Historical trends in ship design efficiency

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Preface

This report is a first report of a study into the design efficiency of ships, which CE Delft has undertaken with support from the Clean Shipping Coalition.
A second report will analyse the developments of the design efficiency in the period 2009–2014. During our study, we have received valuable comments from Hans Otto Kristensen and John Calleya. Any remaining errors can, of course, only be attributed to us.

The authors

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Summary

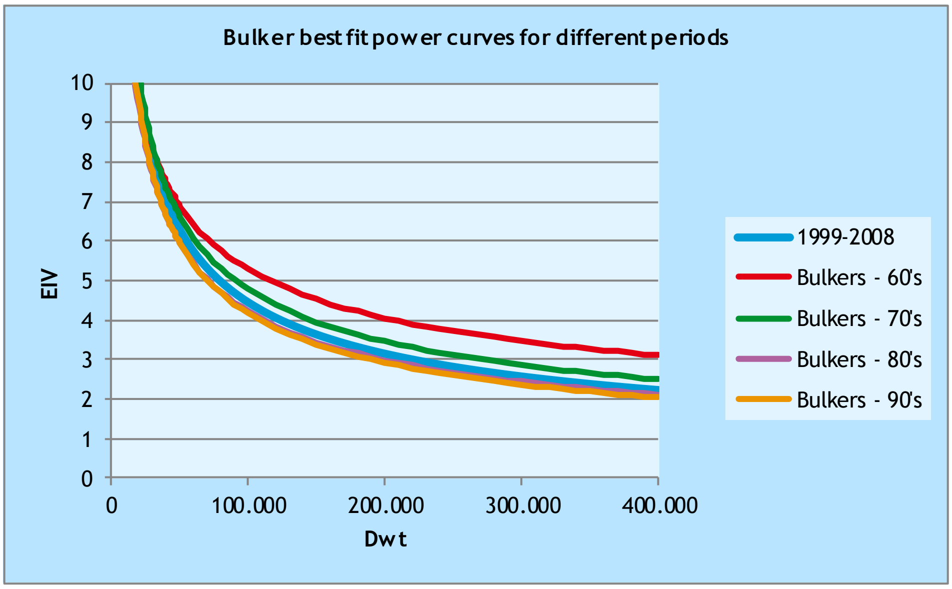
There is a growing interest in the fuel efficiency of ships because of fuel prices, climate change, and energy security issues. This has resulted in, amongst other things, a regulation governing the design efficiency of new ships (the Energy Efficiency Design Index or EEDI for short). As of 2013, new ships need to meet an EEDI target efficiency relative to a baseline constructed from the average design efficiency of ships that have entered the fleet in the period 1999-2008. The targets become more stringent over time.

Currently, the Marine Environment Protection Committee (MEPC) of the International Maritime Organization (IMO) is reviewing the targets. One of the main questions being addressed is the feasibility of the targets.

The historical development of design efficiency can provide relevant information to answer this question in three ways. First, it can elucidate how the design efficiency in the reference line period 1999–2008 compares to other periods. Second, it can show what the timeframe for market driven efficiency improvements has been. And third, it can show which design changes have resulted in efficiency changes.

This study shows that, 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 1 shows the best fit power curves for bulkers for five decades, including the decade in which the reference line was set. It shows that the design efficiency in the 1980s and 1990s was up to 10% better than in the period 1999–2008. A similar pattern can be observed for tankers and container ships.

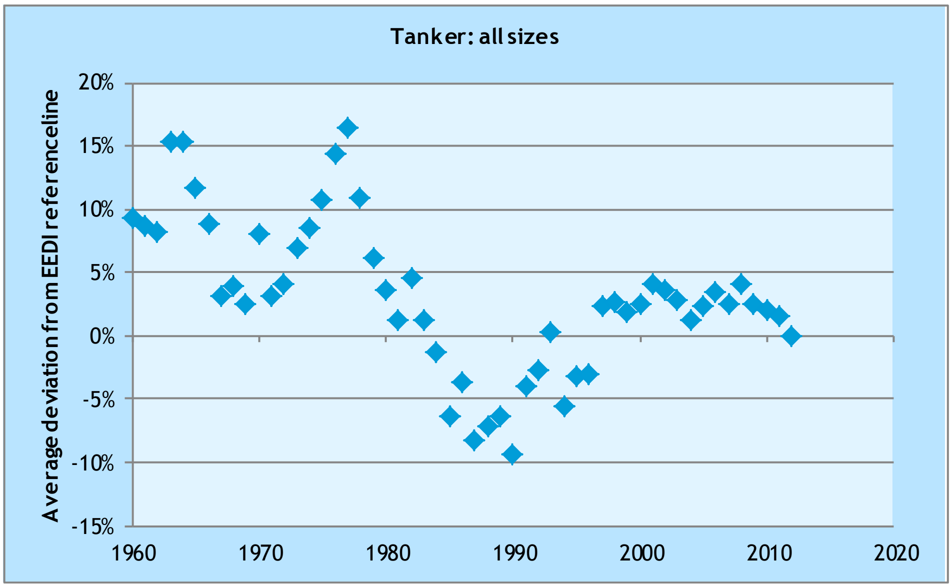
Figure 1 Best fit power curves for bulk carriers, 1960s-2000s



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

In the 1980s design efficiency improved by up to 28%, as shown in Figure 2 for tankers. Similar patterns exist for bulkers and container ships, and also for specific size categories of these ships. In the 1990s the design efficiency of tankers deteriorated by over 10%. This provides an estimate of the minimum efficiency changes that are possible.

Figure 2 Development of the design efficiency of new tankers, 1960-2012

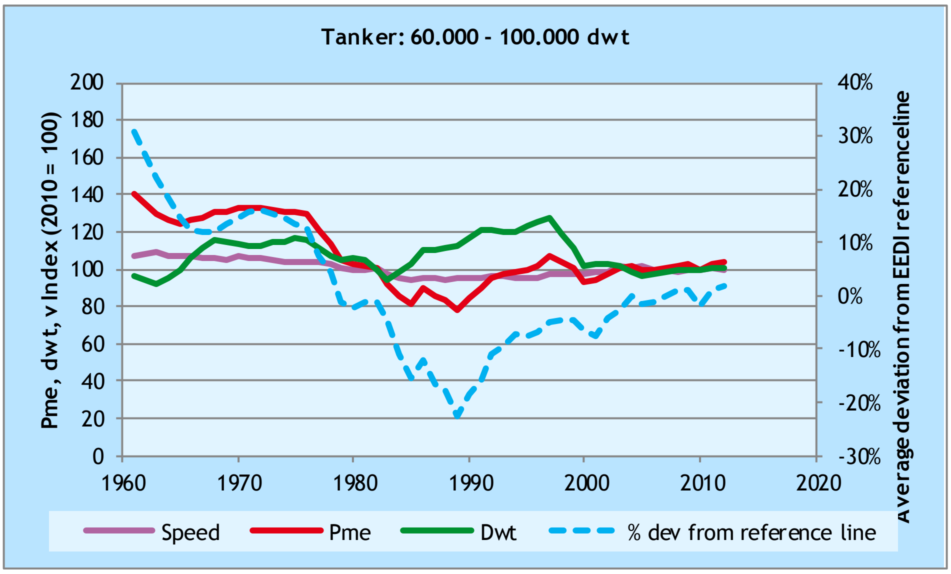


Source: IHS Maritime World Register of Ships, Clarkson World Fleet Register, calculation CE Delft.

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

Figure 3 shows how the design efficiency of tankers between 60,000 and 100,000 dwt evolved over time, as well as how the average speed, main engine power and size have changed. Between 1977 and 1987 their size increased while their speed and main engine power decreased. The decrease in main engine power was larger than would be expected on the basis of the change in speed. Conversely, in the following period the speed increased but the engine power increased by a larger margin than can be explained by speed changes alone. In this period, the block coefficient and other design parameters deteriorated, resulting in less efficient hulls.

