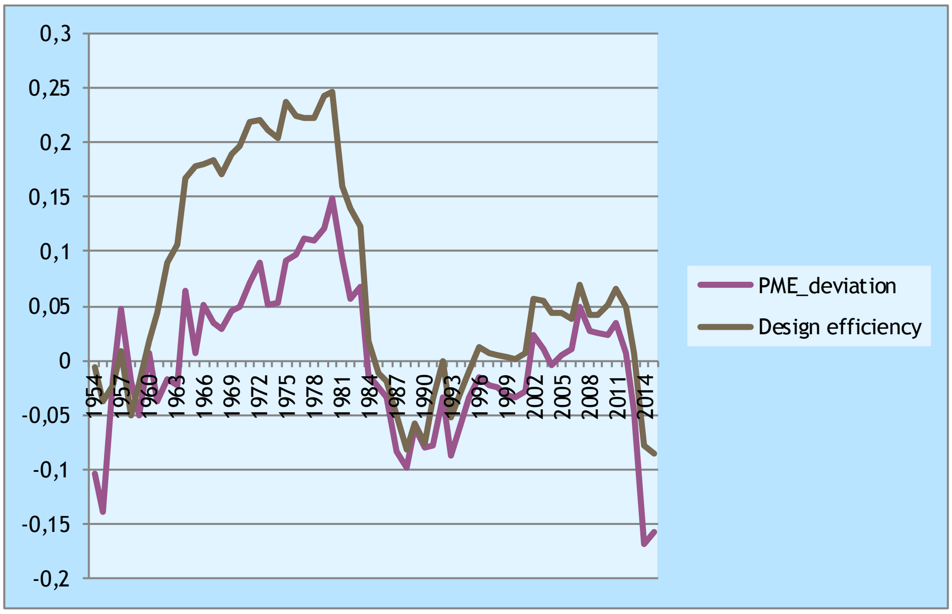
**Figure 16 Development of expected Pme and actual Pme for Bulk carriers**




Source: IHS Maritime World Register of Ships, Clarkson World Fleet Register, calculation CE Delft.

The relation between the design efficiency and the deviation from the expected main engine power is shown in Figure 17, which plots the development of design efficiency ($log\,\frac{EIV}{EIV_{ref}}$) and deviations from expected engine power ($\log(PME_{deviation})$) over time.

Figure 17 The development of design efficiency and deviations from expected power over time, for bulk carriers



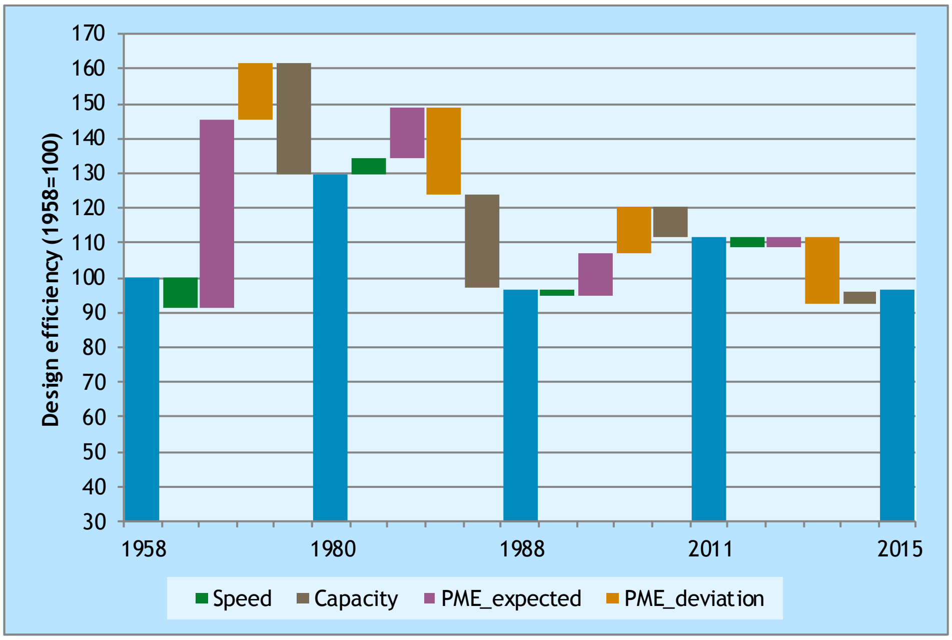

Source: IHS Maritime World Register of Ships, Clarkson World Fleet Register, calculation CE Delft.

Figure 17 shows a good resemblance in development of design efficiency and deviations from expected engine power. In fact, the correlation between design efficiency and deviation from expected PME is 88%.

### 2.3.2 Changes in design efficiency as a consequence of design speed, capacity, expected engine power and deviations from expected engine power

Figure 17 shows that the design efficiency of bulk carriers deteriorated between 1958 and 1980, improved significantly until 1980 after which it bounced back until a new era of improvement commenced in 2011. These developments can be explained on the basis of changes in the average speed of new vessels, average size, changes in $P_{ME\_expected}$ which are the result of a change in frictional resistance caused by changes in speed and wetted surface area, and changes in $P_{ME\_deviation}$. Figure 7 shows the contribution of each of these factors to the changes in the design efficiency.

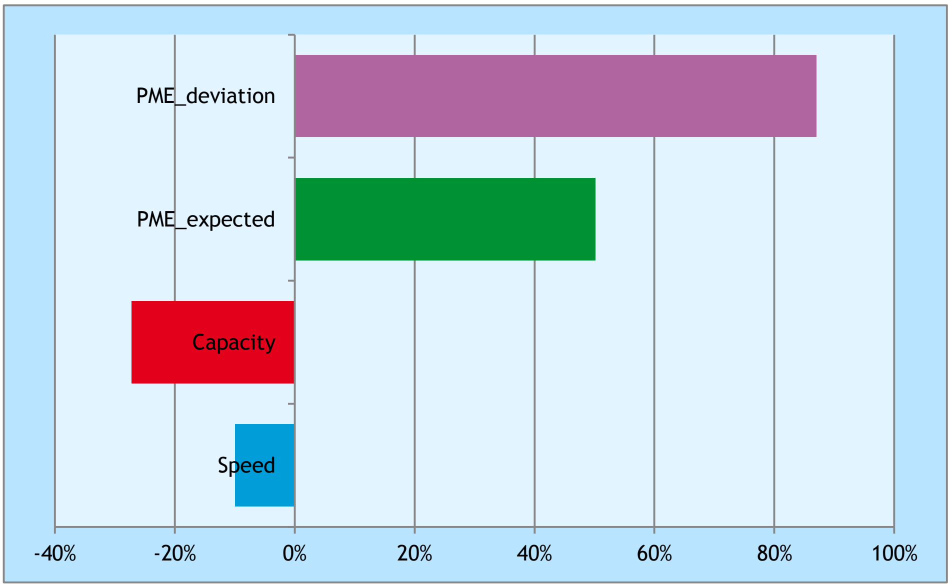
**Figure 18** **% change of design efficiency due to % changes in speed, capacity, expected main engine power and deviations from expected main engine power, for bulk carriers**




Source: CE Delft.

Figure 18 shows that in both periods in which the design efficiency improved, the improvement could not be explained on the basis of changes in speed, capacity or expected main engine power (the power required to overcome frictional resistance at the design speed). Rather, reductions in other types of resistance or improvements in propeller efficiency or yet other design improvements must have been responsible. The same is true for the periods in which the design efficiency deteriorated: the efficiency worsened partly because of increases in speed and frictional resistance, but also because of changes in design that resulted in a higher power requirement.

**Figure 19** **Relative contributions of four factors that explain the pattern in the % change of design efficiency for bulk carriers**




Source: IHS Maritime World Register of Ships, Clarkson World Fleet Register, calculation CE Delft.

Figure 19 shows the relative contribution of speed, capacity, expected main engine power and the deviation from expected main engine power in the explanation of % changes of design efficiency over time. We see that the deviation from expected main engine power is the major factor. It explains 87% of movements in design efficiency. Expected main engine power explains 50%. The other two factors generally have a counteracting contribution to the movement in design efficiency. This means that design speed and capacity tend to fall when efficiency improves, and rise when efficiency deteriorates. The contributions are -10% for speed and -27% for capacity.

### 2.3.3 The interpretation of the deviation from main engine power

$PME_{deviation}$ is strongly linked to the admiralty coefficient ($r^2$ = 0.90), as was the case for bulk container ships and tankers. It is not correlated with changes in design speed or ship size.

As discussed in Section 2.1.3, the strong correlation shows that ships with a lower than expected main engine power have been designed more efficiently.

## 2.4 Conclusions

Historical pattern of design efficiency shows profound peaks and troughs from the 60's to the recent times. All the ship types analysed in this study have witnessed a sharp improvement in the design efficiency of new ships in the 1980s, a gradual deterioration in the 1990s and 2000s, and improvements in recent years.

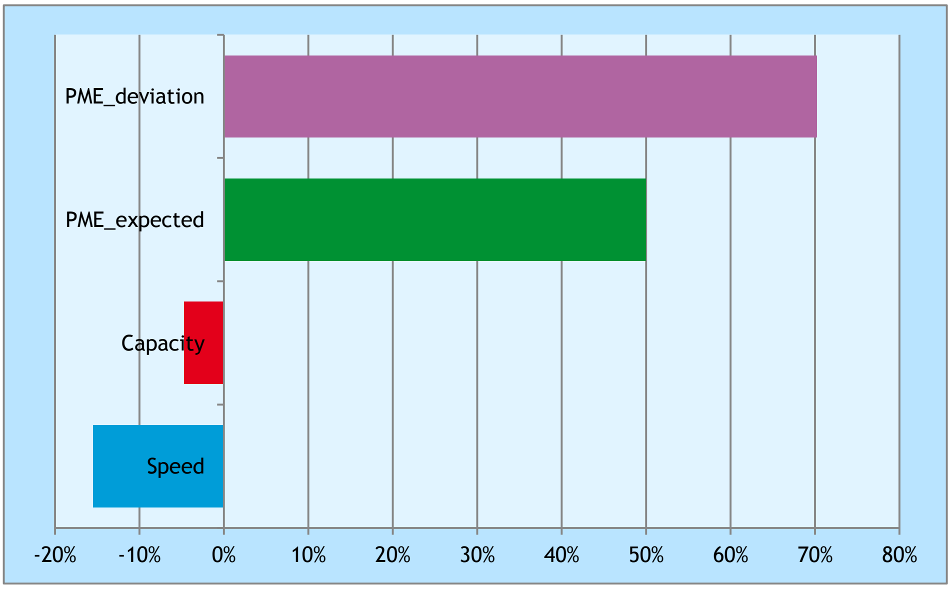
These efficiency changes were not due to changes in engine technology, or due to changes in the average size of new ships. The engine fuel efficiency is a constant in the measure used to analyse design efficiency, while the fact that large ships are more efficient is accounted for by comparing the design efficiency of a ship with the EED reference line.

