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Reductions in cost and greenhouse gas emissions with new bulk ship designs enabled by the Panama Canal expansion

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HIGHLIGHTS

- We have assessed cost and emissions as a function of alternative bulk vessel designs.
- The design focus has been on vessel beam, length, hull slenderness and bow section length.
- The assessment has taken into account three different fuel price scenarios.
- When the block coefficient is reduced and the hull becomes more slender the emissions drop.
- With a fuel price of 600 USD/t, emissions can be reduced by up to 15–25% at a negative abatement cost.

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ABSTRACT

Historically, fuel costs have been small compared with the fixed costs of a bulk vessel, its crewing and management. Today, however, fuel accounts for more than 50% of the total costs. In combination with an introduction of stricter energy efficiency requirements for new vessels, this might make design improvement a necessity for all new bulk vessels. This is in contradiction to traditional bulk vessel designs, where the focus has been on maximizing the cargo-carrying capacity at the lowest possible building cost and not on minimizing the energy consumption. Moreover, the Panama Canal has historically been an important design criterion, while the new canal locks from 2014 will significantly increase the maximum size of vessels that can pass. The present paper provides an assessment of cost and emissions as a function of alternative bulk vessel designs with focus on a vessel's beam, length and hull slenderness, expressed by the length displacement ratio for three fuel price scenarios. The result shows that with slenderer hull forms the emissions drop. With today's fuel price of 600 USD per ton of fuel, emissions can thus be reduced by up to 15–25% at a negative abatement cost.

1. Introduction

Historically, fuel costs have been small compared with the fixed costs of a bulk vessel, its crewing and management. Today, however, fuel cost accounts for more than 50% of the total costs. In combination with the introduction of stricter energy efficiency requirements for new vessels, such high costs might make design improvement a necessity for all new bulk vessels. This is contradictory to traditional bulk vessel designs, where the focus has been on maximizing the cargo-carrying capability at the lowest possible building cost, and not on minimizing energy consumption per transported unit. The outcome has been shoebox-shaped vessels with short bow and aft ship sections and hence rather poor hydrodynamic lines and high resistance even in calm seas. In rough seas, these designs perform even worse compared with vessels with the same cargo-carrying capability designed for good hydrodynamic performances. If we assume that a typical bulk vessel is operated 25 years before it is scrapped, the difference in energy consumption adds up to a significant tonnage of fuel and greenhouse gas (GHG) emissions for each vessel and the fleet in total.

With increasing world trade due to globalization, the emissions stemming from the resulting sea and air transport are causing increasing concern. Since 1990, total transport emissions have grown faster than total emissions, and transport emissions now account for more than 20% of global anthropogenic greenhouse gas (GHG) emissions (IEA, 2009). While road and rail are

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important for national and regional trade, more than 80% of international trade measured in (metric) tons is performed by seagoing vessels. When comparing greenhouse gas emissions, marine transport accounts for 3.3% of all anthropogenic CO_2 emissions (Buhaug et al., 2009), while aviation is responsible for 2.1% of this total (IATA, 2011). These emissions are expected to increase as a result of continued globalization, with growing trading and more passenger transport under "business as usual" scenarios (Buhaug et al., 2009; Lee et al., 2009; Sgouridis et al., 2011), while the fulfillment of anticipated climate requirements might call for significant reductions either within the sectors or through measures extending beyond them.

Within the shipping sector, previous studies have documented that it is possible to reduce GHG emissions in a cost-effective manner, i.e., emissions can be cut with net cost savings (Faber et al., 2009; Longva et al., 2010). These studies can be grouped into two categories: those that focus on the total improvement potential through technical and operational improvements such as the *Second IMO GHG study 2009* (Buhaug et al., 2009) and *Pathways to low carbon shipping* (DNV, 2010). Those that focus on what can be achieved by devoting efforts to one or more measures, such as the relationship between emissions and economies of scale by building larger vessels (Cullinane and Khanna, 2000; Notteboom and Vernimmen, 2009; Stott and Wright, 2011; Lindstad et al., 2012a). The key insight is that when the ship's cargo-carrying capacity is doubled, the required power increases with two thirds of the increase in ship size, which implies that when the ship's size is increased, fuel consumption per freight unit is reduced. Another reduction measure is the relationship between speed reduction and emission reduction (Corbett et al., 2009; Sea at Risk and CE Delft, 2010; Lindstad et al., 2011). The background for the focus on speed reductions is that ships have typically been built to operate at a specific design speed and a key insight is that the power output required for propulsion is a function of the speed to the power of three to four (Kristensen, 2010), this simply implies that when a ship reduces its speed, the fuel consumption per freight work unit is reduced.

While speed reductions and economies of scale often require changes of the supply chain due to longer transport times when the speed is reduced, and fewer yearly shipments due to larger quantities moved per shipment, it is possible to introduce energy efficient designs without changes to the logistics. On the other hand, infrastructure limitations regarding maximum allowable measurements tend to limit the opportunities for improving the energy efficiency of vessels intended to pass specific canals and serve specific ports. This is not due to the maximum measurements as such limiting the design opportunities, but rather to commercial market having established unofficial shipping quantities based on a carrying capacity that cannot be met by more energy-efficient designs built within these maximum dimensions. These limitations can be divided into soft and hard restrictions, where maximum draft is a typical example of a soft restriction since vessels with a larger maximum draft can pass if they are short-loaded, i.e., the cargo load is reduced from its maximum down to the amount which gives the allowable draft. An example of a hard restriction is the maximum vessel beam and length measurement allowed for passing through canal locks.