Figure 3 **Development of the design efficiency, main engine power, speed and capacity of aframax tankers**



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

An analysis of the factors that have contributed to fuel efficiency improvement shows that to a limited extent, efficiency improvements have been brought about by reductions in design speed. In some cases, the size of the ships has increased. However, these two developments cannot explain the efficiency improvements to the full extent. In most cases, improvements in hull design and propulsion efficiency have contributed significantly to efficiency improvements. Likewise, the deterioration of efficiency after the 1990s has been caused at least partly by deteriorating designs.

The changes in design efficiency 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 built, the payback period of the additional capital expenditure is shorter when fuel prices are high.

However, fuel prices are not the only relevant factor: freight rates are also an important factor. When freight rates are high, new ships are in high demand and yards can build standard designs with a low risk 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.

There can be several other reasons why ship owners choose to build ships that are less fuel-efficient. One is that in some ports and canals, ship dimensions are restricted. In order to be able to maximise transport work, ship owners can choose to choose to maximise cargo capacity within these constraints. This is especially attractive when freight rates are high and fuel prices are low. The second is that fuller form ships are cheaper to build as they require less steel and also less manpower to assemble. So when steel prices and wages are high while fuel is cheap, fuller form ships become more attractive.

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 (until recently), 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.

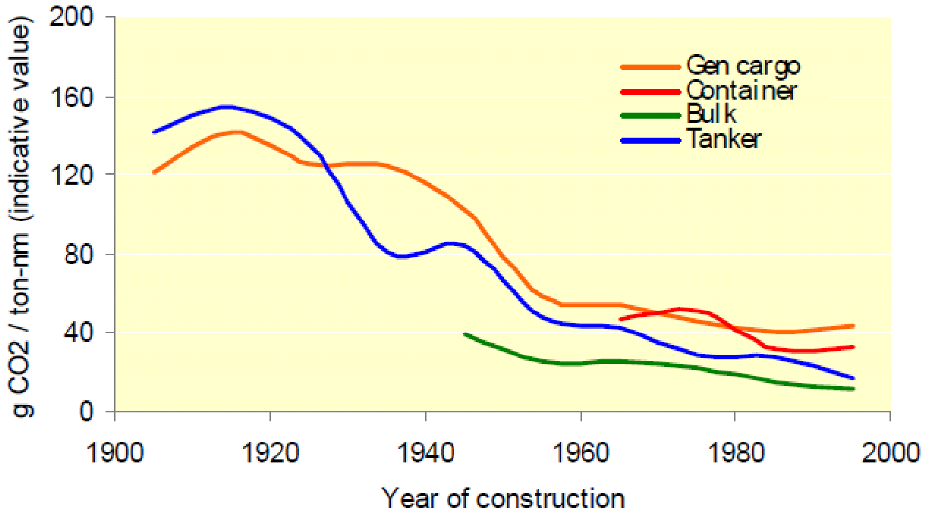
At a global level, states have taken action by including energy efficiency regulations in Annex VI of the MARPOL Convention. All ships need to have a ship energy efficiency management plan, specifying how they monitor and control operational efficiency.

In addition, as of 2013, new ships are required to establish their 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 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.

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 containers has deteriorated in the early 1990s (see Figure 4). It does not present an analysis of the factors that contributed to these trends.

Figure 4 **Indicative development in average ship design transport efficiency**



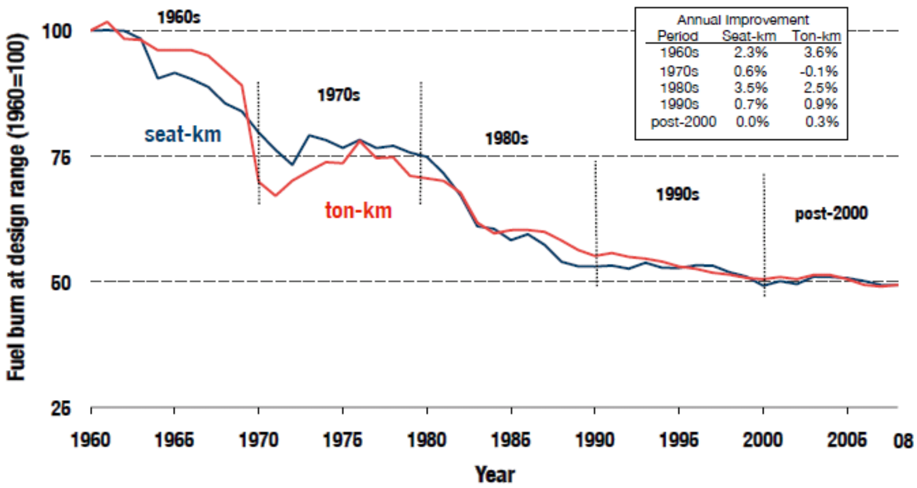
Source: (Buhaug, et al., 2009).
Note that the design efficiency is expressed in a different metric than used in this report.

Mortenson (2009) confirms the general trend but shows that the efficiency of specific ship types follows different trends (Mortensen, 2009). His article is based on a Lloyds Register study that uses an indicator called the 'fuel consumption index'.[1] While the efficiency of 1,800 TEU and 4,500 TEU containerships improved between 1990 and 2000 using this index 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.

The lack of historical data on the design efficiency of ships is surprising in comparison with other transport modes. For aircraft, Figure 5 shows how efficiency has improved since the 1960s: after a steep decline between 1960 and 1990, improvements have levelled off in the 2000s. For trucks, there appears to be more variation in efficiency, as shown in Figure 6. In this case, efficiency improvements have almost come to a standstill between 1990 and 2009.

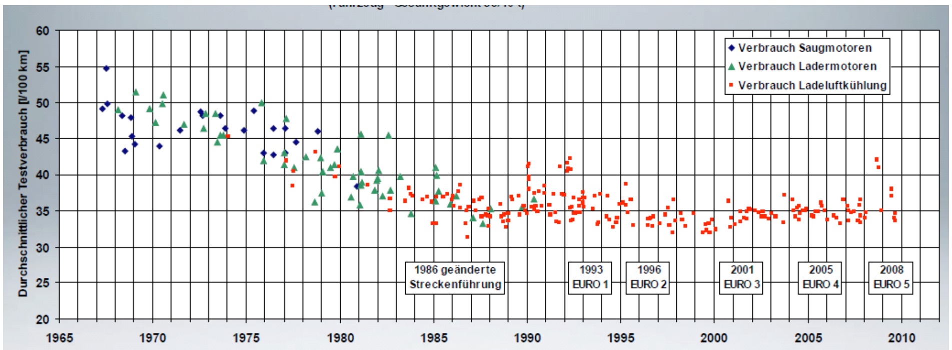
[1] We have not been able to locate the study and do not know what this indicator is.

Figure 5 Development of aircraft design efficiency



Source: (ICCT, 2009).

Figure 6 Efficiency of new trucks, 38/40 tonnes, 1965-2009



Source: http://www.nvfnorden.org/lisalib/getfile.aspx?itemid=4270, accessed 6-2-2015.

A historical analysis can shed light on current state of the art and possibility to improve efficiency using existing technology. It may also show what drivers of efficiency improvements have been, and where regulation has had or can have an impact.

1.2 Subject of the study

This study analyses the development of the design efficiency of new ships in the last 50 years. To that end, it analyses these three research questions:

- How has the design efficiency changed over time?
- Which changes in design have contributed to the changes in efficiency?
- Which drivers and barriers have resulted in design changes?

There are many definitions and metrics of design efficiency of ships. In this study, we have chosen to use the Estimated Index Value (EIV) because it has formed the basis for the current regulation of the design efficiency by requiring ships to have a maximum Energy Efficiency Design Index (EEDI). The EIV is a simplified form of the EEDI.

In order to assess how good a ship's design efficiency is, we have compared its EIV to the reference line for the EEDI. The reference line is the best fit of a power function through the EIVs of ships that have entered the fleet between 1999 and 2008. A value above the reference line means that a ship emits more CO2 per tonne-mile under standard conditions, and it therefore less efficient, than the average comparable ship built between 1999 and 2008.