In this study, an efficient ship is a ship that requires a low engine power to move the ship through the water at its design speed. An inefficient ship requires relatively more engine power. Engine power is mainly used to overcome resistance, the largest component of which is frictional resistance.

This study explains the efficiency in terms of speed, capacity and power required to overcome frictional resistance. It finds that efficient ships require relatively little additional engine power to overcome other forms of resistance, while inefficient ships require more. This must mean that efficient ships have more efficient hulls, more efficient propellers and rudders. In sum, the ship design has contributed significantly to changes in design efficiency.

Figure 20 shows that, on average for the three ship types analysed, changes in frictional resistance due to changes in speed and capacity explain 30% of the changes in design efficiency. The other 70% of the changes are related to better hull, rudder, and propeller designs, reduced shaft resistance and other factors that reduce the required engine power of a ship.

**Figure 20** **Relative contributions of four factors that explain the pattern in the % change of design efficiency, average for the three ship types**[4]




Source: CE Delft.

[4] The average for the three ship types is calculated as the (unweighted) average of the relative contributions over the three ship types.

# 3 Drivers of efficiency change

The previous chapter has shown that large changes in the design efficiency of ships have occurred within the timeframe of decades. This chapter sets out to explore why these changes have occurred. The literature mentions two drivers for fuel-efficiency changes: changes of the fuel price (Smit & Pijcke, 1985) and changes in freight rates (Mortensen, 2009). In addition, steel and labour costs, yard availability, dimensions of locks and quays and other factors may play a role. In recent years, the EEDI regulation may also have had an impact.

## 3.1 The impact of fuel prices and freight rates on design efficiency

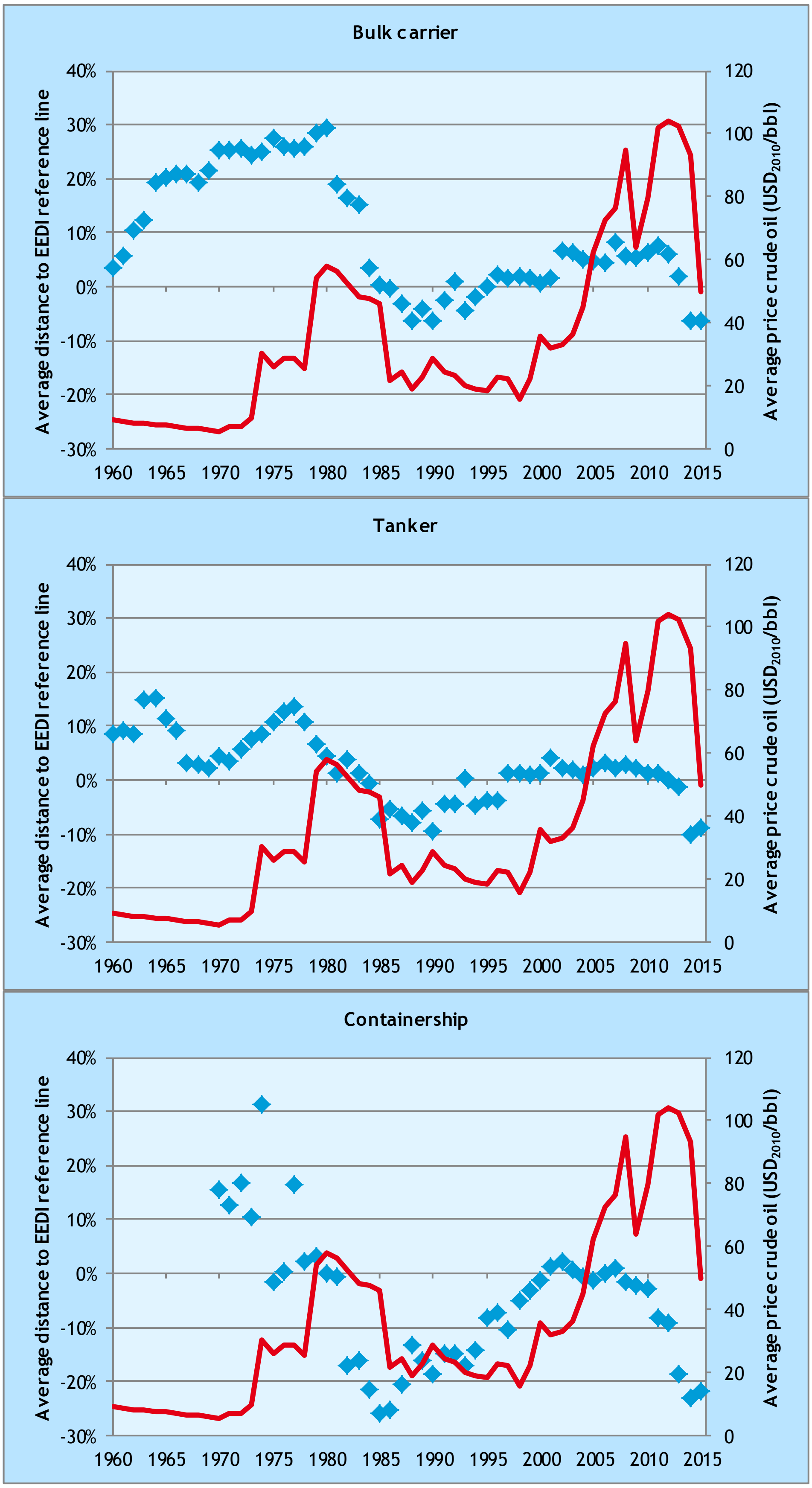
Higher fuel prices make fuel-efficient ships more attractive, because efficiency reduces the total cost of ownership. Assuming that fuel-efficient hull designs are more expensive to build (higher steel costs, higher labour costs), the additional capital expenditures can be earned back over the lifetime of the ship by lower fuel costs. Conversely, when fuel costs are relatively low, the capital expenditures are a larger share of the total costs of ownership and ship-owners may opt for a cheaper, less efficient design.

The impact of freight rates is less straightforward. According to Mortensen, when freight rates are high, owners queue up to order ships, lowering the incentive of shipyards for innovative designs and thus keeping efficiency low (Mortensen, 2009). Conversely, when freight rates are low, shipyards compete for clients and offer more efficient designs. Another possible explanation of the impact of freight rates would be that when rates are high, shipping companies make money regardless of the efficiency of their ships, and when they are low, only fuel-efficient ships can be operated profitably.

Figure 21 shows how fuel prices and design efficiency have moved over time. The fuel price is the real average crude oil price, which is strongly correlated to the real HFO price (ICCT, 2009). In the 1970s and 1980s, a large increase in fuel prices was followed by a large improvement in fuel efficiency of new ships. The lag between the two seems to be between four and eight years. There are two explanations for this time lag. First, it takes a few years before fuel price increases translate into higher fuel price projections. Second, as contemporary observers noticed, an increase in fuel prices first triggers studies into more fuel-efficient designs, which take time to be completed, ordered and then built (Smit & Pijcke, 1985).

Figure 21 also shows that the reaction to the fuel price increases in the 2000s was much less pronounced than in the 1970s. One possible explanation could be freight rates. In contrast to the 1980s,when freight rates were more or less stable, they increased in the 2000s reaching all time highs around 2008 (tankers freight rates reached maxima in the early 2000s) (UNCTAD, 2011). With such high freight rates, the pressure on fuel efficiency is weaker. Moreover, when length or draught is constrained, a higher block coefficient could increase the deadweight tonnage and therefore the cargo capacity of a ship, which could offset the higher fuel costs.

Figure 21 Fuel prices are an important driver for design efficiency




Source: World Bank (fuel price), CE Delft.

Hence, fuel prices are a driver of efficiency improvements, but high freight rates can mitigate the signal by reducing the need to improve fuel efficiency for shipping companies and reducing the incentive for yards to offer innovative designs. Since most ships are ordered when freight rates are high, this combination of driver and barrier results in lower efficiency improvements than would occur without the freight rate counterincentive.

## 3.2 The impact of the EEDI regulation on the design efficiency of ships

All ships built after 1 January 2013 are required to have an EEDI that is better than the reference line. The definition of the building date has resulted in the fact that some ships that entered the fleet in 2014 and 2015 fell under the EEDI regulation, while others did not. Ships are required to have an EEDI when:
- the building contract is placed on or after 1 January 2013; or
- in the absence of a building contract, the keel is laid or after 1 July 2013; or
- the delivery of which is on or after 1 July 2015.

Many ships that entered the fleet in 2014 and the first half of 2015 had a contract date before 1 January 2013 and subsequently were not required to have an EEDI (Table 3).

**Table 3** **2014 and 2015 new buildings with and without a required EEDI**

| | Contract on or after 1 January 2013; or delivery on or after 1 July 2015 | Contract before 1 January 2013 and delivery before 1 July 2015 |
|---|---|---|
| Container ships | 116 | 165 |
| Tankers | 160 | 100 |
| Bulk Carriers | 505 | 431 |

Note: This table only includes ships above the applicable size threshold for which sufficient data was available to calculate the EIV.

Source: CE Delft.