Worldwide, out of all these restrictions, none have had the same impact on vessel design as the existing Panama Canal locks, limiting the maximum beam of the vessels wishing to pass to 32.3 m. This can be illustrated by the fact that in 2007, which was the year after the expansion of the locks was announced (Panama Canal authority, 2006), only 5% of the world's cargo vessel fleet consisting of 45 000 vessels as listed in the IHS-Fairplay database (2007) was too large to go through the canal. The new Panama Canal locks, scheduled to open in 2014, will increase the maximum beam width from 32.3 m to 49 m and the vessel length from 289.6 m to 366 m, while the draft (which is a soft restriction) increases from 12 m to 15.2 m (Panama Canal Authority, 2010). In previous studies regarding the expansion of the canal, the main focus has been on the requirements of the container and the consequent effect benefits on container vessel design (Panama Canal Authority, 2006; Payer and Brostella, 2007; Thomson, 2008). Much less has been published on the effects on design within other shipping segments. Nevertheless, one exception is the study by Stott and Wright (2011) which addresses how larger vessels will permit economies of scale in dry bulk shipping and how the hull forms can be made more energy-efficient by alternating the main ratios between beam, draft and length.

Recently, and as a result of the expansion announcement in 2006 by the Panama Canal authorities, ship delivery lists show new vessels that have been delivered both with the old Panamax maximum measures and larger vessels where the beams vary from 35 to 45 m and the lengths from 220 to 250 m. The larger of these vessels are called Handy-Cape. However, apart from alterations of main measurements, such as the relationship between length, beam and draft, and the obtained benefit (Stott and Wright (2011), the main priorities for these designs involve maximizing the cargo-carrying capability at the lowest possible building cost and not minimizing the energy consumption per transported unit. This is a certainly design strategy that works and is profitable at low fuel prices. However, with more recent (higher) fuel prices and potential further increases due to stricter marine fuel regulations, it becomes a less profitable strategy. In addition, new energy-efficient requirements set by IMO will basically leave the designer with three choices to satisfy the threshold given by the Energy Efficiency Design Index (EEDI): reducing the installed power and thereby reduce the design speed; improving the hydrodynamic performance and hence reducing the power needed; or combining a number of fuel-saving technologies such as waste heat recovery to reduce power needed and hence satisfy the requirements. While utilizing economies of scale cannot be used since the advantage of building larger vessels is incorporated into the EEDI threshold.

For these reasons, the present study has focused on cost and emissions for vessels operating in traditional Panamax bulk trades. A central hypothesis is that the expansion of the Panama Canal locks will only marginally increase the standard bulk shipment sizes through the canal compared with the existing bulk fleet. The main reasons are that there is size restrictions in ports and fairways as already described in addition to limitations in the supply chains. Examples of supply chain restrictions are physical constraints such as storage capacities and financial limitations including total cost of delivered goods exceeding the total cash available and increased financial cost for carrying large stocks in average. This study has used power and cost models to compare a standard Panamax design with alternative designs where the width and length of the vessels are stepwise increased and the slenderness of the hull expressed by the length displacement ratio M are stepwise reduced from traditional bulk designs block coefficients C_B to values more typical for faster vessels. The employed power models reflect real sea conditions as opposed to still water, and the economical assessment has been carried out for a low, medium and high fuel price. The developed model is described in Section 2, its application and data are presented in Section 3, and the obtained results are discussed in the final section

2. Model description

The main objective of the developed model has been to enable a comparison of the cost, power and emissions of standard vessel designs with those of alternative designs. The system boundaries focus on the vessels and their use, for which reason the landside of the terminal and the port has been excluded. The model consists of four main equations, of which the power model is the most important.

The developed power model takes into account the power production and propulsion efficiency K, the power needed for still water conditions P_s, the additional power required for waves P_w, the power needed for wind P_a, and the required auxiliary power P_{aux}, as a function of the vessel speed and cargo load as expressed by Eq. (1). Comparing this formula to well-established practice, the power needed for still water and aerodynamic resistance is calculated in a standard manner (Lewis, 1988). The additional power for waves (Lloyd, 1988) has been modified by using empirical data to generate the wave drag coefficient C_W QUOTE . On the contrary, a new notation based on work by Minsaas (2006), Lloyd (1988), Hollenbach and Friesch (2007), and Orsic et al., 2012 was required to give a good representation of the power production and propeller efficiency as a function of speed and sea conditions. The notation replicates the fact that the efficiency drops when the engine output is reduced at lower speeds due to increase in specific fuel consumption per kilowatt-hour produced, increased friction in percentage of power produced and propeller being less efficient. And the efficiency drops when the significant wave height increases, due to less optimal water flows around the propeller, increased turbulence, more air in the water and even propeller being partly out of the water under extreme conditions.

$$P = K \times (P_s + P_w + P_a) + P_{aux} \tag{1}$$

$$K = \eta(v,\ H_{1/3}) = max\left(\frac{1}{\eta(j + k \times \sqrt{v/V_d})}, \frac{1}{\eta(1 - r \times H_{1/3})}\right)$$

$$P_s = \frac{\rho \times C_s \times S \times v^3}{2},\quad C_s = P_{Sref} \times \frac{S \times F_n \times C_B}{S_{ref} \times F_{n\_ref} \times C_{B\_ref}}$$

$$P_w = \frac{C_w \times \rho \times g \times (H_{1/3}/2)^2 \times B^2}{L} \times (v + u),$$

$$C_w = C_{w\_ref} \times \frac{\sqrt{B/L_f}}{\sqrt{B_{\_ref}/L_{f\_ref}}}$$

$$P_a = \frac{C_a \times \rho_a \times A \times (v + u_a)^3}{2}$$

here, K gives the propeller (propulsion) efficiency as a function of the vessel speed and sea condition, and η corresponds to the propulsion efficiency at the design speed V_d and calm sea $H_{1/3}$. Typically, η values lie within the range of 0.6 to 0.7. When the speed is reduced, as expressed by $\sqrt{v/V_d}$, the efficiency drops, and when the significant wave height $H_{1/3}$ increases as expressed by $r \times H_{1/3}$, the efficiency drops.

