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# Revitalization of short sea shipping through slender, simplified and standardized designs

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*Despite the political objective of decreasing road transport and transfer cargo to rail and sea, short sea shipping is struggling. Historically, building larger vessels has been the main pathway for reducing fuel consumption and cost, however while ships in deep-sea trades competes against similar ships and partly other ship types, their major competitor in short sea trades are the trucks. The benefit of trucks is that they transports small batch sizes, i.e. 20 – 25 tons from door to door, and that the frequency can be anything from minutes to days. In contrast typical frequencies for scheduled shipping lines are once a day, or two or three times a week, and while trucks are standardized and built in huge numbers, short sea vessels are less standardized and typically built in short series.*

*The results of this study indicate that significant fuel and cost savings can be achieved by designing and building slender, simplified and standardized short sea ships and that these savings might be of a similar magnitude as the traditional Economies of Scale benefits which are achievable by doubling the vessel size. Significant cost reductions without increasing vessel sizes will enable shipping lines to keep the sailing frequencies and hence increase their market share versus road transport*

KEY WORDS: Shipping and Environment; Energy efficient designs; Ship design; Short Sea Shipping; CO<sub>2</sub>; European transport Policy.

## INTRODUCTION

The European Commission (EC) has an active policy to promote Short Sea Shipping due to its high environmental performance and energy efficiency. In addition, Short Sea Shipping has the potential to solve road congestion problems affecting many parts of the European continent. Despite the political objectives of decreasing road transport and transfer cargo to rail and sea, short sea shipping is struggling. In Europe, research projects funded both at national and EU level have addressed these challenges and the recommended solutions have been: i) to focus on the whole supply chain, ii) new or improved technologies or iii) all of this in combination with larger vessels. In comparison, there has been little attention on the need for improving the cost competitiveness of short sea shipping versus road transport.

The benefit of trucks is that they transport small batch sizes, i.e. 20 – 25 tons, allowing shipments door to door at high frequencies. In scheduled maritime shipping, frequencies can be two or three times a week or at best daily. Also,

while trucks are standardized and built in huge numbers, short sea vessels are less standardized and typically built in series from a few up to one hundred. Moreover, the main truck manufacturers have used huge resources during the last decades on reducing their lightweight and improving the engines – in other ways – reducing the fuel consumption of their trucks.

Increasing vessel size or reducing operational speeds are two well-known principles for reducing the fuel consumption and cost per transported unit. First; larger ships – and shipments - tend to be more energy efficient per freight unit transported than smaller (Cullinane and Khanna, 2000; Sys et al., 2008; Notteboom and Vernimmen, 2009; Stott and Wright, 2011; Lindstad et al., 2012; Lindstad 2013; Lindstad 2015; Lindstad and Eskeland, 2015). The key observation is that when the ship's cargo-carrying capacity is doubled, the required power and fuel use typically increases by about two thirds, so fuel consumption per freight unit is reduced. The vessel building cost increases with about half of the increase in cargo capacity, and the costs of crew, maintenance and management rise less than proportionally with cargo capacity. However, in short-sea trades available cargoes and the required frequencies will often limit the opportunities for increasing the vessel size, or vessel sizes might be limited

due to port restrictions. Second, reducing operational speeds, the explanation for improved fuel economy is that the power output required for propulsion is a function of the speed to the power of three and beyond. This implies that when a ship reduces its speed, the power required and therefore the fuel consumed per transported unit is considerably reduced (Corbett et al., 2009; Seas at Risk and CE Delft, 2010; Psaraftis and Kontovas, 2010; Lindstad et al, 2011; Psaraftis and Kontovas, 2013). Accordingly, average operational speeds have been reduced in the later years (Smith et al. 2014) due to higher fuel prices compared to in the nineties and early 2000's. However, in short sea trades such as in Europe, vessels often compete with road transport both cost and time wise, this limits the opportunities for reducing their operational speeds (Pedersen et al 1999; Lindstad 2002; Lindstad and Pedersen 2009).

Shipyards build large bulk and tanker vessels according to standardized designs. It is quite common that yards within a few years builds more than 50 sister vessels for different owners. In comparison Short sea vessels are less standardized, but are still built in series from a few, up to one hundred nearly equal vessels. Container vessels are also built in series, but these are often shorter than for bulkers and tankers, since the larger container ship companies tend to develop their own company specific designs. One such example is the Triple – E class built for Maersk, with a capacity of 18 000 TEU's, where the E's stands for Economies of Scale, Efficiency, and Environment. When vessels are built in series, the development cost for the design can be divided on more vessels. Second, shipyard workers will learn by doing and hence reduce hours spent from the first to the second and from the second to the third vessel until the full effect is reached after 5 – 8 vessels, like on Liberty vessels built during the Second World War. Third, machinery and other parts, which are bought from external manufactures, can be ordered in larger quantity, reducing part costs and overhead cost. Standardized vessels of different sizes - i.e. vary only the length – extends all these advantages.