Table 4 compares the average distance to the reference line for the ships that entered the fleet in 2014 and 2015, disaggregated by whether they fall under the EEDI regulation or not. It shows that EEDI bulk carriers and tankers were one or two percentage points more efficient than the ships that did not fall under the EEDI. For containerships, the opposite is true. The differences are small and not statistically significant.[5]

[5] For containerships and tankers, the chance that the difference is not due to the selection of the sample but reflects a real difference between the two sets of ships is less than 30% (the p-value is 0.76 for containerships and 0.70 for tankers). For bulk carriers, the chance is less than 90%. The p-value of 0.12 is still larger than commonly required for statistical significance (often a value of 0.10 or less is taken as evidence for statistical significance).

Table 4 Average distance to reference line (%) of EEDI ships and non-EEDI ships for three ship types

| Ship type | EEDI ships | Non-EEDI |
|---|---|---|
| Bulk Carrier | -7% | -5% |
| Containership | -22% | -23% |
| Tanker | -10% | -9% |

Source: CE Delft.

All EIV values of the ships that were analysed are also plotted against the reference line for bulkers, containerships and tankers. Figure 23, Figure 24 and Figure 25 are included in Annex G. These figures also show that the size distribution of both sets is very similar.

## 3.3 Conclusion

Even this short analysis points to a number of situations in which the choice for a less efficient ship would be rational:

- Ships that are designed for trades where length, breadth and draft are constrained face a trade-off between the capacity of a ship and the design efficiency because fuller ships are less fuel-efficient. When freight rates are high, the additional profits that can be earned from a larger capacity may outweigh the higher fuel costs due to the fuller design. Hence, it can be rational to opt for a larger but less efficient ship.
- When freight rates are high, it may be attractive to have a ship as soon as possible. Since fuller ships require less time to build, in general, the benefits of having a ship sooner can outweigh the higher fuel consumption during the life of the ship.
- When labour costs and steel are expensive, the additional capital costs of a more efficient ship may not be earned back within a period that a ship-owner would consider reasonable.

In addition, there may be specific circumstances under which yards and other stakeholders may not want to work towards building more efficient ships. For example, Mortenson points out that when the order books are full, yards are reluctant to change standard designs (Mortensen, 2009). Under those circumstances, it is rational that they minimise the risk of time and cost overruns that are inevitably associated with innovative designs, because it would reduce the number of ships they can build and thus their profitability.

Hence, even this short analysis shows that many factors have to be taken into account when setting the design parameters of new ships. Under some circumstances, like in the 1980s, this can lead to large, market driven improvements in design efficiency. In other circumstances, like in the 1990s and 2000s, this can lead to a deterioration of fuel efficiency.

It is not possible to prove that the EEDI regulation has had a significant impact on the design efficiency of new ships to date. The sharp improvement in the design efficiency of ships that entered the fleet after 2013 is most likely the result of the high oil prices in the period up to mid-2014, when most of these ships were ordered.

This does not mean that the EEDI regulation will not be effective in the future. If the fuel prices continue to be as low as they are at the time of writing of this report, the efficiency of new ships will deteriorate in absence of the EEDI regulation. Moreover, the increasing stringency of the EEDI in the next years will likely result in a larger impact.

# 4 Conclusions

The design efficiency of ships has varied significantly over time. All the ship types analysed in this study have witnessed a sharp improvement in the design efficiency of new ships in the 1980s, a gradual deterioration in the 1990s and 2000s, and improvements in recent years.

The changes in design efficiency were the results of changes in hull and propeller design. Changes in speed and size have contributed less to changes in efficiency. In periods in which new ships were relatively efficient, ships had smaller engines than could be expected on the basis of their design speed and size. This means that the resistance of the ship, other than the frictional resistance which is a function of speed and size, was much smaller or the propulsive efficiency of the propeller was better.

Improvements in design efficiency have always followed periods of increasing fuel prices, and low fuel prices have resulted in deteriorating design efficiency. Other factors such as freight rates, steel and labour costs have also played a role.

The improvement in design efficiency in recent years can be explained by the high fuel prices until mid-2014 and the decrease in freight rates after 2008. There is no evidence to suggest that the EEDI has been the driver for efficiency improvements yet.

This does not mean that the EEDI regulation will not have an impact in the future. If fuel prices continue to be low, ship-owners will have an incentive to opt for less efficient ships if they are cheaper to build. The EEDI can prevent this. Moreover, as the stringency of the EEDI increases, the impact on design efficiency is likely to become larger.

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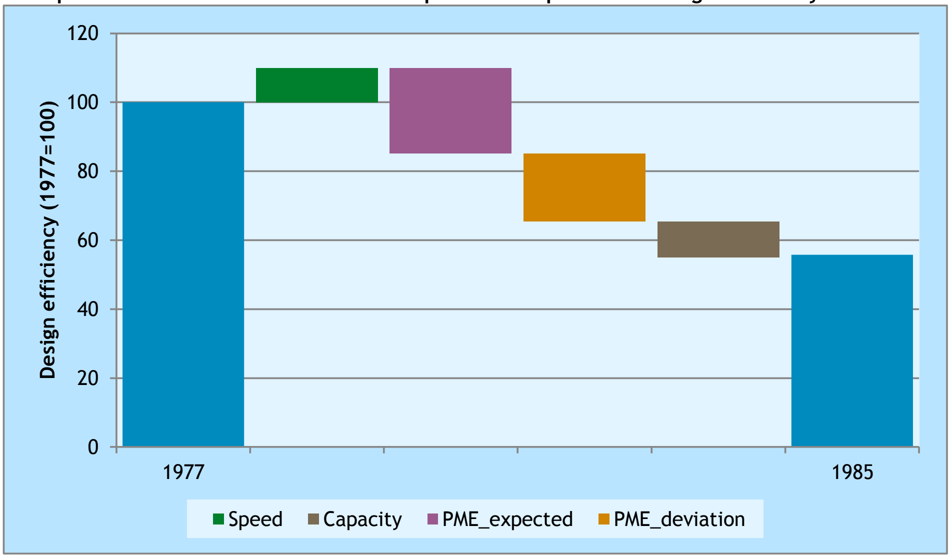
# Annex A Detailed methodological description

Our methodology is designed with the aim of analysing the contribution of different factors to changes in design efficiency of ships, with a focus on the contribution of factors other than design speed and capacity of the ship.
Our methodology can be summarized in two steps: First, we construct an indicator for the design efficiency of ships based on the Estimated Index Value. Second, we unravel the development over time of the design efficiency into the contribution of four factors: design speed, capacity, expected engine power – for the average ship - as a consequence of the frictional resistance the ship meets at the design speed[6], and the deviation of engine power (compared with the expected engine power). We interpret the deviation of engine power over what is expected as an indicator for characteristics of the ship that make it more or less efficient, given its design speed and water displacement volume. Such characteristics include for instance the shape of the hull and the efficiency of transmission.

The methodology allows calculating and plotting percentage changes over time in design efficiency as a consequence of percentage changes in expected engine power, deviations from expected engine power and the other two factors. For an example, see Figure 22.

**Figure 22 Example of contribution of factors that explain developments in design efficiency**




Source: CE Delft.

[6] This is the engine power needed to overcome frictional resistance at the design speed, for a ship with an average smoothness of the hull.

In this example, the percentage change of design efficiency for ships built over the years 1977-1985 equals -44%, which means that ships have become *more* efficient[7]. The -44% follows from subtracting the 1985 value (56%) from the 1977 value (100%).
The green, purple, orange and brown bars indicate the contribution of the 4 factors speed, capacity, PME_expected and PME_deviation to the efficiency improvement of -44%.
Developments in speed have led to a deterioration of design efficiency of 10%. This is a consequence of a *decrease* in design speed for ships in 1985 compared to 1977. As the Estimated Index Value (EIV), on which our measure for design efficiency is based, has a compensation for faster ships, the fall in design speed results in less efficient ships as measured by the EIV.
Developments in Capacity have contributed to this with -10%. This arises because ships built in 1977 had higher lower capacity than ships built in 1985. As the Estimated Index Value has a compensation for vessels that carry more cargo, the rise in capacity results in more efficient ships.
The percentage change in expected power of the main engine (as a consequence of expected frictional resistance for the ship's design speed and displacement volume) contributes to design efficiency with a fall of 25%. This is a consequence of a fall in expected engine power over the years 1977-1985, as higher engine power is penalised in the calculation of EIV.
Finally, turning to the deviation of engine power from what is expected, this has contributed with -20% to the fall in design efficiency over the period 1977-1985. This indicates that the design efficiency has improved substantially because of advances in e.g. hull smoothness and transmission efficiency.

Below, we will explain our methodology in more detail.

The methodology starts with the construction of a measure of design efficiency of ships that allows for the decomposition into the four factors. This measure is $\frac{EIV}{EIV_{ref}}$, where $EIV$ is the Estimated Index Value, calculated in conformity with resolution MEPC.215(63) (MEPC, 2012) and $EIV_{ref}$ is the reference value.
Our indicator of design efficiency thus measures the relative deviation in $EIV$ as a share of its reference $EIV_{ref}$.
In conformity with the resolution, our measure of design efficiency depends on the values of three factors, notably the power of the main engine, the capacity and the design speed of the vessel.

In line with resolution MEPC.215(63) (MEPC, 2012), the following assumptions have been made in calculating the EIV:
1. The carbon emission factor is constant for all engines, i.e. CF,ME = CF,AE = CF = 3.1144 g $CO_2$/g fuel.
2. The specific fuel consumption for all ship types is constant for all main engines, i.e. $SFC_{ME}$ = 190 g/kWh.
3. $P_{ME(i)}$ is main engines power and is 75% of the total installed main power (MCRME(i)).
4. The specific fuel consumption for all ship types is constant for all auxiliary engines, i.e. $SFC_{AE}$ = 215 g/kWh.
5. $P_{AE}$ is the auxiliary power and is calculated according to paragraphs 2.5.6.1 and 2.5.6.2 of the annex to MEPC.212(63).
6. No correction factors on ice class, voluntary structural enhancement, etc. are used.

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7 We have defined design efficiency in terms of EIV, a lower EIV means the ship is more efficient.

7. Innovative mechanical energy efficiency technology, shaft motors and other innovative energy efficient technologies are all excluded from the calculation, i.e. PAEeff = 0, PPTI = 0, Peff = 0.