The still water power is given by P_s, where, ρ is the density of water, C_s is the total still water drag coefficient, S is the wetted surface and v is the ship speed. The still water drag coefficient C_s for a specific design is generally found through model or full-scale tests which in this case would be quite resource demanding when a number of alternative designs shall be compared. Instead, new notation based on regression analysis of the existing fleet of bulk, container, tank and deep sea RoRo vessels in combination with towing tank test data from our facilities was required to enable power calculations for bulk designs with more slender designs than previously considered. The notation enables calculation of required power for any alternative designs based on the relationship between hydrodynamic values for the reference (standard) design and the alternative designs. Where P_{Sref} is the power for the reference vessel, S_{ref} is the wetted area of the reference vessel, F_{n_ref} is the Froude number of the reference vessel for the speed which is used for comparison, $C_{B_{ref}}$ is the block coefficient of the reference vessel while S, F_n, and C_B are the same values for the alternative designs.

The additional power for wave resistance is given by P_w, where C_w is the drag coefficient for the wave resistance, ρ is the density of water, g is the vertical force, $H_{1/3}$ is the significant wave height for which the amplitude is half the height, B is the width of the ship at the waterline, L is the length of the ship at the waterline, v is the vessel speed, and u corresponds to the speed of the waves relative to that of the vessel. The drag coefficient for the waves C_w for a specific design can be found through model or full scale tests or by advanced computerized simulations. Distinctive of the wave drag coefficient C_w is that it goes from low values with short waves up to a peak when the encountered frequency multiplied with the relative speed of the waves equals the length of the vessel (i.e., the wave length equals the vessel length). When the drag coefficient is known for a specific vessel design, it renders it possible to calculate the wave drag coefficient for alternative designs through the relationship established by the STAWAVE method develop by MARIN (Van der Boom, 2010). The main parameters include the length of the vessels bow section measured from the forward point along the centerline of the vessel to the point where the beam becomes 95% of the maximum beam of the vessel. It then follows from the STAWAVE method that if two vessels have same beam measurements, the one with the longest bow section will experience less added resistance in waves compared to the one with a shorter bow section. Based on the known drag coefficient for the reference vessel the wave drag coefficient C_w for alternative designs can then be calculated for alternative designs by varying the length of the bow section and the vessel beam as shown in the second part of the equation. Here, C_{w_ref} is the drag coefficient of the reference vessel, $B_{\_ref}$ is the beam of the reference vessel, L_{f_ref} is the length of the bow section of the reference vessel, and B and L_f are respectively the beam and length of the front section for the actual vessel.

The additional power for wind resistance is given by P_a, where C_a is the drag coefficient for the aerodynamic, ρ is the density of air, A is the surface area projected for the wind, v is the vessel speed, and u_a corresponds to the speed of the wind in relation to that of the vessel. When the surface area projected for the wind changes, the required power is altered proportionally.

The auxiliary power P_{aux}, needed for running pumps and for producing electricity for lighting as well as all the supporting systems of the ship is a function of the vessel type and size, and also of the cargo it carries. IMO, have decided to use the following standard auxiliary power definitions in its EEDI regulation. Auxiliary power at sea equals 5% of the maximum main engine power for vessels with engine sizes of 10,000 kW or less and 250 kW+2.5% of the maximum engine power above.

The fuel consumption F of a vessel is the total fuel used on cargo voyages and on ballast voyages, as expressed by

$$F = K_f \times \left[\left[\left(\left(\frac{P_c \times D_c}{v_c}\right) + P_{l\&d} \times T_{l\&d} + P_{s\&w} \times T_{s\&w}\right) \times N_c\right] + \left[\left(\left(\frac{P_b \times D_b}{v_b}\right) + P_{s\&w} \times T_{s\&w}\right) \times N_b\right]\right] \tag{2}$$

here, the first term gives the fuel used on cargo voyages, the second term gives the fuel used on ballast voyages and K_f is the amount of fuel (in grams) per produced kilowatt-hour. Moreover, P_c represents the power used to achieve the speed on the cargo voyages, D_c is the distance of the cargo voyages and v_c is the corresponding speed. $P_{l\&d}$ is the power requirement during loading and discharging and $T_{l\&d}$ is the time used, $P_{s\&w}$ is the power requirement in slow zones and waiting and $T_{s\&w}$ is the time used. In the second term, P_b represents the power used to achieve the speed on ballast voyages, D_b is the distance of the ballast voyages and v_b is the corresponding speed. $P_{s\&w}$ is the power requirement in slow zones and waiting and $T_{s\&w}$ is the time used.

The annual amount of CO_2 emitted per ton nautical mile ε is calculated as follows (Buhaug et al., 2009):

$$\varepsilon = \left(\frac{F}{D_c \times M \times N_c} \right) \times K_e \tag{3}$$

where F is the annual fuel consumption per vessel as described in Eq. (2), K_e is the CO_2 emitted per unit of fuel burnt and $D_c \times M \times N_c$ is the annual freight work measured in tons nautical miles, for which D_c is the distance of the cargo voyage, M is the weight of the cargo and N_c is annual number of cargo voyages.