The EIVs have been calculated in conformity with resolution MEPC.215(63) (MEPC, 2012a). 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) (MEPC, 2012b) ;

6. no correction factors on ice class, voluntary structural enhancement, etc. are used;

7. innovative mechanical energy efficiency technology, shaft motors and other innovative energy efficient technologies are all excluded from the calculation, i.e. P_{AEeff} = 0, P_{PTI} = 0, P_{eff} = 0.

This results in the following formula:

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

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, 2012a), only ships of 400 GT or above are included.

The study focusses on bulk carriers, tankers and container ships, which are the three major ship types in terms of greenhouse gas emissions (IMO,MEPC, 2014).

Reference line values have been calculated according to the guidelines set out in (MEPC, 2011) Annex 19. Each ship type has a different reference line that is an exponential function of DWT. These functions are shown in Table 1 and in the graphs in the second chapter.

Table 1 Reference line value for different ship types

Ship type	Reference line value
Bulk carrier	$961.79*(dwt)^{-0.477}$
Tanker	$1218.8*(dwt)^{-0.488}$
Container ship	$174.22*(dwt)^{-0.201}$

Source: MEPC.203(62) Annex 19.

The data used in this study have been taken from the IHS Maritime World Register of Ships (for ships that are not active) and from Clarksons World Fleet Register (for active ships). For each ship for which sufficient data are available, the EIV has been calculated and compared with the reference line. Ships for which one or more relevant data fields did not contain a value have not been included in the analysis. In addition, we have excluded ships below 4,000 dwt (tankers) and 10,000 dwt (bulk carriers and container ships), since for these ships there are no EEDI requirements or the EEDI targets are less stringent than for ships above this value.

1.3 Outline

This report first analyses the design efficiency of new bulk carriers, tankers, and container ships in Chapter 2. Chapter 3 briefly discusses the main barriers and drivers, and Chapter 4 concludes.

2 Historical design efficiency

2.1 Introduction

This chapter presents the analysis of the historical development of the EIV of bulk carriers, containerships and tankers. For all ships for which data was available, we have calculated the EIVs according to the method described in Section 1.2 and compared it with the reference line. The difference is a measure for the relative efficiency of the ship, compared to a similar ship that has entered the fleet between 1999 and 2008.

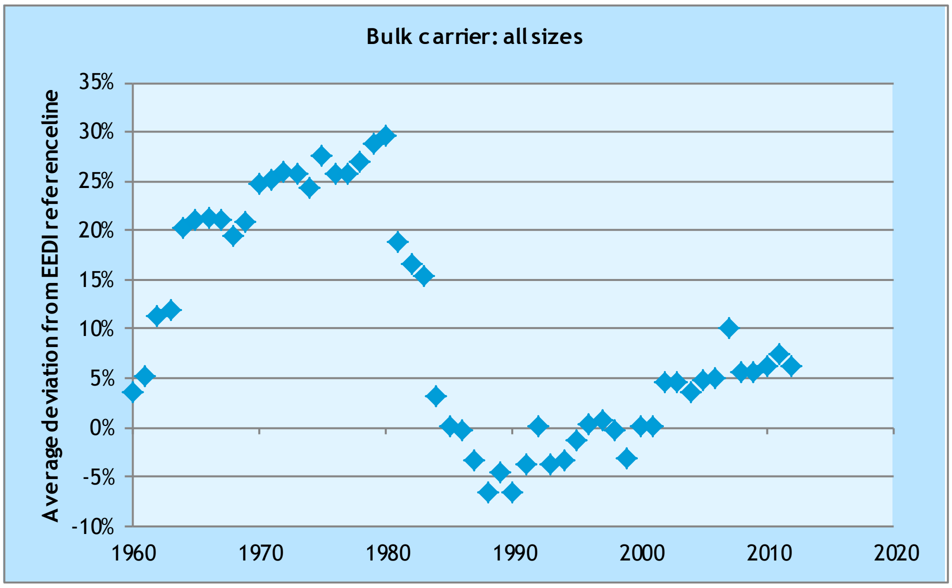
For bulk carriers and container ships, the data allow us to analyse the development of the design efficiency from 1960. Container ships were built in sufficiently large numbers for a statistical analysis only from the 1970s onwards.

The remainder of this section presents for each ship type the overall development of the design efficiency, the development of the underlying factors main engine power, speed and capacity, and the same for specific size categories of ships. Section 2.2 presents the analysis for bulk carriers, 2.3 for tankers and Section 2.4 for container ships.

2.2 Historical design efficiency of bulk carriers

For bulk carriers there was sufficient data to calculate the EIV scores from 1960. Figure 7 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 7 **Development of the design efficiency of new bulk carriers, 1960-2012**



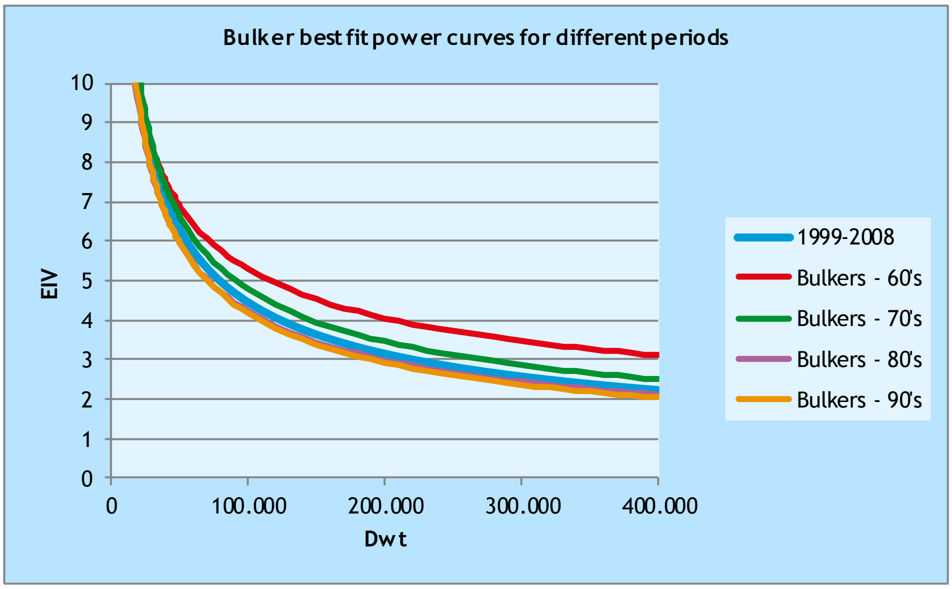
Source: IHS Maritime World Register of Ships, Clarkson World Fleet Register, calculation CE Delft.

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

Another way to present the development in design efficiency is to compare the reference line that has been calculated for ships that have entered the fleet between 1999 and 2008 (and which has been taken as the EEDI reference line) with the best fit power curves for other decades.

Figure 8 shows the EEDI reference line in blue. Bulk carriers that entered the fleet in the 1960s and 1970s were less efficient than ships that entered the fleet at the first decade of the new millennium. In contrast, ships in the 1980s and 1990s were more efficient.

Figure 8 **Best fit power curves for bulk carriers, 1960s-2000s**



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

Table 2 shows the coefficients for the EEDI referenced line and the best fit power curves through the EIVs of new ships built in five consecutive decades. Because of a slightly different sample, we have recalculated a reference line for 1999-2008, which is marginally different from the EEDI reference line, and compared the best fit curves from other decades to the recalculated line.[2] In order to facilitate the comparison, the relative difference is also shown for bulk carriers of four different sizes. Ships from the 1960s and 1970s were about one fifth to a quarter less efficient than the EEDI reference line, whereas ships from the 1980s and 1990s were up to one tenth more efficient. Especially the larger ships from the 1980s and 1990s were more efficient than the corresponding ships built during the reference line period 1999–2008.