This results in the following formula:

$$EIV = 3.1144 * \frac{190 * \sum_i^{NME} PME_i + 215 * P_{ae}}{Capacity * \mathrm{V_{ref}}}$$

Capacity is defined as 70% of dead weight tonnage (dwt) for containerships and 100% of dwt for other ship types. $V_{ref}$ refers to design speed. In conformity with the reference line calculations (MEPC.215(63) (MEPC, 2012), only ships of 400 GT or above are included.

To obtain our measure of efficiency, we divide by $EIV_{ref}$ to obtain:

$$\frac{EIV}{EIV_{ref}} = 3.1144 * \frac{190 * \sum_i^{NME} PME_i + 215 * P_{ae}}{Capacity * \mathrm{V_{ref}} * EIV_{ref}}$$

This formula allows to calculate design efficiency.

In order to break developments in design efficiency into contributions from speed, capacity, expected power of the main engine and deviation from what is expected, we need to remove $EIV_{ref}$ from the right side of the formula above. We do this by expressing $EIV_{ref}$ in terms of $Capacity$, using the formula's in the Annex B.
Next, we abstract from the power generated by the auxiliary engines[8].
This allows for a convenient logarithmic transformation (see below).
Finally, the ships for which we can calculate the design efficiency, have only one main engine.

We thus obtain:

$$\frac{EIV}{EIV_{ref}} = 3.1144 * \frac{190 * PME}{Capacity^{1-\alpha} * \mathrm{V_{ref}}}$$

Where the coefficient $\alpha$ reflects that $EIV_{ref}$ decreases when capacity rises. We have calculated $\alpha$ for the three ship types analysed using the values in the Annex B.

Now, we need to decompose the power of the main engine into two factors. On the one hand the power that would be expected as a consequence of the frictional resistance[9] that is caused by the ship design speed and displacement volume. On the other hand, the deviations in the main engine power from what is expected. We will elaborate on how we perform this decomposition below.

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[8] We do this, because we aim to Later we will show that we are able to predict changes in efficiency quite accurate, in spite of this abstraction.

[9] Engine power is designed with the aim to reach a certain design speed. Forces resulting from the speed that the engine has to compensate come from frictional resistance and wave resistance. To allow for our decomposition, we have calculated expected engine power to meet frictional resistance. In the appendix, we show that our abstraction from wave making resistance is of no meaningful consequence to our analysis.

But first, notice that with the decomposition, we have obtained four factors that potentially explain the development over time of the design efficiency: speed, capacity, expected PME, and deviations from it. To be able to unravel the contribution of each of these four factors, we take the (natural) logarithm of design efficiency of ships and express this in terms of the four factors, to obtain:

$$log\frac{EIV}{EIV_{ref}} = \log(PME_{expected}) + \log(PME_{deviation}) - \log(Speed) - (1-\alpha)\log(Capacity) + c$$

In words: the logarithm of efficiency $\frac{EIV}{EIV_{ref}}$ equals the sum of the logarithms of expected engine power from frictional resistance ($PME_{expected}$), engine power deviations from what can be expected ($PME_{deviation}$), minus the design speed ($Speed$) and a fraction of Capacity($Capacity$) .

The coefficient $c$ is a constant that summarises factors that appear in the formula to calculate the $EIV$, such as the specific fuel consumption and the carbon emission factor.
The formula allows calculating the contribution of the four factors to the development of design efficiency of ships over time, where the percentage change of design efficiency is the sum of the percentage changes of the four factors:

$$\%change\frac{EIV}{EIV_{ref}} = \%\text{change}(PME_{expected}) + \%\text{change}(PME_{deviation}) - \%\text{change}(Speed) - (1-\alpha)\,\%\text{change}(deadweight)$$

## A.1 The decomposition of $PME$ into $PME_{expected}$ and $PME_{deviation}$

To obtain values of $PME_{expected}$ and $PME_{deviation}$, we have estimated a regression model that explains the (natural) logarithm of $PME$ by the logarithm of frictional resistance multiplied by the design speed (see Annex C for the results). Frictional resistance is calculated as in the Annex D.
The residuals of this regression indicate the deviations of the main engine power of the ship over what is estimated to overcome frictional resistance for a ship with average characteristics. A positive $PME_{deviation}$ (positive residual) indicates that the ship's engine power is bigger than what would be expected given its frictional resistance at the design speed. The ship is thus less efficient. A negative $PME_{deviation}$ indicates the ship has less engine power than what would be expected from frictional resistance. A ship with a negative $PME_{deviation}$ is more efficient.

# Annex B The calculation of the reference value (Vref)

Table 5 Values for α

| | Reference line value | Value for α |
|---|---|---|
| Bulker | $961.79*(dwt)^{-0.477}$ | -0.477 |
| Tanker | $1218.8*(dwt)^{-0.488}$ | -0.488 |
| Container ship | $174.22*(dwt)^{-0.201}$ | -0.201 |

# Annex C Results of regressions for splitting $PME$ into $PME_{expected}$ and $PME_{deviation}$

## C.1 Container ships

| Dependent Variable: LOG(PMX) | | | | |
|---|---|---|---|---|
| Method: Least Squares | | | | |
| Date: 02/15/16 Time: 16:58 | | | | |
| Sample: 1 31905 IF FILTER="Yes" AND MIN_DWT_FILTER="Yes" AND | | | | |
| CB<0.9 AND SHIP TYPE="Containership" | | | | |
| Included observations: 5,576 | | | | |
| HAC standard errors & covariance (Bartlett kernel, Newey-West fixed Bandwidth = 10.0000) | | | | |
| Variable | Coefficient | Std. Error | t-Statistic | Prob. |
| LOG(SPEED*FRICTRES) | 0.915130 | 0.000293 | 3118.491 | 0.0000 |
| R-squared | 0.955487 | Mean dependent var | | 10.03257 |
| Adjusted R-squared | 0.955487 | S.D. dependent var | | 0.719313 |
| S.E. of regression | 0.151762 | Akaike info criterion | | -0.932831 |
| Sum squared resid | 128.4012 | Schwarz criterion | | -0.931643 |
| Log likelihood | 2601.734 | Hannan-Quinn criter. | | -0.932417 |
| Durbin-Watson stat | 1.457424 | | | |

## C.2 Tankers

| Dependent Variable: LOG(PMX) | | | | |
|---|---|---|---|---|
| Method: Least Squares | | | | |
| Date: 02/15/16 Time: 16:58 | | | | |
| Sample: 1 31905 IF FILTER="Yes" AND MIN_DWT_FILTER="Yes" AND | | | | |
| CB<0.9 AND SHIP TYPE="Tanker" | | | | |
| Included observations: 1,1281 | | | | |
| HAC standard errors & covariance (Bartlett kernel, Newey-West fixed Bandwidth = 12.0000) | | | | |
| Variable | Coefficient | Std. Error | t-Statistic | Prob. |
| LOG(SPEED*FRICTRES) | 0.926237 | 0.000338 | 2738.862 | 0.0000 |
| R-squared | 0.901222 | Mean dependent var | | 8.959838 |
| Adjusted R-squared | 0.901222 | S.D. dependent var | | 0.757485 |
| S.E. of regression | 0.238069 | Akaike info criterion | | -0.032422 |
| Sum squared resid | 639.3162 | Schwarz criterion | | -0.031772 |
| Log likelihood | 183.8742 | Hannan-Quinn criter. | | -0.032203 |
| Durbin-Watson stat | 1.599036 | | | |

## C.3 Bulk carriers

| **Dependent Variable: LOG(PMX)** | | | | |
|---|---|---|---|---|
| Method: Least Squares | | | | |
| Date: 02/15/16 Time: 16:58 | | | | |
| Sample: 1 31905 IF FILTER="Yes" AND MIN_DWT_FILTER="Yes" AND | | | | |
| CB<0.9 AND SHIP TYPE="Bulk Carrie"" | | | | |
| Included observations: 14,909 | | | | |
| HAC standard errors & covariance (Bartlett kernel, Newey-West fixed Bandwidth = 13.0000) | | | | |
| Variable | Coefficient | Std. Error | t-Statistic | Prob. |
| LOG(SPEED*FRICTRES) | 0.920958 | 0.000223 | 4128.533 | 0.0000 |
| R-squared | 0.738565 | Mean dependent var | | 9.096747 |
| Adjusted R-squared | 0.738565 | S.D. dependent var | | 0.397311 |
| S.E. of regression | 0.203148 | Akaike info criterion | | -0.349695 |
| Sum squared resid | 615.2413 | Schwarz criterion | | -0.349184 |
| Log likelihood | 2607.798 | Hannan-Quinn criter. | | -0.349525 |
| Durbin-Watson stat | 1.797069 | | | |

# Annex D The calculation of frictional resistance

The calculation of frictional resistance follows the following steps:

1. Calculation of the Reynolds number.
2. Calculation of the Ship Frictional resistance coefficient (from the Reynolds number).
3. Calculation of frictional resistance.

**1. Calculation of the Reynolds number ($Rn$):**

$$Rn = (V * L/v)$$

With:

$v$ = Kinematic viscosity of water, taken at 20 degree Celsius[10] $= 1.05 * 10^{-6}\, m^2/s^{-1}$.

$V$ = Ship design speed.

$L$ = Ship length.

**2. Calculation of Ship frictional resistance coefficient ($Cf$):**

$$Cf = 0.075 \,/\, (log10\, Rn - 2)^2$$

**3. Calculation of Frictional Resistance**

$$Frictional\ Resistance = 0.5 * Cf * \rho * WSA * V^2$$

With:

$\rho$ = Sea water density, taken at 0 °C and salinity 35 g $kg^{-1}$ = [11]1.025 tonnes/$m^3$.

$WSA$ = Wetted surface area of ship, calculated as[12]:

$$WSA = L * (B + 2 * T) * Cm^{0.5} * (0.453 + 0.4425 * Cb - 0.2862 * Cm + 0.003467 * B/T + 0.3696 * Cw)$$

Values for the parameters are:

$Cm = 0.98$, and

$Cw = 0.90$.

[10] Source: (Kaye & Laby National Physical Laboratory, 2015).

[11] Source: (Kaye & Laby National Physical Laboratory, 2015).