The cost per ton nautical mile C comprises the annual freight work, the cost of fuel and the annual time charter cost of the vessel as expressed by

$$C = \frac{1}{D_c \times M \times N_c} \left[(F \times C_{Fuel}) + (Capex_v \times (k_1 + k_2) + k_3) \right],$$
$$Capex_v = Capex_{v_{ref}} \times \left(\left(\frac{Q}{Q_{ref}} \times q \right) + (1-q) \right) \tag{4}$$

The first factor, i.e. $D_c \times M \times N_c$, transforms the cost from an annual cost per vessel in order to enable comparisons of freight cost per unit for vessels (to be drawn) of different sizes and types employed in various trades. The cost of fuel is then calculated by multiplying the annual amount of fuel F from Eq. (2) by the average cost of fuel C_{Fuel}. The annual cost for operating a vessel is based on current new-building prices and the cost comprises financial items, depreciation and operating costs, expressed as $(Capex_v \times (k_1 + k_2) + k_3)$ Here, $Capex_v$ is the price for constructing a new vessel, k_1% of $Capex_v$ are fixed costs, consisting of a financial cost including depreciation and a return on own capital, and k_2% of $Capex_v$ plus a basic amount k_3 is the variable cost. When the new-construction price $Capex_{v_{ref}}$ is known for a specific vessel, it renders it possible to calculate the new building price $Capex_v$ for alternative designs based on the difference in weight Q of the empty vessels. In this equation, Q_{ref} is the weight of the reference vessel, Q is the weight of the actual vessel, and q is the weight constant factor.

To summarize, combining Eqs. (1)–(3) enables us to compare power requirements and greenhouse gas emissions for standard vessel designs with alternative designs, while Eq. (4) enables us to compare cost.

3. Application and analysis

The objectives of the analysis were first to assess power requirements, emissions and building costs as a function of alternative bulk vessel designs by varying the vessel beam length, the slenderness of the hull and the length of the bow section. Subsequently, the aim was to calculate and compare the resulting transport cost for alternative bulk vessel designs for three fuel price scenarios.

3.1. Data set used in the analysis and validation of the model

The vessel types in focus for this study were ocean-going vessels that transport dry bulk, break bulk and wet bulk. Dry bulk commodities are in solid form and can be handled mechanically by grabs, conveyor belts, bucket units or pneumatic systems. Typical dry-bulk commodities include iron ore, coal, grain, cement, fertilizer and aggregate. Break bulk commodities are also in solid form and are generally handled by cranes. Forest products, like pulp and timber, and steel products are examples of break bulk products. Wet bulk commodities are in liquid form and are handled by pipes and pumps. Crude oil, refined oil products and chemicals are the main wet bulk commodities. The total freight work by these bulk vessels adds up to 30,000 billion t nm, of which 26,000 billion t are transported with vessels with Panamax beams of 32.3 m or larger (from 2014 onwards the restriction will be 49 m). This means that bulk vessels with a beam of 32 m or more transport nearly 65% of the total sea freight work of 41 000 billion ton nautical miles in 2007 (Lindstad et al., 2012a). In comparison, container vessels performed 18% of the total freight work, bulk vessels with a beam of less than 32 m transported 10% of the total freight work while all other vessels performed 9% of the total freight work. Table 1 shows the main figures for each of the vessel groups and the totals.

Within the group bulk vessels with beams from 32 m and upward, the dry bulk Panamax vessels are the largest class measured in number of vessels. The total number of dry bulk Panamax vessels (2007) adds up to 1447 with an average deadweight tonnage of 72,000 t, a design speed of 14 knots and an installed power of 9800 kW (Lindstad et al., 2012b). However, since the size of these vessels have increased year on year, we focus on the typical specification for new-built Panamax vessels, and not on the average taking into account all the vessels built during the last 25 years. Today, a typical new-built Panamax vessel (2012) has a maximum deadweight tonnage of 80,000 t, a designed speed of 14 knots, an installed power of 10,700 kW, a block coefficient of 0.87 and a light weights (empty weight of ship without bunker, ballast, supplies and cargo) of 12,000 t. The annual cost of operating such a vessel $Capex_v \cdot (k_1 + k_2) + k_3$ is calculated on the basis of the 2012 new-building contract price of 30 million USD, where $k_1 = 8\,\%$ covers the fixed cost, and where $k_2 = 3\%$ plus a basic amount $k_3 = 2000$ USD per day cover the variable costs. When it comes to the fuel price, three price levels are used where the first is based on a 2011–2012 average cost of fuel C_{Fuel}, i.e., 600 USD/t, the second level is a low level based on the fuel price level 10 years back in time of 120 USD/t and the third is a high level based on the price being driven up due to conversion from heavy fuel oil to distillates as a result of stricter IMO rules (PWC, 2011). The latter price corresponds to 1 200 USD/t. The weight of alternative designs, are calculated based on an

Table 1
Annual freight work and CO_2 emitted as a function of vessel type.

Vessel type	Number of vessels	Average vessel size in dwt (t)	Speed (knots)	Average engine size (kW)	Freight work (billion t nm)	Total CO_2 emitted (million t)	Gram CO_2 per freight unit (g/t nm)
Bulk vessels above 15,000 dwt	10,900	72,000	14.6	10,300	30,000	364	12
Container vessels	4400	34,000	20.3	22,500	7500	261	35
All other vessels	29,700	5000	12.7	3800	3500	195	56
Total World Cargo fleet	45,000	24,000	13.9	5000	41,000	820	20

investigation of vessels built during the last ten years. The result shows that when vessels are built more slender and deadweight tonnage is kept constant by increasing the beam, or the length, or both the lightweight of the vessels will increase. When the lightweight increase, the building cost will increase, which implies that building more slender designs gives higher building cost compared to shoe box designs per deadweight tonnage.