Table 2 Coefficients for best fit power curves of bulk carriers in different periods

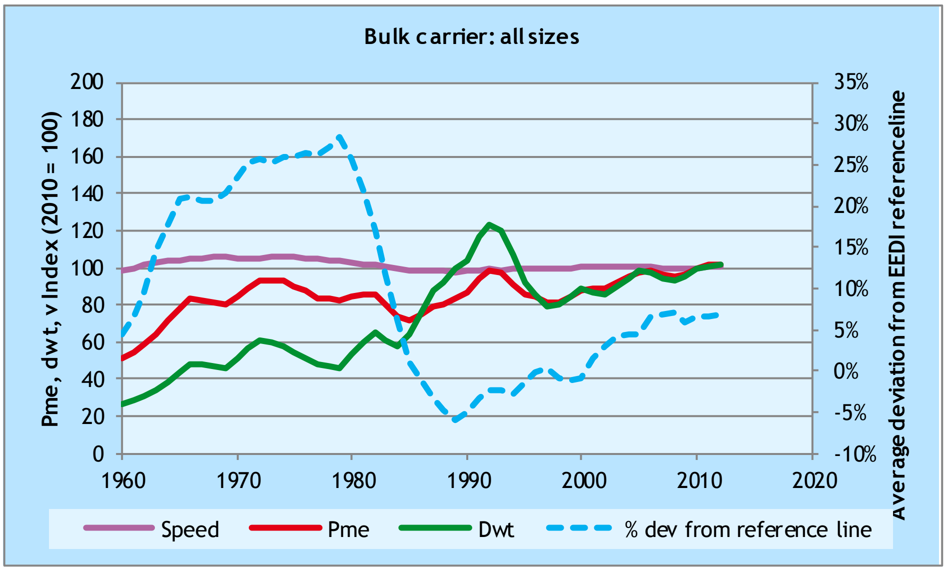
Reference line	a	b	50,000	100,000	200,000
EEDI reference line	961,8	-0,48			
1999-2008	1.357,6	-0,51	0%	0%	0%
60's	709,1	-0,43	+15%	+21%	+27%
70's	1.416,3	-0,49	+20%	+21%	+22%
80's	3.164,4	-0,58	+0%	-5%	-10%
90's	1.572,1	-0,52	-5%	-7%	-8%

2.2.1 The contribution of size, power and speed

Changes in the EIV and in our efficiency metric are the result of changes in the main engine power, capacity or speed of ships. Figure 9 shows how the design efficiency of bulk carriers, their average speed, main engine power and capacity have changed since 1960. Design efficiency is expressed as the average difference between the EIV and the reference line, whereas the other parameters are indexed to their 2010 values. The graph shows that the main engine power increased sharply in the 1960s and varied between 80% and 100% of its 2010 value since the 1970s. Speed increased initially to about 5% above the average 2010 value in 1975, then declined to just below the 2010 value in 1990 and increased gradually to its 2010 average. The development of the average size shows the largest changes. Bulk carriers have increased in size from about 25% of their 2010 level in 1960s. The increase in the late 1980s, beginning 1990s was particularly fast, but followed by a sharp decline in the mid-1990s.

[2] Our sample does not include bulkers below 10,000 dwt, which is the value below which bulkers do not need to comply with the EEDI, tankers below 4,000 dwt and containerships below 10,000 dwt, whereas the reference lines have been calculated for all ships over 400 GT.

Figure 9 Development of the design efficiency, main engine power, speed and capacity of bulk carriers

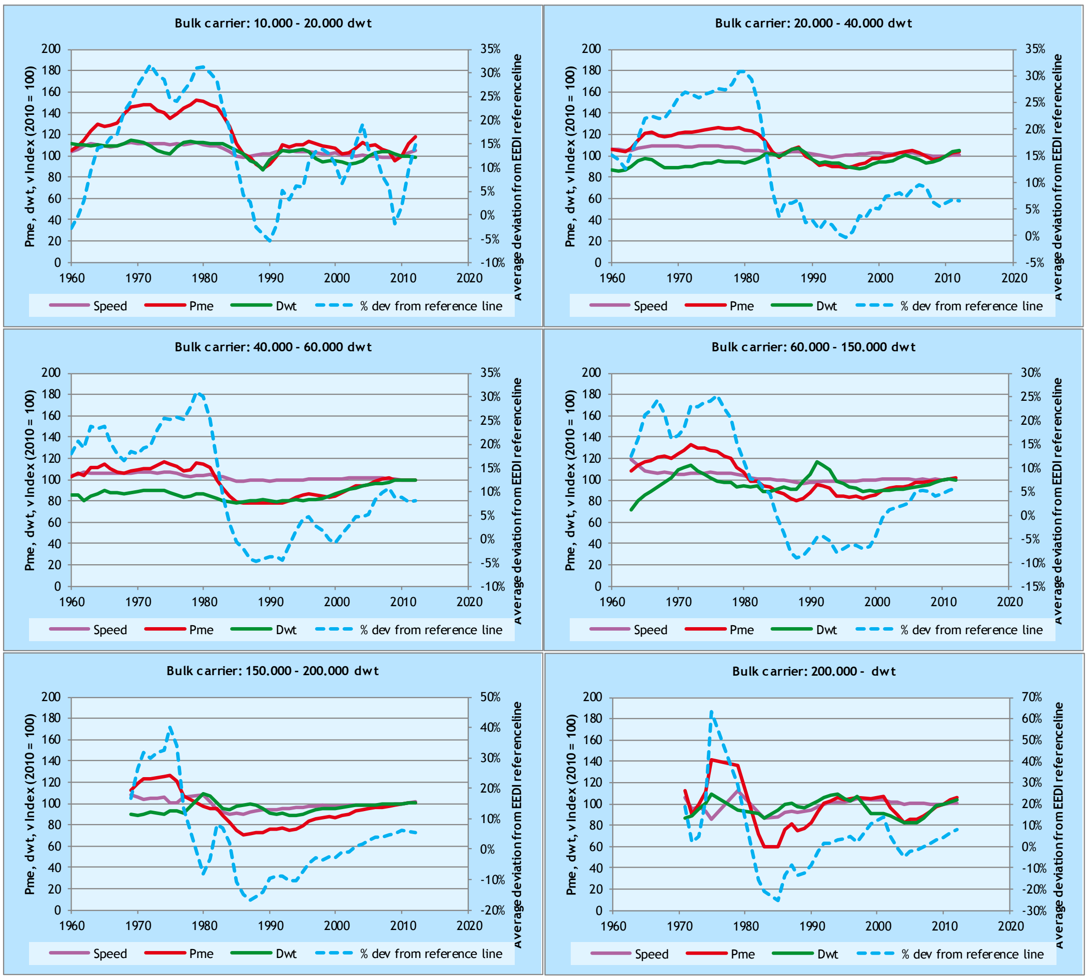


Source: IHS Maritime World Register of Ships, Clarkson World Fleet Register, calculation CE Delft.

The decomposition of Figure 9 is not easy to interpret because factors are interrelated and because design efficiency is defined as the difference between the EIV and the reference line. The interrelation between the factors is clear in the 1960s. The increase in main engine power between 1960 and 1970 coincided with a deterioration of the design efficiency, but did not necessarily cause it, because the increase in power also coincided with an increase in the average size. However, in the chosen measure for design efficiency an increase in engine power and a corresponding increase in size need not result in a change in the design efficiency. If, for example, the average size of bulk carriers increases from 30,000 dwt to 50,000 dwt, and their design speed remains equal, the engine power can increase by 22% without changing the average design efficiency, because the difference with the reference line would remain equal.

Figure 10 shows how the design efficiency and the factors that are used to calculate it have changed over time for six size categories of bulk carriers. For all these categories, size has remained fairly constant over time, generally showing a gradual increase of about 20% or less in five decades.
The population of the fleet has changed to include more large ships over time. In fact, the largest ship size categories in the figure have only been built in sufficient numbers from 1970 onwards, which is why the 1960s are not included in the two bottom panels of Figure 10.