[12] Source: (Holtrop & Mennen, 1982).

# Annex E Results of regressions for interpretation of $PME_{deviation}$

## E.1 Container ships

### E.1.1 Admiralty coefficient

| Dependent Variable: LOG(ADMCOEF) | | | | |
|---|---|---|---|---|
| Method: Least Squares | | | | |
| Date: 02/11/16 Time: 17:05 | | | | |
| Sample: 1 31905 IF FILTER="Yes" AND MIN_DWT_FILTER="Yes" AND | | | | |
| CB<0.9 AND SHIP TYPE="Containership" | | | | |
| Included observations: 5,576 | | | | |
| HAC standard errors & covariance (Bartlett kernel, Newey-West fixed Bandwidth = 10.0000) | | | | |
| Variable | Coefficient | Std. Error | t-Statistic | Prob. |
| RESPMXCONTLOG | -1.166136 | 0.010325 | -112.9399 | 0.0000 |
| C | 6.282677 | 0.002540 | 2473.170 | 0.0000 |
| R-squared | 0.809375 | Mean dependent var | | 6.279257 |
| Adjusted R-squared | 0.809341 | S.D. dependent var | | 0.196678 |
| S.E. of regression | 0.085878 | Akaike info criterion | | -2.071412 |
| Sum squared resid | 41.10871 | Schwarz criterion | | -2.069036 |
| Log likelihood | 5777.098 | Hannan-Quinn criter. | | -2.070584 |
| F-statistic | 23666.73 | Durbin-Watson stat | | 0.957784 |
| Prob(F-statistic) | 0.000000 | Wald F-statistic | | 12755.42 |
| Prob(Wald F-statistic) | 0.000000 | | | |

### E.1.2 Wave making resistance

| Dependent Variable: RESPMXCONTLOG | | | | |
|---|---|---|---|---|
| Method: Least Squares | | | | |
| Date: 02/11/16 Time: 17:05 | | | | |
| Sample: 1 31905 IF FILTER="Yes" AND MIN_DWT_FILTER="Yes" AND | | | | |
| CB<0.9 AND SHIP TYPE="Containership" | | | | |
| Included observations: 5,576 | | | | |
| HAC standard errors & covariance (Bartlett kernel, Newey-West fixed Bandwidth = 10.0000) | | | | |
| Variable | Coefficient | Std. Error | t-Statistic | Prob. |
| LOG(SPEED*FROUDE) | -0.266559 | 0.025581 | -10.42031 | 0.0000 |
| C | 0.614471 | 0.059867 | 10.26399 | 0.0000 |
| R-squared | 0.092576 | Mean dependent var | | 0.002933 |
| Adjusted R-squared | 0.092413 | S.D. dependent var | | 0.151733 |
| S.E. of regression | 0.144552 | Akaike info criterion | | -1.029992 |
| Sum squared resid | 116.4708 | Schwarz criterion | | -1.027615 |
| Log likelihood | 2873.617 | Hannan-Quinn criter. | | -1.029163 |
| F-statistic | 568.6622 | Durbin-Watson stat | | 1.437492 |
| Prob(F-statistic) | 0.000000 | Wald F-statistic | | 108.5828 |
| Prob(Wald F-statistic) | 0.000000 | | | |

## E.2 Tankers

### E.2.1 Admiralty coefficient

| Dependent Variable: LOG(ADMCOEF) | | | | |
|---|---|---|---|---|
| Method: Least Squares | | | | |
| Date: 02/11/16 Time: 17:05 | | | | |
| Sample: 1 31905 IF FILTER="Yes" AND MIN_DWT_FILTER="Yes" AND | | | | |
| CB<0.9 AND SHIP TYPE="Tanker" | | | | |
| Included observations: 11,281 | | | | |
| HAC standard errors & covariance (Bartlett kernel, Newey-West fixed Bandwidth = 12.0000) | | | | |
| Variable | Coefficient | Std. Error | t-Statistic | Prob. |
| RESPMXTANKLOG | -1.354057 | 0.017813 | -76.01582 | 0.0000 |
| C | 6.123427 | 0.002098 | 2919.046 | 0.0000 |
| R-squared | 0.876356 | Mean dependent var | | 6.103438 |
| Adjusted R-squared | 0.876345 | S.D. dependent var | | 0.343687 |
| S.E. of regression | 0.120856 | Akaike info criterion | | -1.388251 |
| Sum squared resid | 164.7440 | Schwarz criterion | | -1.386951 |
| Log likelihood | 7832.430 | Hannan-Quinn criter. | | -1.387814 |
| F-statistic | 79942.51 | Durbin-Watson stat | | 1.397395 |
| Prob(F-statistic) | 0.000000 | Wald F-statistic | | 5778.405 |
| Prob(Wald F-statistic) | 0.000000 | | | |

### E.2.2 Wave making resistance

| Dependent Variable: RESPMXTANKLOG | | | | |
|---|---|---|---|---|
| Method: Least Squares | | | | |
| Date: 02/11/16 Time: 17:05 | | | | |
| Sample: 1 31905 IF FILTER="Yes" AND MIN_DWT_FILTER="Yes" AND | | | | |
| CB<0.9 AND SHIP TYPE="Tanker" | | | | |
| Included observations: 11,281 | | | | |
| HAC standard errors & covariance (Bartlett kernel, Newey-West fixed Bandwidth = 12.0000) | | | | |
| Variable | Coefficient | Std. Error | t-Statistic | Prob. |
| LOG(SPEED*FROUDE) | -0.291502 | 0.030001 | -9.716280 | 0.0000 |
| C | 0.483716 | 0.049678 | 9.737026 | 0.0000 |
| R-squared | 0.044742 | Mean dependent var | | 0.014762 |
| Adjusted R-squared | 0.044657 | S.D. dependent var | | 0.237611 |
| S.E. of regression | 0.232245 | Akaike info criterion | | -0.081870 |
| Sum squared resid | 608.3639 | Schwarz criterion | | -0.080571 |
| Log likelihood | 463.7894 | Hannan-Quinn criter. | | -0.081433 |
| F-statistic | 528.2770 | Durbin-Watson stat | | 1.577452 |
| Prob(F-statistic) | 0.000000 | Wald F-statistic | | 94.40609 |
| Prob(Wald F-statistic) | 0.000000 | | | |

## E.3 Bulk Carriers

### E.3.1 Admiralty coefficent

| Dependent Variable: LOG(ADMCOEF) | | | | |
|---|---|---|---|---|
| Method: Least Squares | | | | |
| Date: 02/11/16 Time: 17:05 | | | | |
| Sample: 1 31905 IF FILTER="Yes" AND MIN_DWT_FILTER="Yes" AND | | | | |
| CB<0.9 AND SHIP TYPE="Bulk Carrier" | | | | |
| Included observations: 14,909 | | | | |
| HAC standard errors & covariance (Bartlett kernel, Newey-West fixed Bandwidth = 13.0000) | | | | |
| Variable | Coefficient | Std. Error | t-Statistic | Prob. |
| RESPMXBULKLOG | -1.160330 | 0.005984 | -193.9160 | 0.0000 |
| C | 6.210028 | 0.001201 | 5170.588 | 0.0000 |
| R-squared | 0.903341 | Mean dependent var | | 6.204769 |
| Adjusted R-squared | 0.903335 | S.D. dependent var | | 0.247948 |
| S.E. of regression | 0.077090 | Akaike info criterion | | -2.287561 |
| Sum squared resid | 88.58952 | Schwarz criterion | | -2.286541 |
| Log likelihood | 17054.63 | Hannan-Quinn criter. | | -2.287223 |
| F-statistic | 139315.7 | Durbin-Watson stat | | 1.357356 |
| Prob(F-statistic) | 0.000000 | Wald F-statistic | | 37603.43 |
| Prob(Wald F-statistic) | 0.000000 | | | |

### E.3.2 Wave making resistance

| Dependent Variable: RESPMXBULKLOG | | | | |
|---|---|---|---|---|
| Method: Least Squares | | | | |
| Date: 02/11/16 Time: 17:05 | | | | |
| Sample: 1 31905 IF FILTER="Yes" AND MIN_DWT_FILTER="Yes" AND | | | | |
| CB<0.9 AND SHIP TYPE="Bulk Carrier" | | | | |
| Included observations: 14,909 | | | | |
| HAC standard errors & covariance (Bartlett kernel, Newey-West fixed Bandwidth = 13.0000) | | | | |
| Variable | Coefficient | Std. Error | t-Statistic | Prob. |
| LOG(SPEED*FROUDE) | -0.437910 | 0.017470 | -25.06661 | 0.0000 |
| C | 0.683837 | 0.027375 | 24.98045 | 0.0000 |
| R-squared | 0.102508 | Mean dependent var | | 0.004532 |
| Adjusted R-squared | 0.102447 | S.D. dependent var | | 0.203098 |
| S.E. of regression | 0.192413 | Akaike info criterion | | -0.458209 |
| Sum squared resid | 551.8996 | Schwarz criterion | | -0.457188 |
| Log likelihood | 3417.717 | Hannan-Quinn criter. | | -0.457870 |
| F-statistic | 1702.612 | Durbin-Watson stat | | 1.681817 |
| Prob(F-statistic) | 0.000000 | Wald F-statistic | | 628.3349 |
| Prob(Wald F-statistic) | 0.000000 | | | |

# Annex F Data

Data on ship type, design speed, capacity, year of delivery (built), propulsion power together with data on breadth, depth and length have been gathered from both Clarksons Research World Fleet Register and IHS Fairplay World Fleet Statistics. IHS was used only for broken up ships before March 2015, supplemented with data from Clarksons on the active fleet as of 31/12/2015 and broken up ships after March 2015.

Bulk carriers, Containerships and Tankers were included in the dataset. Ships with insufficient data to calculate the EIV (design speed, engine power and deadweight tonnes) or the lightweight (length, breadth and depth) have been excluded from the dataset.

Table 6 shows the number of ships included in the calculations per ship type and per decade. Also the source (IHS or Clarksons) is given.