These vessels will operate in major trades worldwide where wind and wave conditions will vary from one sea or ocean to another. However, since it is important to compare designs based on real sea conditions, we have chosen to use the most typical sea condition for the North Atlantic (Bales et al., 1981). This involves a significant wave height between 2 and 5.5 m, which the vessels will experience 55% of the time. In the model, we use 4 m as a proxy for the significant wave height of 2–5.5 m and assume that the accumulated annual effect of the waves resulting from head-waves, side-waves and following-waves will be 50% of 4 m significant head waves.

3.2. *Cost and emissions as a function of vessel beam, length and block coefficient*

This section employs the developed power and cost models to compare a standard Panamax design with alternative bulk vessel designs. The focus has been placed on vessel beam, vessel length, hull slenderness and length of the bow section for three fuel price scenarios. The comparison methodology involved increasing the width and the length of the vessels in a stepwise manner, while the block coefficient (slenderness of the hull) was stepwise reduced from traditional bulk designs to values more typical for faster vessels. Moreover, the main focus was on combinations of measurements and coefficients giving a cargo-carrying capacity equal to the standard Panamax (2012) vessels. Due to this we have compared alternative designs where the beam is increased by 10%, 20%, 30% and 40% for a length corresponding to the length of the standard Panamax (2012) and for a case where the length is increased by 10%. This gives eight alternative combinations of beam and lengths for which emissions and cost figures have been calculated. It should be noted that none of these designs where the beam has been increased can be used in trades through the existing canal, but with the new locks being finished in 2014 all of them will be within the new maximum allowable dimensions.

Table 2 presents key figures for the compared designs based at 13 knots speed where the values for the standard Panamax (2012) is given in the first column and then follows the values for the alternative designs. It should here be noted that while 14 knots to 15 knots is a typical design speed for these vessels at calm water conditions, 13 knots is used in the comparison to reflect that the speed will be reduced with 4 m head waves. The first row gives the length, the second the breadth (beam) and the third the calculated block coefficient which keeps the deadweight tonnage constant at 80,000 t. The fourth row gives the building cost of the alternative designs as a percentage of the building cost of the standard Panamax (2012) vessel. The figures reflect that when vessels are built more slender and deadweight tonnage is kept constant the building cost will increase. The explanation is that slenderer hull forms increases the lightweight due to additional steel, and they are more complicated to build and hence more man hours are needed. The fifth row gives the power required for still water, waves and wind calculated by the model as described in Section 2, while the sixth row gives the required power calculated based on Holtrop and Mennen (1984), including a 15% sea margin. The explanation for the sea margin is that Holtrop and Mennen (1984) is a prediction methodology for still water power, where the additional power required for waves and wind is included through an add on percentage based on vessel type and sea condition in the foreseen operational area. In this comparison we have chosen to use 15% since that equals the required add on power for wind and waves as calculated by our model for the standard Panamax (2012) with the voyage profile and sea conditions as described in the previous section

Comparing the results, Holtrop and Mennen (1984) gives larger power reductions for the 10% increase of breadth, while there are only marginal differences for the other alternatives. The explanation for the difference on the 10% increase on breadth is that the model calculates an added resistance in waves for this specific design while Holtrop and Mennen (1984) gives a reduction of the added resistance because it calculates the added resistance as a percentage of a still water resistance which is lower for this design than the standard design. Without going further into details, we conclude that the developed method can be used to calculate and compare required power for alternative designs.

For the trades, the comparison is based on an equal number of loaded and ballast voyages per year and we have chosen to compare the vessels and the designs on sea voyages only and not include the performance in ports. This is a simplification, but for ocean-going bulk vessels, the number of annual port calls is small and nearly all fuel is consumed at sea. Fig. 1 shows CO_2 emission as a function of main measurements and block coefficients for all investigated combinations.

In the figure, the dashed horizontal line represents emissions from a standard Panamax which are 8.3 kg per thousand ton nautical miles (8.3 g per ton nautical miles). This is higher than the emissions from any of the alternative designs. Another observation is that when the block coefficient is reduced and the hull becomes more slender, the emissions drop for all the designs and the lowest emissions are found for the lowest block coefficient investigated. Regarding the cargo-carrying capacity, the highest block coefficient gives the largest deadweight tonnage and hence the largest cargo-carrying capacity, while the lowest factor which here gives the lowest emissions, corresponds to the smallest cargo-carrying capacity. In the figure, a dotted line is used to show the Panamax-equivalent capacity for each of the alternative designs. It can be seen that a 10% wider vessel with a block of 0.8 had the same carrying capacity as the standard Panamax with a block of 0.87. A 20% wider vessel with a block of 0.75 had the same capacity as the standard Panamax, as did a 10% longer and 40% wider counterpart, with a block of 0.6.

Table 2
Key figures for the compared designs, dwt=80,000 t, fully loaded.

Length loa (m)	224	224	224	224	224	246	246	246	246
Beam (m)	32.2	35.4	38.6	41.9	45.1	35.4	38.6	41.9	45.1
Block coefficient	0.87	0.80	0.73	0.68	0.64	0.74	0.68	0.63	0.59
Building cost of the Standard Panamax (2012) vessel (%)		102	104	106	108	108	110	113	115
Power for still water, waves and wind resistance calulated by the model (kW)	8500	7900	7100	6700	6500	6900	6500	6200	5900
Power by Holtrop model including 15% sea margin (kW)	8500	7500	7200	6500	6400	6700	6500	6400	6300
Power reduction calculated by the model (%)		7	16	21	24	19	24	28	30
Power reduction calculated by the Holtrop model (%)		11	15	23	25	21	24	25	26