While speed reductions and economies of scale in vessel and shipment sizes often require changes in the supply chain due to longer transport times, port requirements and storage facilities, it is possible to introduce more energy efficient designs without changes to the logistics (Lindstad et al, 2013; Lindstad et al 2014; Lindstad 2015; Lindstad et al. 2015). Traditionally, ships have been built to operate at their boundary speeds based on hydrodynamic considerations (Faltinsen et. al.1980). For any given hull form, the boundary speed can be defined as the speed range where the resistance coefficient goes from nearly a constant to rise rapidly and make further speed increases prohibitively costly (Silverleaf and Dawson, 1966). For an average

Panamax bulker or tanker with block coefficient in the 0.85 to 0.9 range (1.0 for a shoebox) the boundary speed area starts at 12 – 13 knots, with a gradual increase in the resistance coefficient, which approaches infinity at speeds above 16 – 17 knots (Lindstad et al. 2014). As a simplification, the form of the resistance coefficient can be compared to a quarter pipe, where the flat area in the bottom represents the lower speeds at which the power required for propulsion is a function of the speed to the power of three. The usual practice in naval architecture is to pick the achievable speed in the middle of the quarter-pipe curve, where the power required for propulsion is a function of the speed to the power of four to five, (usually known as the maximum economic speed), and to install the required power to achieve that speed. Lindstad (2015) have analysed potential cost and emission reductions for Panamax bulkers by increasing the vessel beam (width) to enable more slender hull forms and longer bow sections, while maintaining the cargo carrying capacity. These changes reduce the block coefficient and increase the boundary speed, allowing a reduction in fuel consumption per freight unit. Comparing vessel types, more slender vessels designs such as deep-sea car-carriers and container vessels typically have block coefficients in the 0.55 to 0.65 range. This gives boundary speeds of 20 to 25 knots. In comparison, the small tank and general cargo vessels, i.e. with 2000 tons cargo carrying capacity, have boundary speeds around eight (8) knots. The explanation is their short length in combination with high block coefficients. The key lesson is that reducing the block coefficient makes the hull form more slender, increases the boundary speed, and enables higher operational speeds or lower fuel consumption when speed is kept at the same level as the more full bodied designs. See Larsson and Raven (2010) for a more extensive discussion of how hull resistance depends on speed and hull form.

In Europe, the three main vessel types used in short sea shipping are General Cargo, Ro-Ro and Tank vessels. The General cargo vessels are used for container transport to and from the main container hubs, for break bulk, forest products and pure bulk transport. The Ro-Ro vessels, which includes the car carriers, transport new cars, trucks, trailers, project cargoes, forest products, and high and heavy units. The tankers transport oil products and chemicals. Fig 1 shows a map of Europe and European Seas with main cargo flows both at sea and at land. In the figure, the thickness of the flow indicates the freight tonnages transported. The brown colour are used for the associated members of the European community (EC), i.e. Iceland, Norway, Switzerland, the light brown for the EC member states, i.e. France, Germany and 26 others, and the white colour is used for the other European nations including Russia. The map illustrates the importance of sea transport in North Europe, i.e. the North Sea and the Baltic. In addition (not indicated in the map), there is a substantial sea transport to and from

the Norwegian West coast, i.e. from the most southern point of Norway, to the most North Easterly point where Norway has the common border with Russia, and to and from the Russian Barents ports. Moreover, the main cargo types here are aggregates, gas (LNG), fish, minerals, metals, oil, and oil products.



**Fig. 1:** European Cargo Flows (Source: Baltic Maritime Outlook 2006)

Compared to USA and Canada, Europe has more ports relative to the population. To give one example, Norway with 5 million people has nearly 80 cargo ports, which is more than you will find along the whole West coast of USA and Canada. Some of these ports have major volumes and are served with large vessels, but the majority of the ports are served with small, general cargo vessels. The Global General Cargo fleet adds up to 16 – 17 000 vessels, with an average size of 5 300 dwt compared to 30 800 dwt as an average for the global fleet. Table 1 shows key 2012 figures per vessel type and the totals for the global cargo fleet (Lindstad et al., 2015). In this article all tons and all other measurements are metric, apart from nautical mile (nm) 1 nm = 1 852 meters and 1 knot = 1 852 meters per hour.