**Table 6 Number of ships included in the dataset**

| Ship type | Source | '60 | '70 | '80 | '90 | '00 | '10 |
|---|---|---|---|---|---|---|---|
| **Bulk Carrier** | IHS | 1,173 | 2,051 | 1,382 | 245 | 1 | |
| | Clarksons | 2 | 79 | 526 | 1,631 | 2,990 | 4,677 |
| **Containership** | IHS | 68 | 343 | 381 | 327 | 2 | |
| | Clarksons | | 10 | 88 | 832 | 2,396 | 1,102 |
| **Tanker** | IHS | 826 | 1,648 | 779 | 278 | 2 | |
| | Clarksons | 19 | 153 | 423 | 1,234 | 4,074 | 1,472 |

Source: CE Delft.

In total, 14,757 Bulk Carriers, 5,549 containerships, and 10,908 tankers are included in the dataset.

76 outliers were excluded from the dataset (0.2% of all ships). They were defined as ships with an EIV more than 100% above the reference line, or more than 75% below the reference line.

# Annex G EEDI and non-EEDI ships

This annex shows supporting graphs and tables for Section 3.2.

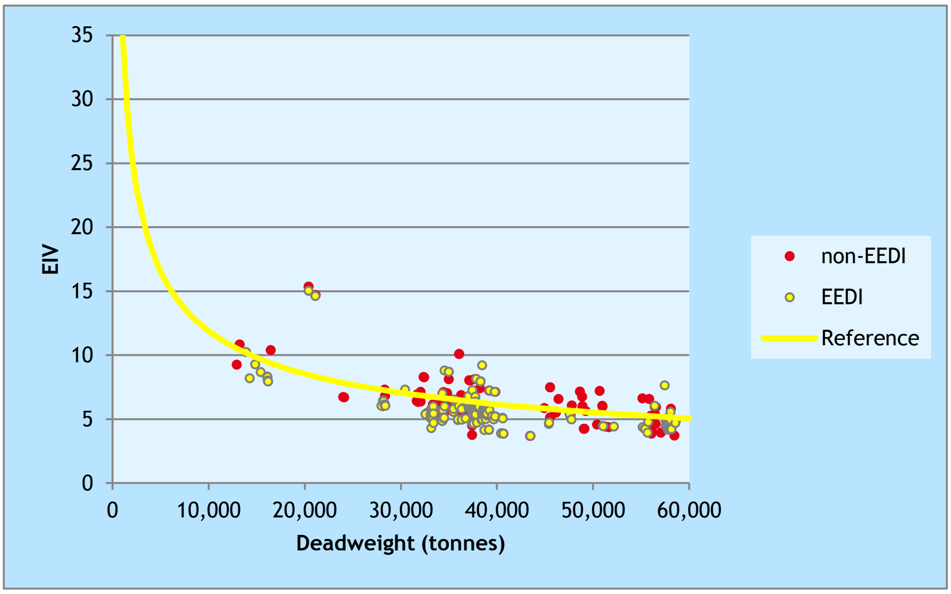
Table 7 **Ships delivered in 2014 and 2015**

| Ship type | Contract_after2013 | Delivery_afterjul2015 | Non-EEDI |
|---|---|---|---|
| Bulk Carrier | 485 | 20 | 431 |
| Containership | 113 | 9 | 167 |
| Tanker | 175 | 5 | 107 |
| Bulk Carrier | -7% | | -5% |
| Containership | -22% | | -23% |
| Tanker | -10% | | -9% |

## G.1 Bulk carriers

Figure 23 shows a graph of the EIV of bulk carriers that have entered the fleet in 2014 and 2015. The yellow dots denote ships that are required to have an EEDI; the red dots ships that are not required to have an EEDI because they were contracted before 1 January 2015 and delivered before 1 July 2015.

Figure 23 **EIV of EEDI and non-EEDI ships (built in 2014-2015): Bulk carriers**




Source: CE Delft.

Bulk carriers that are required to have an EEDI have an EIV that is, on average, 7% below the reference line while ships that do not fall under the EEDI requirement have an EIV 5% below the reference line on average. Table 8 shows that the difference is not statistically significant because the p-value of the variable EEDI_IS_1 is larger than 0.1.

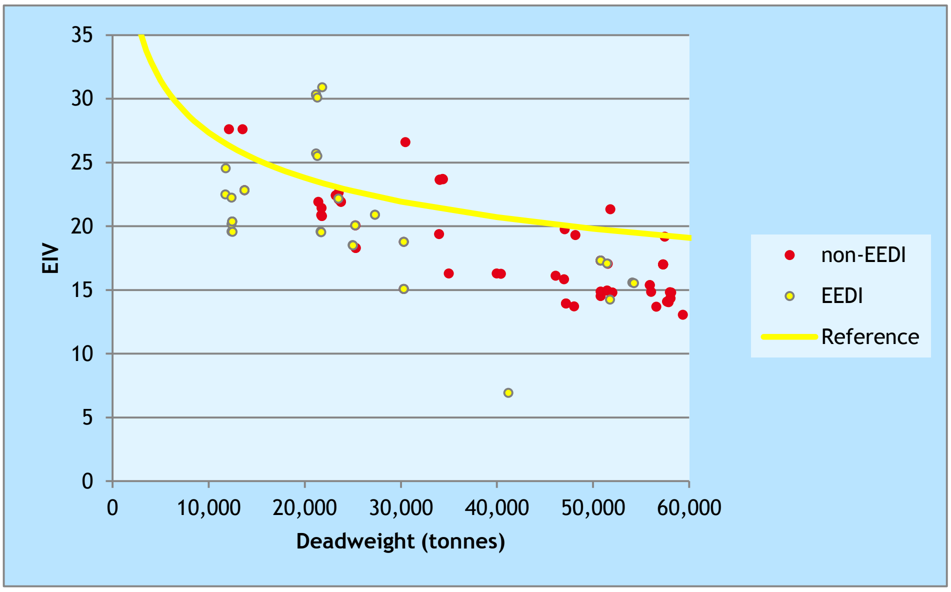
Table 8 **Statistical analysis of the EIVs bulk carriers that entered the fleet in 2014 and 2015**

| **Dependent Variable: _DOE** | | | | |
|---|---|---|---|---|
| Method: Least Squares | | | | |
| Date: 02/29/16 Time: 10:57 | | | | |
| Sample: 1 31905 IF FILTER="Yes" AND MIN_DWT_FILTER="Yes" AND | | | | |
| CB<0.9 AND SHIP TYPE="Bulk Carrier" | | | | |
| Included observations: 931 | | | | |
| HAC standard errors & covariance (Bartlett kernel, Newey-West fixed Bandwidth = 7.0000) | | | | |
| Variable | Coefficient | Std. Error | t-Statistic | Prob. |
| EEDI_IS_1 | -0.021485 | 0.013645 | -1.574550 | 0.1157 |
| C | -0.052023 | 0.010093 | -5.154149 | 0.0000 |
| R-squared | 0.003344 | Mean dependent var | | -0.063654 |
| Adjusted R-squared | 0.002271 | S.D. dependent var | | 0.185222 |
| S.E. of regression | 0.185011 | Akaike info criterion | | -0.534652 |
| Sum squared resid | 31.79897 | Schwarz criterion | | -0.524262 |
| Log likelihood | 250.8804 | Hannan-Quinn criter. | | -0.530690 |
| F-statistic | 3.117268 | Durbin-Watson stat | | 0.004796 |
| Prob(F-statistic) | 0.077795 | Wald F-statistic | | 2.479206 |
| Prob(Wald F-statistic) | 0.115701 | | | |

## G.2 Containerships

Figure 24 shows a graph of the EIV of containerships that have entered the fleet in 2014 and 2015. The yellow dots denote ships that are required to have an EEDI; the red dots ships that are not required to have an EEDI because they were contracted before 1 January 2015 and delivered before 1 July 2015.

Figure 24 **EIV of EEDI and non-EEDI ships (built in 2014-2015): Containerships**




Source: CE Delft.

Containerships that are required to have an EEDI have an EIV that is, on average, 22% below the reference line while ships that do not fall under the EEDI requirement have an EIV 23% below the reference line on average.

Table 9 shows that the difference is not statistically significant because the p-value of the variable EEDI_IS_1 is larger than 0.1.

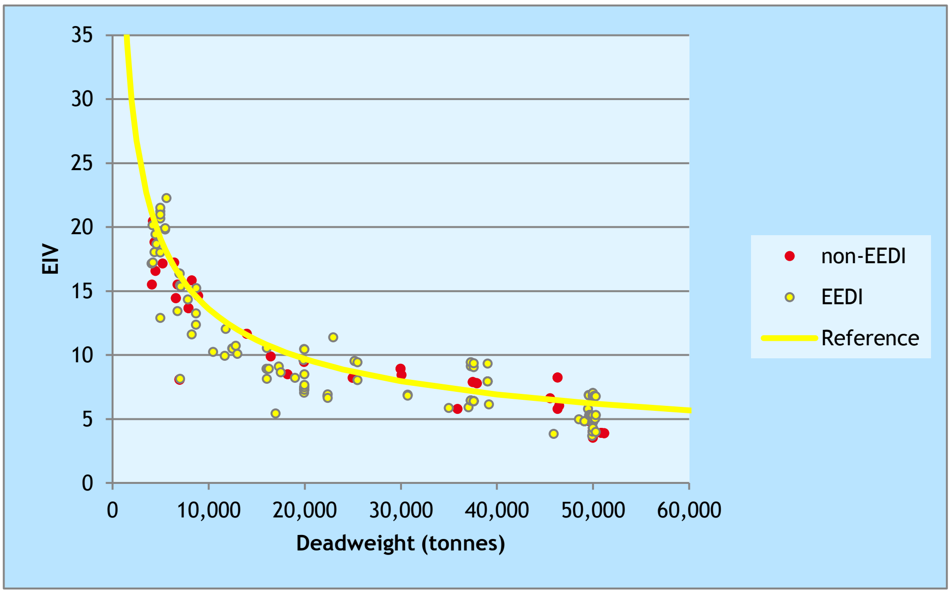
**Table 9** **Statistical analysis of the EIVs containerships that entered the fleet in 2014 and 2015**

| **Dependent Variable: _DOE** | | | | |
|---|---|---|---|---|
| Method: Least Squares | | | | |
| Date: 02/29/16 Time: 11:03 | | | | |
| Sample: 1 31905 IF FILTER="Yes" AND MIN_DWT_FILTER="Yes" AND | | | | |
| CB<0.9 AND SHIP TYPE="Containership" | | | | |
| Included observations: 281 | | | | |
| HAC standard errors & covariance (Bartlett kernel, Newey-West fixed Bandwidth = 6.0000) | | | | |
| Variable | Coefficient | Std. Error | t-Statistic | Prob. |
| EEDI_IS_1 | 0.011275 | 0.037464 | 0.300952 | 0.7637 |
| C | -0.229724 | 0.019980 | -11.49776 | 0.0000 |
| R-squared | 0.000994 | Mean dependent var | | -0.225069 |
| Adjusted R-squared | -0.002586 | S.D. dependent var | | 0.176361 |
| S.E. of regression | 0.176588 | Akaike info criterion | | -0.622897 |
| Sum squared resid | 8.700196 | Schwarz criterion | | -0.597001 |
| Log likelihood | 89.51705 | Hannan-Quinn criter. | | -0.612512 |
| F-statistic | 0.277667 | Durbin-Watson stat | | 0.000406 |
| Prob(F-statistic) | 0.598653 | Wald F-statistic | | 0.090572 |
| Prob(Wald F-statistic) | 0.763676 | | | |