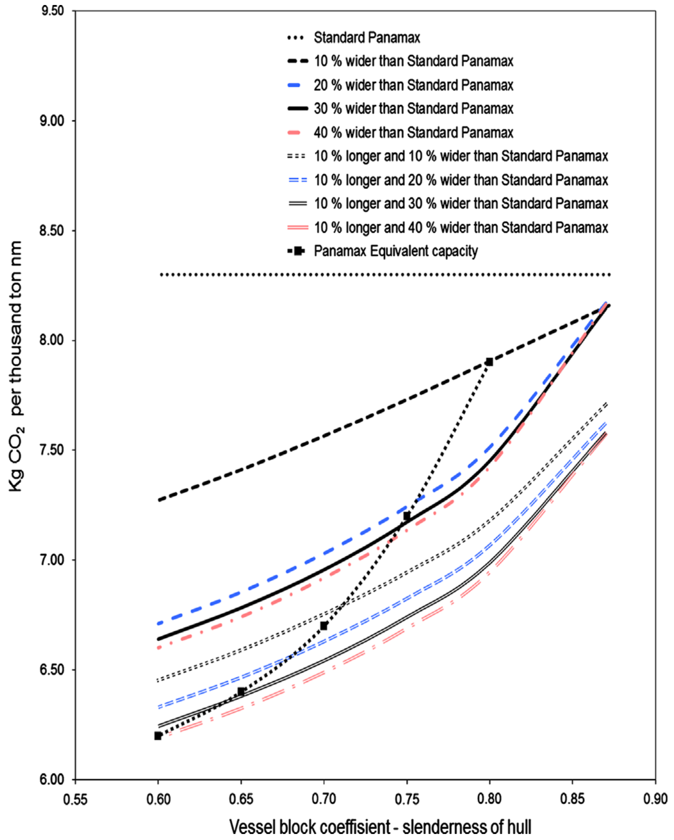

Fig. 1. CO_2 emission as a function of main measurements and the block coefficient.

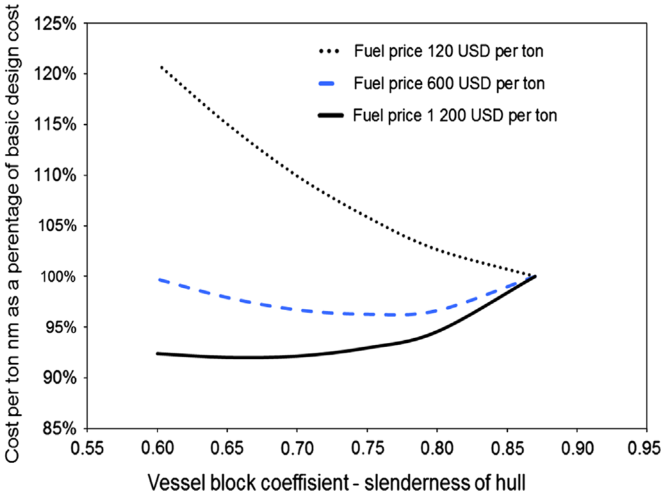

Fig. 2. Cost per ton nautical miles as a function of block coefficient and fuel price.

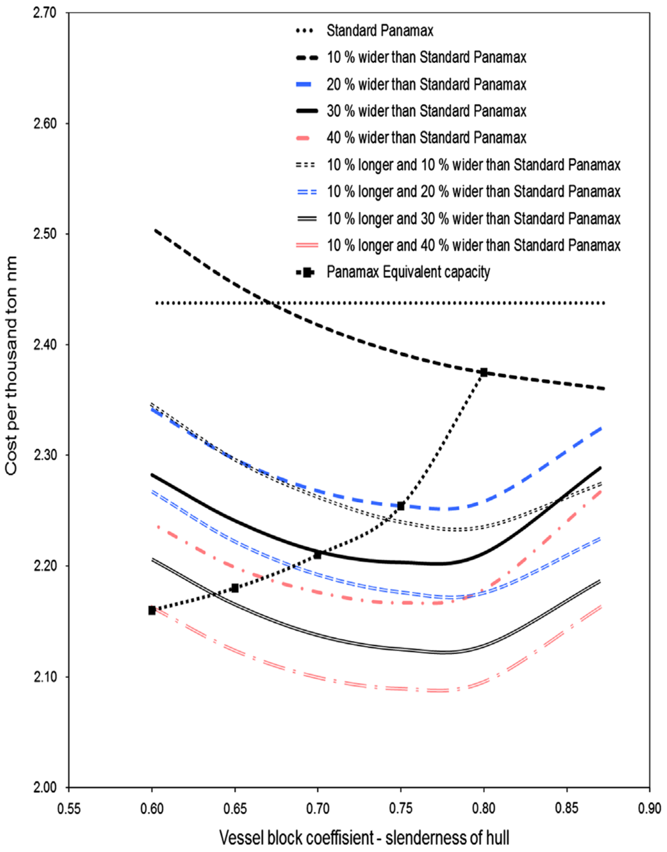

Fig. 3. Cost as a function of block coefficient for a medium fuel price.

This also signifies that combinations on the left side of the dotted line have a cargo-carrying capacity that is below that of the standard Panamax while combinations on the right-hand side present a larger capacity. However, while emission reductions have become important due to the on-going climate change debate, ship owners and the whole shipping community are in the business of making a living and a decent profit and not of reducing emissions as such. Their main motivation for carrying out emission reductions is therefore the rising fuel costs in recent times (fuel usage and emission reductions were hardly issues with the low fuel prices we had 10 to 15 years ago).

Fig. 2 illustrates the cost as a function of block coefficient for three fuel prices scenarios. Here, 120 USD per ton corresponds to the fuel price 10 to 15 years back in time, 600 USD per ton corresponds to the current level (2012) and 1200 USD per ton is a level that we might soon experience as a consequence of stricter fuel rules set by IMO.