Figure 10 **Development of the design efficiency, main engine power, speed and capacity of bulk carriers of different sizes**



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

Within all size categories, the design efficiency has improved considerably in the 1980s. Some size categories started early: the efficiency of ships above 60,000 dwt started improving after around 1975, whereas the improvement of the smaller ships did not start until 1980. The design efficiency reached a maximum around 1990 and deteriorated after that for ships over 40,000 dwt.

The efficiency improvement in the 1980s has been brought about by a sharp reduction in the main engine power. The change in average speed was much less than would be expected on the basis of the reduction in engine power and the average size has remained constant or increased only slightly.[3] So the efficiency improvement must have been due to other factors, such as the hull shape. This is corroborated by an article of Smit and Pijcke, who report that in the 1970s, naval architects and maritime engineers focussed in improving the specific fuel efficiency of engines and on improving the hull design through decreasing the block coefficient (Smit & Pijcke, 1985).

3 To be precise, the reduction in main engine power was larger than the change in speed to the third power.

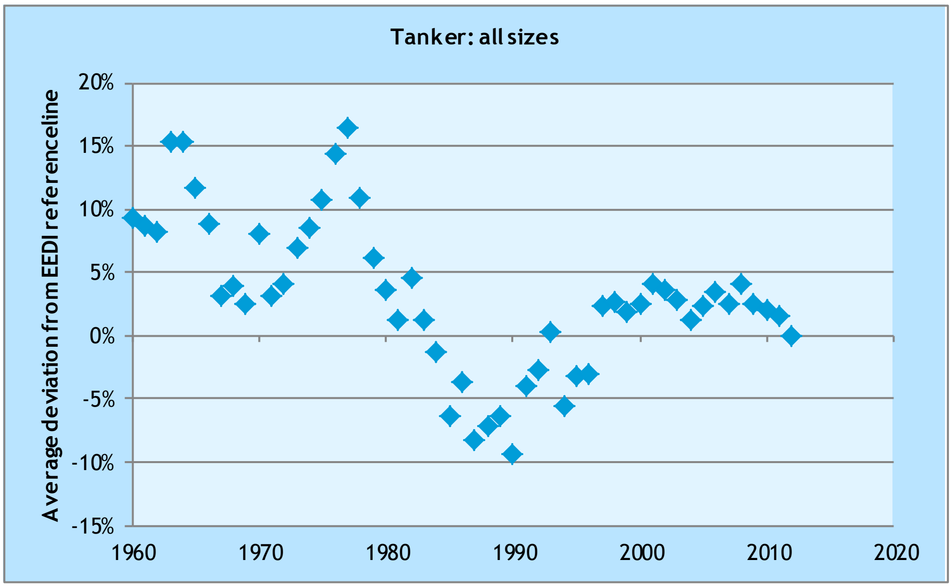
The deterioration of the efficiency after 1990 has been brought about by an increase in main engine power. In some size categories, speed also increased, but much less than can be accounted for by the power increase. Kristensen and Lützen have shown that the block coefficient has increased in this period, i.e. ships have become more box-like (Kristensen & Lützen, 2012). At the same time, the length displacement ratio (L/displ.volume$^{1/3}$) has decreased, so ships have become less slender. Both factors increase the resistance of the hull when moving through water.

There can be several reasons why ship owners choose to build ships that are less efficient. One is that in some ports and canals, ship dimensions are restricted. In order to be able to maximise transport work, ship owners can choose to choose to maximise cargo capacity within these constraints. This is especially attractive when freight rates are high and fuel prices are low. The second is that fuller form ships are cheaper to build as they require less steel and also less manpower to assemble (Smit & Pijcke, 1985). So when steel prices and wages are high while fuel is cheap, fuller form ships become more attractive.

2.3 Historical design efficiency of tankers

Our database contains sufficient data for tankers to calculate the EIV scores from 1960. Figure 11 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.

Figure 11 Development of the design efficiency of new tankers, 1960-2012

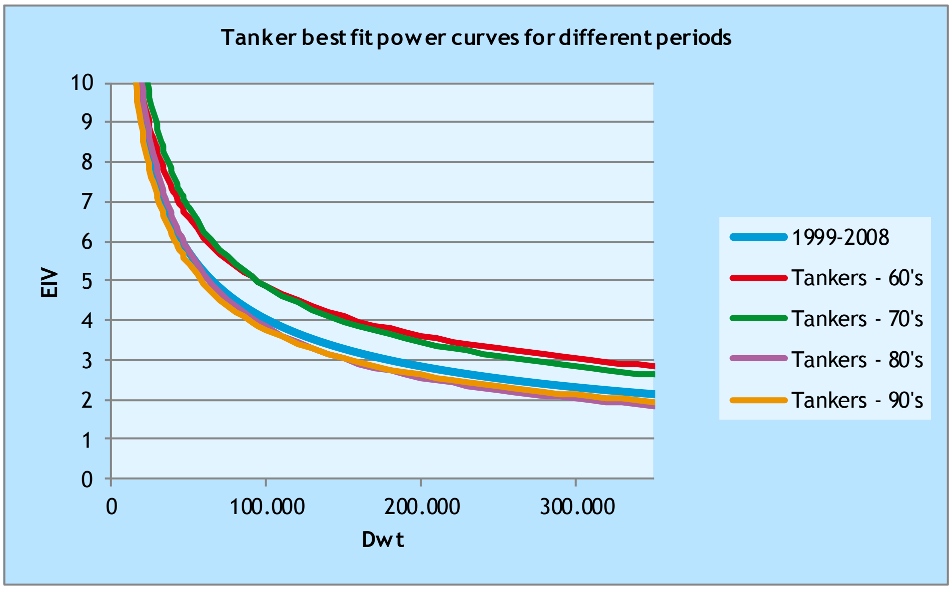


Source: IHS Maritime World Register of Ships, Clarkson World Fleet Register, calculation CE Delft.

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

Figure 12 shows how the EEDI reference line for tankers compares to the best fit power curves for tankers in the decades studied in this report. Because of a slightly different sample, we have recalculated a reference line for 1999-2008, which is marginally different from the EEDI reference line, and compared the best fit curves in other years to the recalculated line.[4] The power curves have come down from the 1960s through the 1990s, before going up again to a level just above the 1980s curve in the years over which the reference line has been established.

Figure 12 Best fit power curves for tankers, 1960s-2000s



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

Table 3 shows the coefficients for the best fit power curves through the EEDI of new tankers built in five consecutive decades. In order to facilitate the comparison, the relative difference is also shown for bulk carriers of three different sizes. Ships from the 1960s were about one tenth to a third less efficient than the EEDI reference line, whereas ships from the 1990s were up to 7% more efficient.

Table 3 Coefficients for reference line of tankers in different periods

Reference line	a	b	50,000	100,000	200,000
EEDI reference line	1.218,8	-0,49			
1999-2008	1.387,9	-0,50	0%	0%	0%
60's	431,9	-0,38	+10%	+19%	+29%
70's	1.063,3	-0,47	+5%	+8%	+10%
80's	1.301,5	-0,50	-5%	-5%	-5%
90's	1.543,5	-0,51	-5%	-6%	-7%