## G.3 Tankers

Figure 25 shows a graph of the EIV of tankers that have entered the fleet in 2014 and 2015. The yellow dots denote ships that are required to have an EEDI; the red dots ships that are not required to have an EEDI because they were contracted before 1 January 2015 and delivered before 1 July 2015.

**Figure 25** **EIV of EEDI and non-EEDI ships (built in 2014-2015): Tankers**




Source: CE Delft.

Tankers that are required to have an EEDI have an EIV that is, on average, 10% below the reference line while ships that do not fall under the EEDI requirement have an EIV 9% below the reference line on average. Table 9 shows that the difference is not statistically significant because the p-value of the variable EEDI_IS_1 is larger than 0.1.

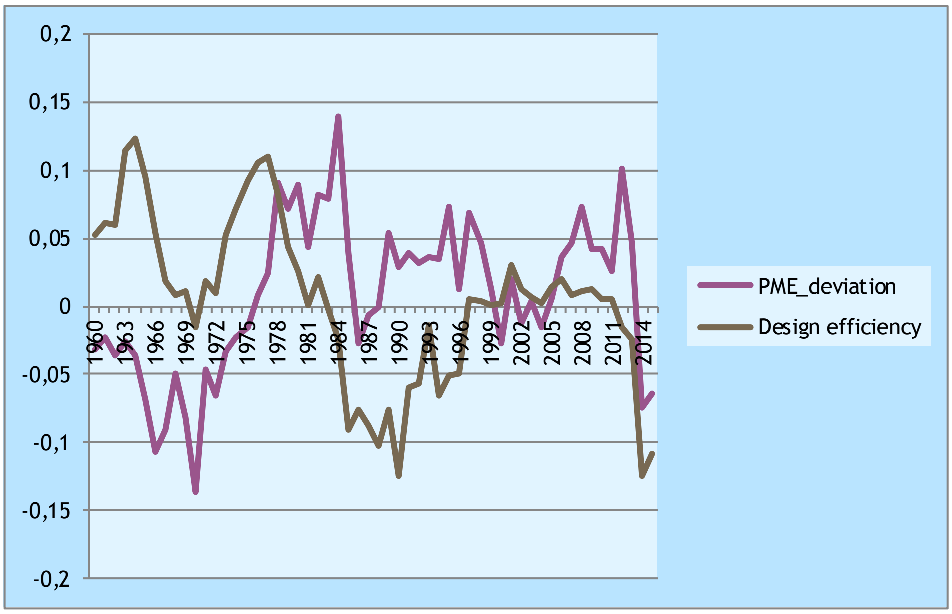
**Table 10 Statistical analysis of the EIVs of tankers that entered the fleet in 2014 and 2015**

| **Dependent Variable: _DOE** | | | | |
|---|---|---|---|---|
| Method: Least Squares | | | | |
| Date: 02/29/16 Time: 11:03 | | | | |
| Sample: 1 31905 IF FILTER="Yes" AND MIN_DWT_FILTER="Yes" AND | | | | |
| CB<0.9 AND SHIP TYPE="Tanker" | | | | |
| Included observations: 261 | | | | |
| HAC standard errors & covariance (Bartlett kernel, Newey-West fixed Bandwidth = 5.0000) | | | | |
| Variable | Coefficient | Std. Error | t-Statistic | Prob. |
| EEDI_IS_1 | -0.010025 | 0.026442 | -0.379137 | 0.7049 |
| C | -0.087901 | 0.023490 | -3.742003 | 0.0002 |
| R-squared | 0.000918 | Mean dependent var | | -0.094086 |
| Adjusted R-squared | -0.002939 | S.D. dependent var | | 0.161131 |
| S.E. of regression | 0.161368 | Akaike info criterion | | -0.802627 |
| Sum squared resid | 6.744253 | Schwarz criterion | | -0.775313 |
| Log likelihood | 106.7428 | Hannan-Quinn criter. | | -0.791647 |
| F-statistic | 0.238091 | Durbin-Watson stat | | 0.001057 |
| Prob(F-statistic) | 0.626001 | Wald F-statistic | | 0.143745 |
| Prob(Wald F-statistic) | 0.704897 | | | |

# Annex H Figures with development of Design efficiency and deviations of PME for tankers of various weightclasses

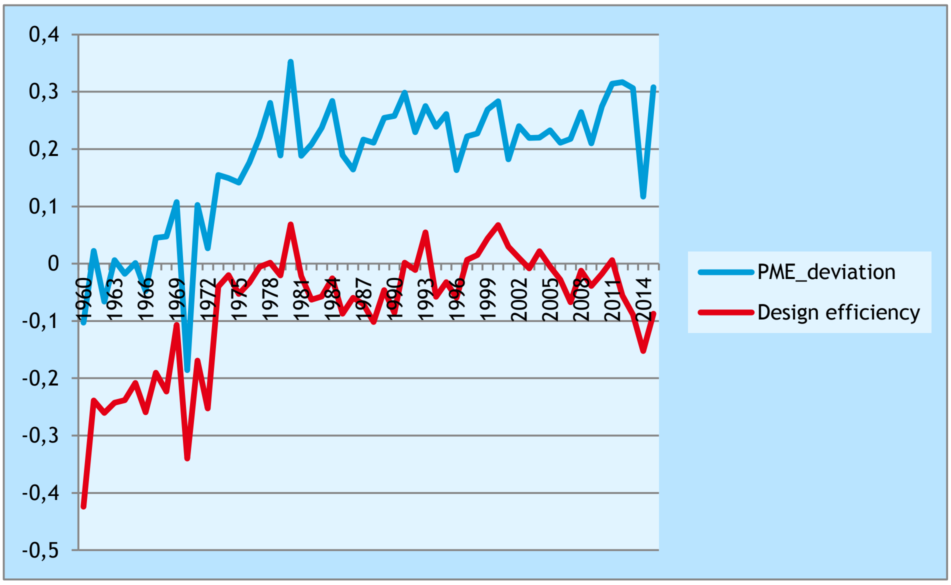
The following sections show the development of design efficiency and deviations from expected power over time, for tankers of various weight classes.

**Figure 26 The development of design efficiency and deviations from expected power over time, for tankers of all weight classes**

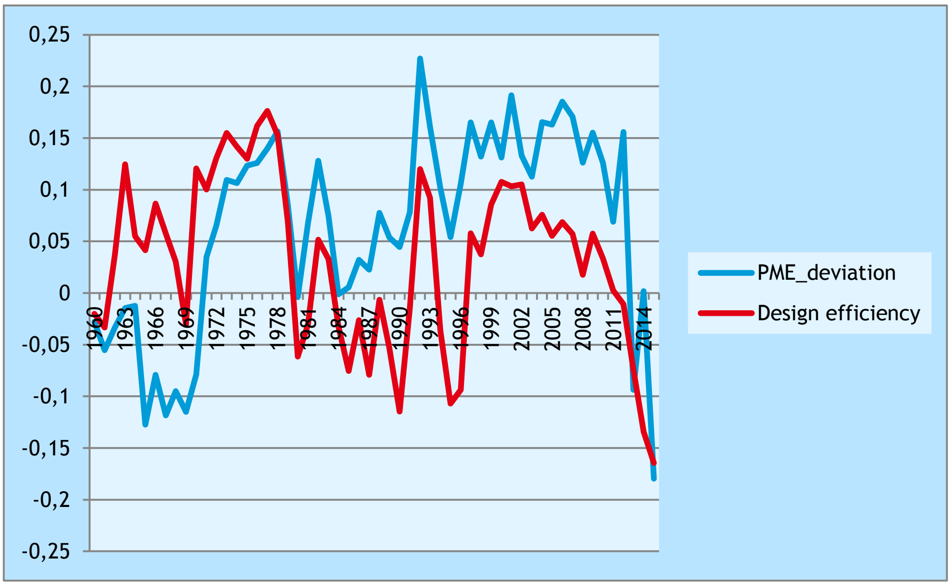



Source: IHS Maritime World Register of Ships, Clarkson World Fleet Register, calculation CE Delft.