The main observations from the figure are that with a low fuel price, the highest block coefficient, i.e. 0.87, gives the lowest cost for all the eight design alternatives. The explanation is that when the fuel cost is low, the fuel saving is the same measured by weight as with a higher fuel price. However, due to the low cost of fuel, the total savings measured in monetary terms become smaller than the additional cost of building a more energy-efficient vessel. With a medium fuel price, the lowest cost is found for block coefficients around 0.75. Moreover, with a high fuel price, the lowest cost is found for block coefficients around 0.65. It should here be noted that Fig. 2 represents the average values for the eight alternative combinations of beam and lengths for which emissions and cost figures have been calculated.

Fig. 3 shows the freight cost as a function of block coefficient with a fuel price of 600 USD per ton, which corresponds to the medium fuel price. Similar to the first figure, the horizontal line gives the reference cost for a standard Panamax and the dotted line is used to illustrate a Panamax-equivalent capacity for each of the alternative designs.

The main observations that can be made are that the standard Panamax has the highest cost, which is 2.43 USD per thousand ton nautical miles, while the alternative designs give cost levels which are 5% to 15% lower. Moreover, with the exception of the 10% wider design that has the lowest cost with the highest block coefficient, all the other alternatives have the lowest cost for block coefficients

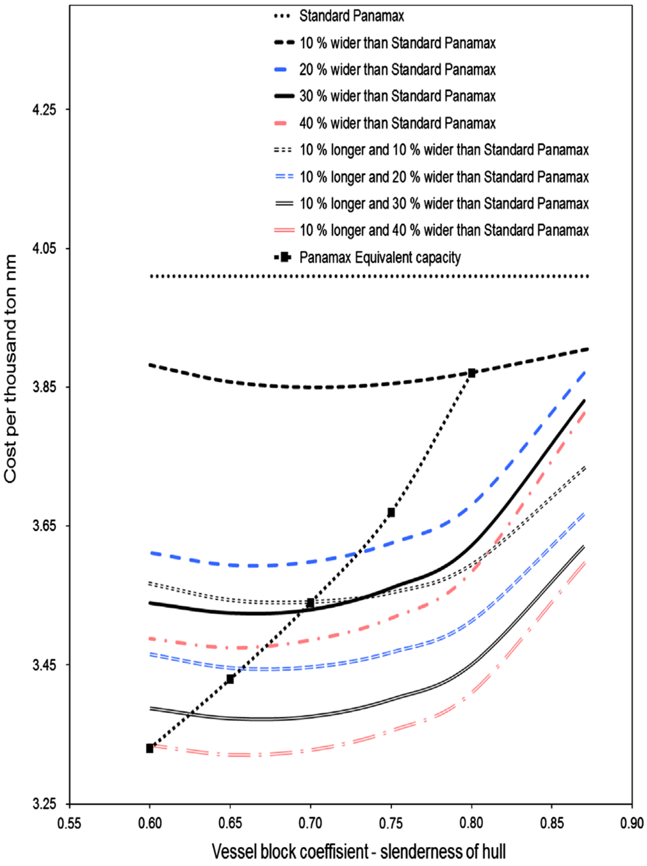

Fig. 4. Cost as a function of block coefficient for the high fuel price.

around 0.75. Comparing numbers for a Panamax-equivalent capacity: using a 10% wider vessel with a block of 0.8 gives a freight cost of 2.38 USD per thousand ton nautical miles; using a 20% wider vessel with a block of 0.75 gives a freight cost of 2.27 USD per thousand ton nautical miles; a 30% wider vessel with a block of 0.7 gives a freight cost of 2.23 USD per thousand ton nautical miles; and a 40% wider vessel with a block of 0.65 gives a freight cost of 2.20 USD per thousand ton nautical miles.

Fig. 4 shows the freight cost as a function of block coefficient with a fuel price of 1200 USD per ton, which corresponds to the high fuel price. Just as in the first and third figure, the horizontal line gives the reference cost for a standard Panamax and the dotted line is used to show the Panamax-equivalent capacity for each of the alternative designs.

The main observations that can be made are that the standard Panamax has the highest cost, i.e., 4.00 USD per thousand ton nautical miles, while the alternative designs present cost levels that are 5% to nearly 20% lower. Another observation is that when the block coefficient is reduced and the hull becomes more slender the cost drops for all the designs and the lowest cost is found for block coefficients around 0.65 as opposed to block coefficients around 0.75 for the medium fuel price scenario. The explanation for this is that with a higher fuel price, total savings measured in monetary terms become larger, and more money can be used for the building of a more energy efficient vessel.

4. Discussion and conclusions

The main objective of this paper has been to develop a model to assess cost and emissions as a function of alternative bulk vessel designs with focus on vessel beam, length, hull slenderness and bow section length. The assessment has taken into account three different fuel price scenarios. The results show that when the block coefficient is reduced and the hull becomes more slender and hence more energy-efficient, the emission per transported unit drops. Moreover, the higher the fuel price renders it more profitable to build bulk vessels with energy-efficient designs. The explanation is that the fuel savings measured in weight are independent of the fuel price; however with a high fuel price, the total savings measured in monetary terms become higher than the additional cost of building a more energy-efficient vessel. With a fuel price of 600 USD per ton, the lowest cost was found for designs with block coefficients around 0.75. With a fuel price of 1200 USD per ton, the lowest cost was found for block coefficients around 0.65 which gives a slender hull form compared to 0.84–0.87 for typical bulk vessels, as shown in Table 2. With today's fuel price of 600 USD per ton fuel, costs can be reduced by 5–15% while emissions can be decreased by 10–25% when the capacity is kept at a Panamax-equivalent level of 80,000 deadweight tonnage. Here, the largest reduction is achieved by using the longest and widest of the alternative designs investigated.