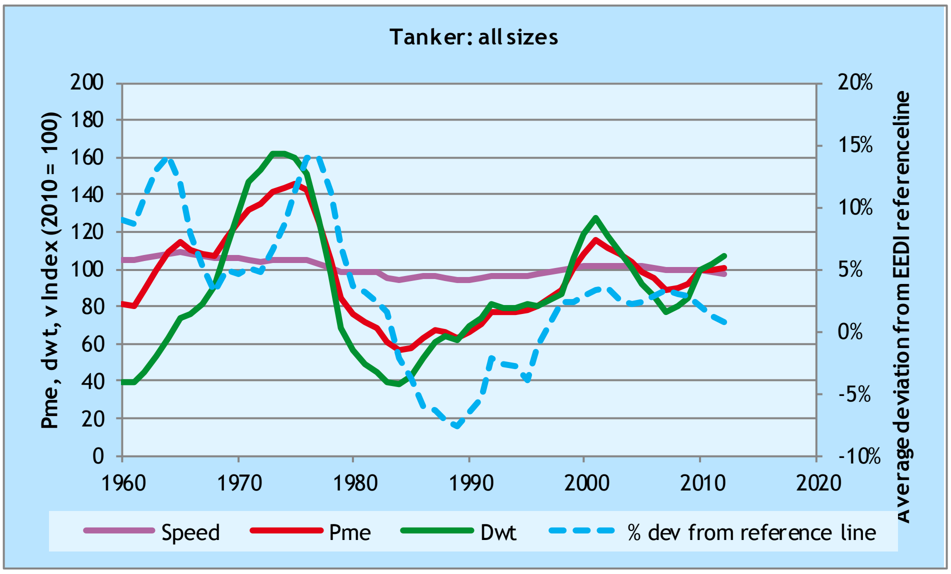
4 Our sample does not tankers below 4,000 dwt (the value below which tankers do not need to comply with the EEDI), whereas the reference lines have been calculated for all ships over 400 GT. This slightly tilts the recalculated line downwards for larger tankers.

2.3.1 The contribution of size, power and speed

Changes in the EIV and in our efficiency metric are the result of changes in the main engine power, capacity or speed of ships. Figure 13 shows how the design efficiency of tankers, their average speed, main engine power and capacity have changed since 1960. Design efficiency is expressed as the average difference between the EIV and the reference line, whereas the other parameters are indexed to their 2010 values.

The graph shows that the average size of new tankers increased strongly between 1960 and 1975, and then declined to the 1960s value by 1984, after which a gradual increase took place. The average speed decreased from above 15 knots in the early 1960s to above 13 knots in the late 1980s before gradually increasing to just above 14 knots in the 2000s. The main engine power appears to track ship size.

Figure 13 Development of the design efficiency, main engine power, speed and capacity of tankers

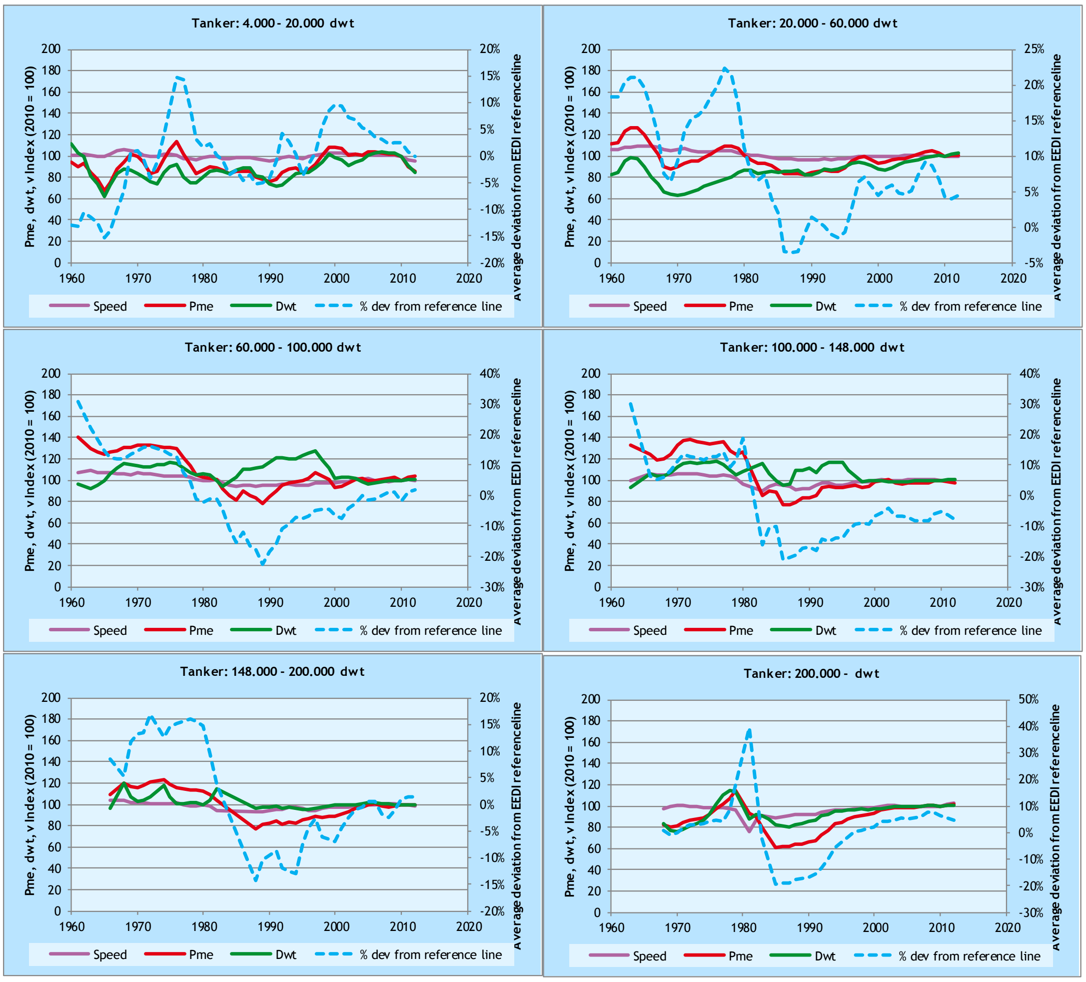


Source: IHS Maritime World Register of Ships, Clarkson World Fleet Register, calculation CE Delft.

Figure 14 shows how the design efficiency and the factors that are used to calculate it have changed over time for six size categories of tankers. Smaller tankers, with a dwt of up to 60,000, have gradually increased in size, while the average size of the larger tankers has remained within a band of ±20% of their 2010 value. The speed has varied by about 10% but the largest variation has been in engine power. To some extent, engine power has changed in line with speed and ship size, but the variation in engine power also points to changes in hull design.

Tankers with a size between 60,000 and 100,000 dwt show the relevance of hull design. Between 1972 and 1989 their size remained constant (with a small dip in the early 1980s) while their speed and main engine power decreased. The decrease in main engine power was larger than could be expected on the basis of the change in speed: the speed decreased by 10% on average, while the engine power decreased by over 40%. This means that the hull efficiency or propulsion efficiency have probably improved significantly in this period. The following period presents a sharp contrast. In this period, the average speed increased from about 14.1 knots to 14.9 knots, a 4.4% increase. According to the rule-of-thumb that propulsion power is correlated with the third power of the speed, such a speed increase would have required a 14% increase in engine power, not counting the average size of the ships that decreased by more than 10% in this period. Instead, the average engine power increased by 30%. This has to be related to a deterioration of the hull and propulsion efficiency. Kristensen and Lützen have shown that for this type of tankers, the block coefficient and the Froude number have both increased, while the length displacement ratio has decreased, all contributing to a less efficient hull form (Kristensen & Lützen, 2012).