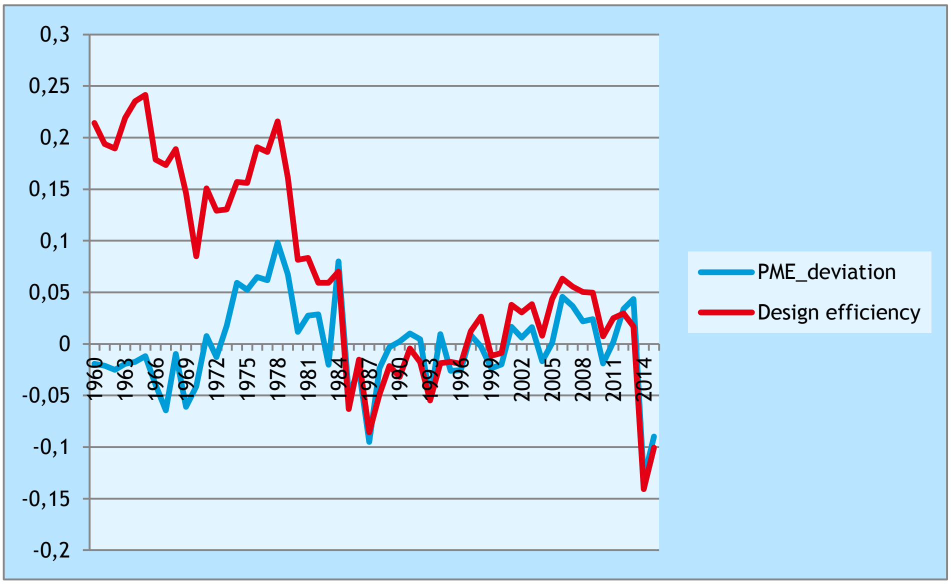
### H.1 4,000-10,000



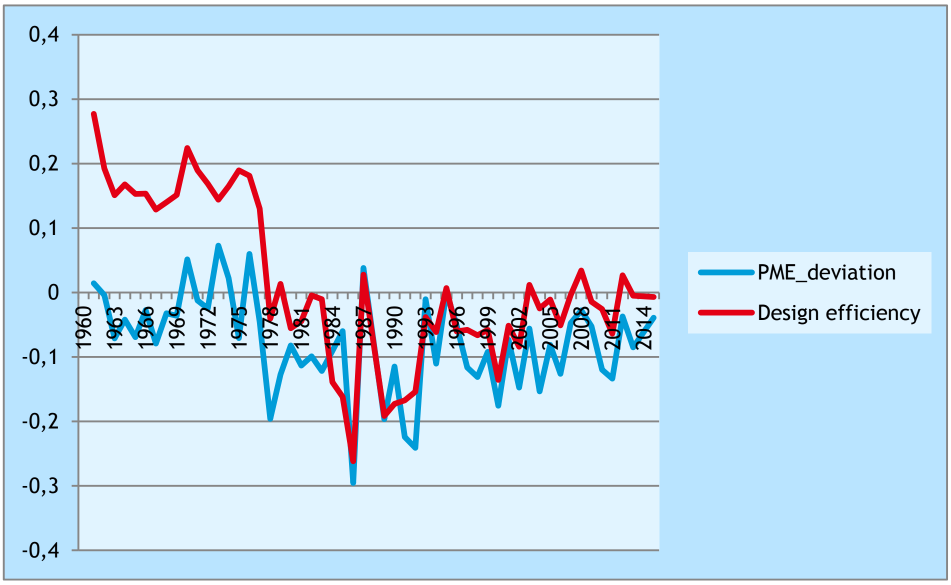

### H.2 10,000-25,000



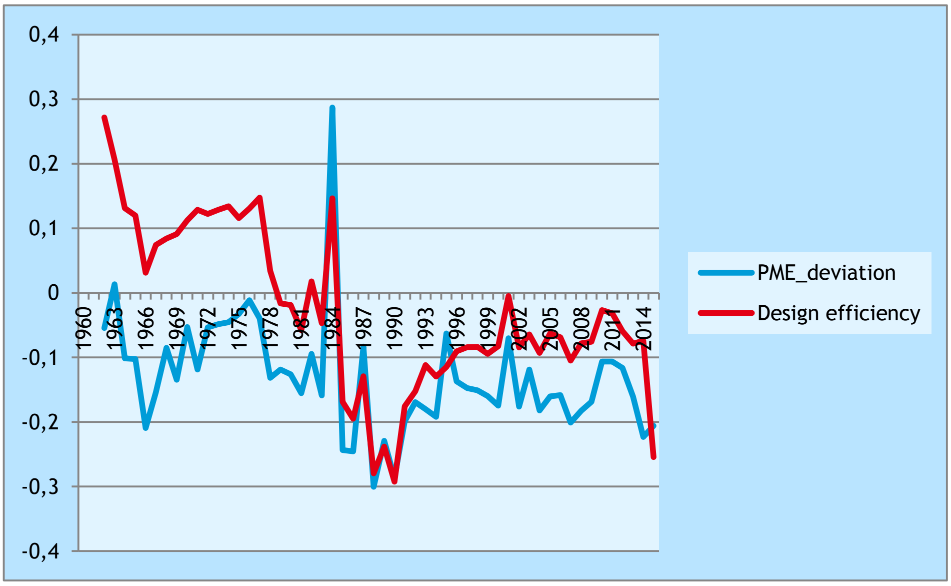
## H.3 25,000-55,000



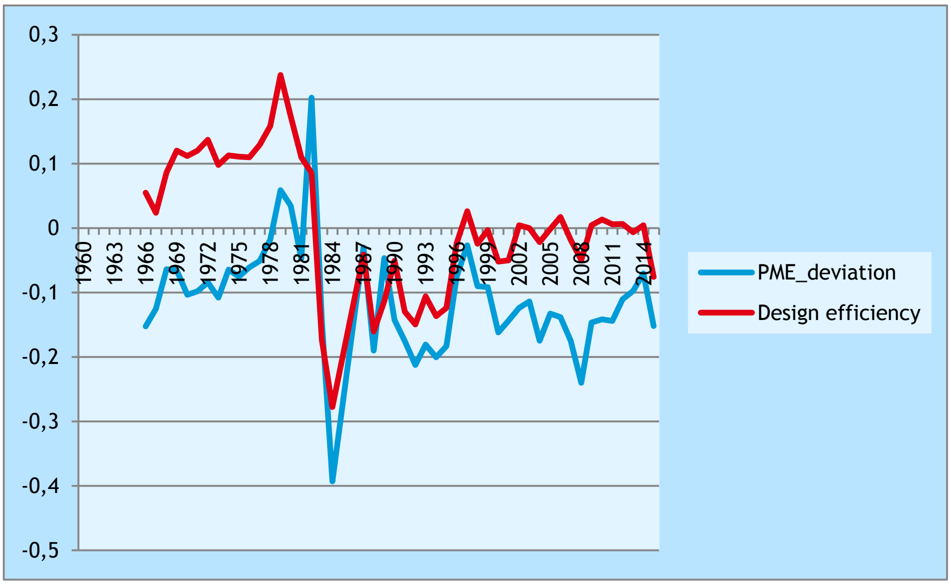

## H.4 55,000-75,000



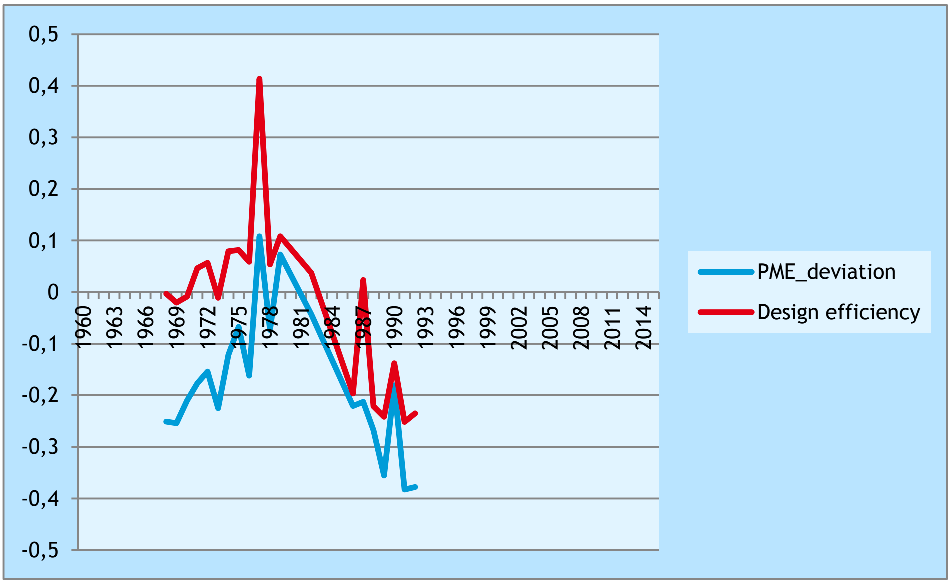
## H.5 75,000-120,000



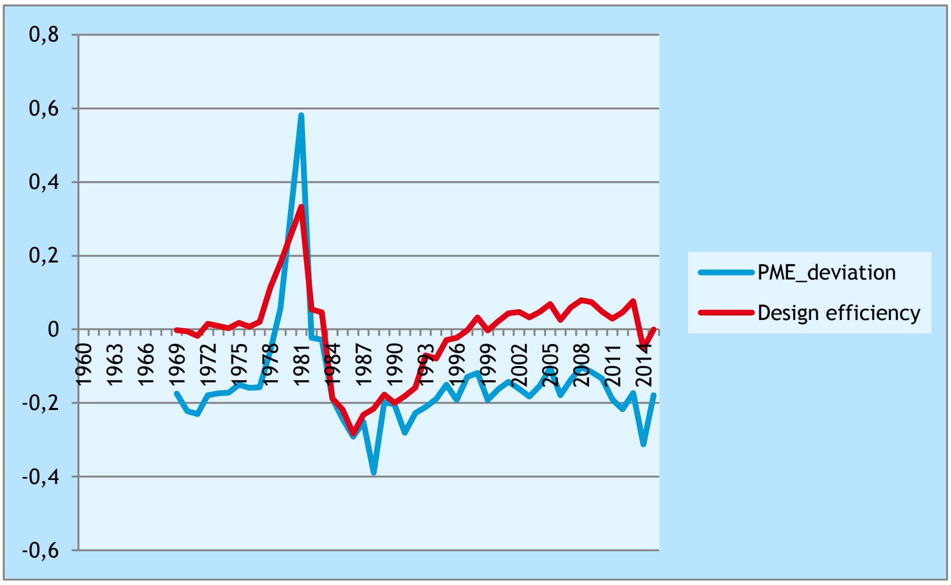

## H.6 120,000-170,000



## H.7 170,000-250,000




## H.8 250,000-330,000



## H.9 330,000 and larger