Comparing these results with the traditional rules of thumb in ship design and operation, the contrast is quite large. While the traditional rule is that bulk vessels should be built with high block coefficients to maximize the cargo-carrying capacity, our conclusion is that due to rising fuel costs more slender designs with lower block coefficients give the lowest costs. In addition, the benefit for society is that more slender bulk designs will contribute to significant emission reductions.

As mentioned in the introduction, CO_2 emissions from maritime transport represent 3.3% of the world's total CO_2 emissions, and they are forecast to increase by 150–250% until 2050, on the basis of "business as usual" scenarios with a tripling of world trade (Buhaug et al., 2009). In response to these challenges, the International Maritime Organization (IMO) is currently debating technical, operational and market-based measures for reducing greenhouse gas releases from shipping. In July, 2009, at the 59th session of the Marine Environmental Protection committee (MEPC), the principles for a mandatory Energy Efficiency Design Index (EEDI) and a Ship Energy Efficiency Management Plan (SEEMP) were agreed upon, and two years later, in July 2011 at the 62nd session of MEPC (Resolution MEPC.203 (62)), the EEDI and SEEMP were adopted as parts of the MARPOL Convention (the International Convention for the Prevention of Pollution from Ships). The EEDI uses a formula to evaluate the CO_2 emitted by a vessel per unit of transport based on a fully loaded vessel as a function of vessel type and size, and an EEDI threshold has been agreed upon for all major vessel types. However, the discussion continues regarding how much tougher the requirements per vessel shall be for new-built crafts in 2020 and 2030 compared with the present threshold.

What the EEDI discussion really boils down to is the availability of new technology, possible gains and achievable emission reductions with more energy-efficient designs. While there are two major discussions regarding market-based measures (MBM): the first concerns whether MBM are needed at all, and the second treats the relationship between the price for emitting CO_2 and potential emission reductions. The findings in our study show that emissions can be significantly reduced by building more slender bulk designs and hence that the EEDI threshold should be made tougher to ensure that more energy efficient designs are built. Secondly, our results demonstrate that the higher the fuel price becomes, the better the payoff from building energy-efficient vessels will be. This means that a low cost of CO_2 in combination with a low fuel price gives nearly no impact, while even moderate costs of CO_2 for fuel prices at the present level will contribute to emission reductions.

Nomenclature Appendix

A	Surface area of vessel projected for wind (m^2)
B	Vessel beam (maximum width) at the waterline (m)
$Capex_v \cdot (k_1 + k_2) + k_3$	Annual cost of a vessel where $Capex_v$ is the new-building price of the vessel, k_1% of $Capex_v$ is the fixed cost that consists of financial costs including depreciation and return on own capital, k_2% of $Capex_v$ plus a basic amount k_3 is the variable (operational) cost (USD)
C	Cost per freight unit (USD/t nautical mile) (all tons are metric)
C_{Fuel}	Cost for fuel per ton (USD/t)
C_B	Block coefficient (non-dimensional)
C_a	Drag coefficient for air resistance (non-dimensional)
C_w	Drag coefficient for the added wave resistance (non-dimensional)
C_s	Calm water resistance coefficient (non-dimensional)
D	Distance (1 nm = 1.852 km) (nautical mile (nm))
D_b	Distance per voyage in ballast (nm = nautical miles)
D_c	Distance per cargo voyage (nm = nautical miles)
$Draft$	The draft of a ship's hull is the vertical distance between the waterline and the bottom of the hull. Draft determines the minimum depth of water a ship or boat can safely navigate on (m)
DWT	Maximum carrying capacity of a vessel including cargo +bunker+supplies and required ballast if any (metric tons)
ε	Quantity of CO_2 emitted per ton nautical mile (gram per ton nautical miles)
F_n	Froude's number (non-dimensional)
F	Fuel consumption (metric tons)
g	The gravity force (m/s^2)
$H_{1/3}$	Significant wave height (m)
j	Propeller constant that is independent of vessel speed (non-dimensional)
k	Propeller constant that is dependent of vessel speed (non-dimensional
K	Propeller (propulsion) efficiency as a function of the vessel speed
$K_e = 3,17$	Emitted CO_2 when one unit of fuel is burnt (based on Endresen, 2007 (g/g = 1)
$K_f = 190$	Amount of fuel used per work unit produced (g/kW h)
L	Length of the ship at the waterline (m)
L_f	Length of the front bow section of the vessel measured at waterline (m)
∇	The volumetric displacement of the hull
M	Length displacement or slenderness ratio ($M = \frac{L}{\nabla^{1/3}}$)
N_c	Annual number of cargo voyages
N_b	Annual number of voyages in ballast
P	Total power required (kW)
P_a	Power required for air resistance (kW)
P_{aux}	Power required for auxiliary machines (kW)
P_w	Additional power required for waves (kW)
P_s	Power required for still water (kW)
$P_{l\&d}$	Power required for loading and discharging (kW)
$P_{s\&w}$	Power required in slow zones and when waiting (kW)
Q	Light weight of vessel (vessel weight when empty) (metric tons)
r	Propeller constant that is wave-dependent (non-dimensional)
ρ	Density of water (kg/m^3)
S	Wetted surface of the vessel (m^2)
T_b	Time used per ballast voyage, (days, hours, minutes)
T_c	Time used per cargo voyage, (days, hours, minutes)
$T_{l\&d}$	Time per voyage for loading and discharging, (days, hours, minutes)
$T_{s\&w}$	Time per voyage in slow zones and waiting, (days, hours, minutes)
u	Wave speed relative to the speed of the vessel
u_a	Wind speed in relation to vessel speed
v	Vessel Speed
v_b	Vessel speed on ballast legs
v_c	Vessel speed on cargo legs

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