Figure 14 **Development of the design efficiency, main engine power, speed and capacity of tankers of different sizes**

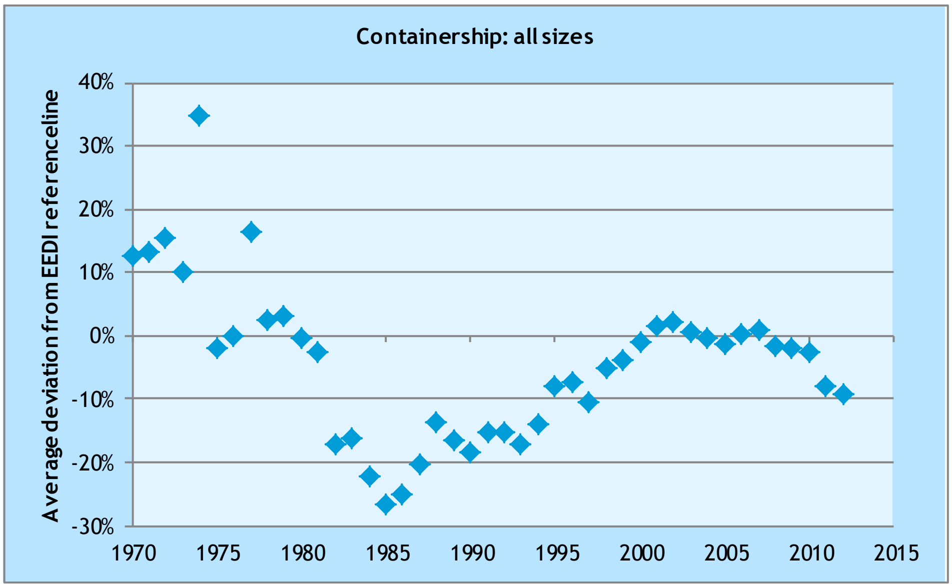


Source: IHS Maritime World Register of Ships, Clarkson World Fleet Register, calculation CE Delft.

2.4 Historical design efficiency of container ships

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 EEDI, so the average is not very reliable. Figure 15 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 15 Development of the design efficiency of new container ships, 1970-2012



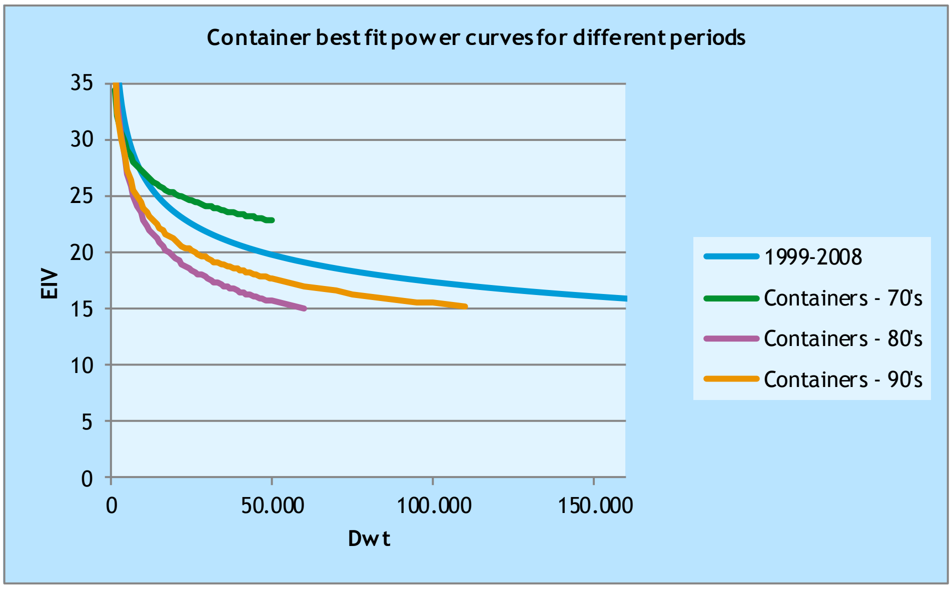
Source: IHS Maritime World Register of Ships, Clarkson World Fleet Register, calculation CE Delft.

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

Figure 16 shows how the EEDI reference line for container ships compares to the best fit power curves for container ships in the decades studied in this report. Because of a slightly different sample, we have recalculated a reference line for 1999-2008, which is marginally different from the EEDI reference line, and compared the best fit curves from other decades to the recalculated line.[5] The most efficient containerships were built in the 1980s. In the subsequent decades the design efficiency deteriorated, albeit never to the level of the 1970s. Note, however, that the comparison does not hold over all sizes, because of the dramatic increase in the size of container ships. The largest containership in our database from the 1970s was 50,000 dwt, increasing to 60,000 dwt in the 1980s, 82,000 dwt in the 1990s and 165,000 dwt in the 2000s.

5 Our sample does not include containerships below 10,000 dwt (the value below which container ships do not need to comply with the EEDI), whereas the reference lines have been calculated for all ships over 400 GT. This slightly tilts the recalculated line downwards for larger ships.

Figure 16 Best fit power curves for container ships, 1970s-2000s



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

Table 4 shows the coefficients for the best fit power curves through the EEDI of new container ships built in five consecutive decades.

Table 4 Coefficients for reference line of containerships in different periods

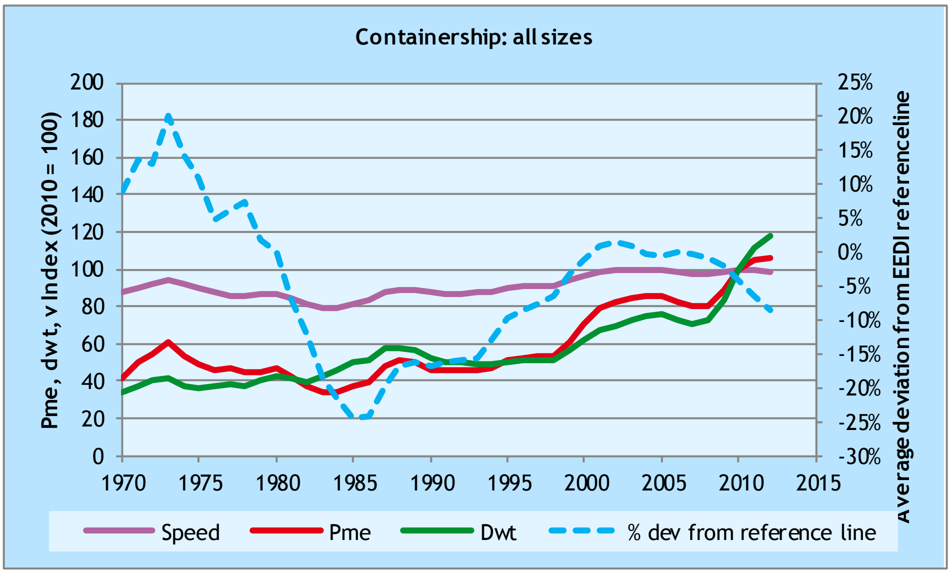
Reference line	a	b	50,000	100,000	200,000
EEDI reference line	174,2	-0,20			
1999-2008	150,0	-0,19	0%	0%	0%
70's	71,4	-0,11	+15%	Not built	
80's	201,6	-0,24	-21%	Not built	
90's	136,9	-0,19	-11%	-11%	Not built

2.4.1 The contribution of size, power and speed

Changes in the EIV and in our efficiency metric are the result of changes in the main engine power, capacity or speed of ships. Figure 17 shows how the design efficiency of container ships, their average speed, main engine power and capacity have changed since 1970. Design efficiency is expressed as the average difference between the EIV and the reference line, whereas the other parameters are indexed to their 2010 values.

The graph shows that the average size of new container ships increased almost continuously, with large increases around 2000 and 2010. The average speed decreased from circa 21 knots in the early 1970s to 18 knots in the late 1980 before gradually increasing to just 23 knots in 2010. The average main engine power decreased between 1973 and 1985 and increased after that year.

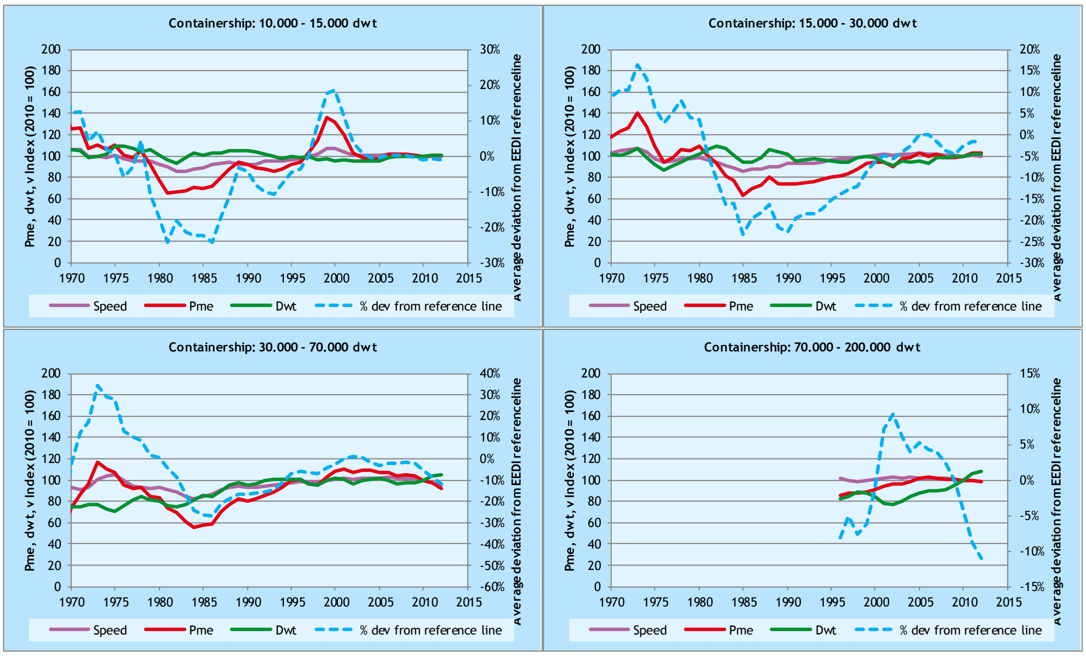
Figure 17 **Development of the design efficiency, main engine power, speed and capacity of container ships**



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

Figure 18 shows how the design efficiency and the factors that are used to calculate it have changed over time for four size categories of container ships. The largest size class has only been built in sufficient numbers since the mid-1990s. All size categories show the V-shaped development on design efficiency that was also apparent in the other ship types.

Figure 18 **Development of the design efficiency, main engine power, speed and capacity of container ships of different sizes**



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

3 Drivers for 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.

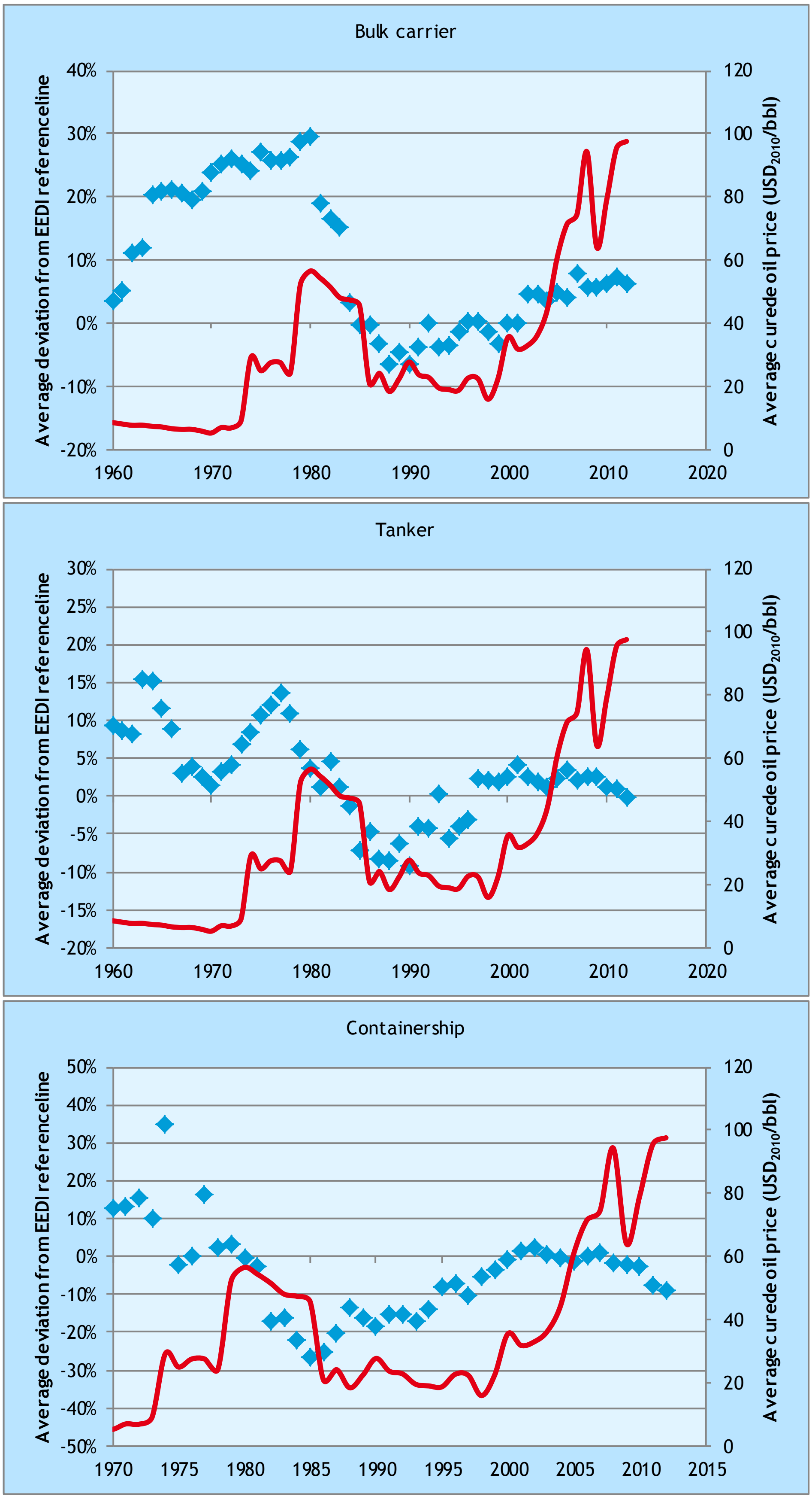
Higher fuel prices make fuel-efficient ships more attractive, because efficiency reduces the total cost of ownership. Assuming that fuel-efficient hull designs are more expensive to built (higher steel costs, higher labour costs), the additional capital expenditures can be earned back over the lifetime of the ship by lower fuel costs.

The impact of freight rates is less straightforward. According to Mortensen, when freight rates are high, owners queue up to order ships and shipyards, lowering the incentive of shipyards for innovative designs and thus keeping efficiency standard (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 19 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 19 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 are 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 19 Fuel prices are an important driver for design efficiency



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

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 shipowner would consider reasonable.

In addition, there may specific circumstances under which yards and other stakeholders may not want to work towards building more efficient ships. For example, Mortenson (2009) points out that when the orderbooks are full, yards are reluctant to change standard designs. 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.

4 Conclusions

This study analysed the development of the design efficiency of new ships in the last 50 years. It shows that after a period of deteriorating or constantly poor efficiency in the 1970s, efficiency improved considerably for all ship types and all size categories in the 1980s, reaching an optimum around 1990. In the 1990s and 2000s, the efficiency deteriorated again.

Historical analysis shows large improvements in design efficiency have occurred within a relatively short timeframe. Depending on the ship type, the average efficiency has improved by 22-28% improvement within a decade. These improvements have been purely market driven by a combination of sharply increasing fuel prices and constant or low freight rates.

An analysis of the factors that have contributed to fuel efficiency improvement shows that in some, but not all cases, efficiency improvements have been brought about by reductions in design speed. In other cases, the size of the ships has increased. However, these two development cannot explain the efficiency improvements to the full extent. In many cases, improvements in hull design and propulsion efficiency have contributed significantly to efficiency improvements. Likewise, the deterioration of efficiency after the 1990s has been caused at least partly by deteriorated designs.

The relevance of this study for the ongoing review of EEDI targets is that it shows that ships can improve their design efficiency by about 5-15% on average just by going back to 1990s designs. If one takes into account improvements in engine technology, and hull, rudder and propeller designs in the past 25 years, larger efficiency improvements are probably within reach. Lower design speeds could improve design efficiencies even more.

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