**Table 1:** Vessel types and Sea-freight in 2012

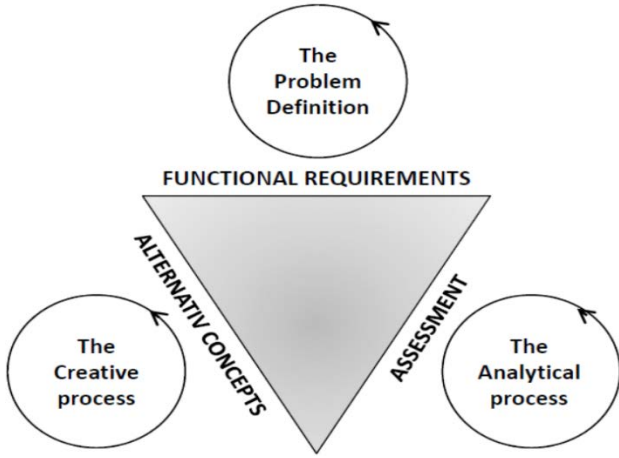
Vessel type	Number of vessels	Average vessel size	Freight work	Market share
	2012	Dwt	Billion ton nm	%
Dry Bulk	10 400	68 600	20 000	42%
General Cargo	16 500	5 300	2 300	5%
Container	5 100	41 600	9 000	19%
Reefer	1 100	5 700	225	0%
RoRo	2 600	7 600	550	1%
OilTanker-mainly crude > 80' dwt	2 000	183 500	10 000	21%
OilTankers-mainly product < 80'dwt	5 400	13 300	2 000	4%
Chemicals	4 900	18 000	2 300	5%
LNG & LPG	1 600	27 600	1 500	3%
RoPax	2 900	1 600	125	0%
Totals	52 500	30 800	48 000	100%

The focus in this study is on the North European General Cargo fleet, which trades in European seas and to and from Europe. The applied methodology is described in "Methodology" section followed by the "Model" description; the existing fleet is described and analysed in "The Existing Fleet" section; the new alternative designs are presented in the Analysis section and the obtained results are discussed in the "Discussion and Conclusion" section.

## METHODOLOGY

While science typically aims at describing the nature of what exists, design is applied and concerned with inventing artefacts that are to be built (Cross 1980). In order to obtain better performance, which could mean lower cost, lower environmental footprint and/or less down time there is a need for fundamental understanding and methodologies to guide the early stages of the project, i.e. the feasibility study, otherwise the ad hoc nature of design cannot be improved (Suh, 1990).

In this project, the ambition is to develop new short sea vessel designs which use significantly less fuel per ton transported and which are competitive versus road only solutions, i.e. cost, frequencies and schedule adherence.. In order to achieve this; we apply the FCA method (see Lindstad et al 2016), i.e. Functional Requirements; Alternative Concepts; and Assessment of Key Performance Indicators (KPI's). Fig. 2 illustrates the core methodology.



**Fig. 2:** The FCA-method

The FCA-method starts with establishment of Functional Requirements based on the problem definition, i.e. by defining the problem in terms of decision variables, constraints and assumptions, and finding an appropriate set of KPI's. Target value limits for the KPI's represents functional requirements for the solution. In the Creative-Process, which requires creative persons that are knowledgeable and willing to take risks, as well as multidisciplinary, the focus is on investigating designs and concepts, which represents a step change, compared to present concepts, i.e. think outside the box. (Suh, 1990). In the Analytical Process, the alternative concepts that have been developed will be analysed quantitatively and qualitatively against the functional requirements and KPI's. For this purpose, we use the model as described in the following section

## MODEL

The main objective of the model is to calculate emissions and costs for the alternative designs as a function of their characteristics and the amount of transported cargo. The model comprises five main equations.

The power function (equation (1)) (Lewis, 1988; Lloyd, 1988; Lindstad 2013; and Lindstad et al. (2014) considers the power needed for still-water conditions,  $P_s$ , the power required for waves,  $P_w$ , the power needed for wind resistance,  $P_a$ , the required auxiliary power,  $P_{aux}$ , and the propulsion efficiency,  $\eta$ . This setup is established practice (Lewis, 1988; Lloyd, 1988; and Lindstad, 2013).

$$P_i = \frac{P_s + P_w + P_a}{\eta} + P_{aux} \quad (\text{Eq. 1})$$

It is noted that for the sake of simplicity the propulsive efficiency  $\eta$  in Eq. 1 is assumed to be constant, even though it varies with speed and propeller loading. How  $P_s$ ,  $P_w$  and  $P_a$  are calculated in this model is described in Lindstad et al. (2014).

The boundary speed function (equation (2)) is based on Silverleaf and Dawson (1966).

$$V_b = (1.7 - 1.4 * C_b) * \sqrt{\frac{L}{0.304}} \quad (\text{Eq. 2})$$

Here,  $C_b$  is the block coefficient and  $L$  is the length of a ship in the waterline from the forward stem, or forward perpendicular, to the sternpost or aft perpendicular. The formula was developed based on analysis of more than 100 single-screw forms and 50 twin-screw forms, having block coefficients in 0.5 to 0.86 range. The constant, i.e. 0.304 converts the ship length in meter to feet. The boundary speed  $V_b$ , is given in knots.

The cost per ton transported comprises the fuel cost and the time charter equivalent costs ( $TCE$ ), where the latter are the financial items, depreciation and operating cost of the vessel, as expressed by equation 3:

$$C = \frac{1}{M} \sum_{i=0}^n \left( \frac{D_i}{v_i} \cdot \left( (K_f \cdot P_i \cdot C_{Fuel}) + \frac{TCE_{k_1 k_2 k_3}}{24} \right) \right) + \left( D_{lwd} \left( (K_f \cdot P_{aux} \cdot C_{Fuel}) + \frac{TCE_{k_1 k_2 k_3}}{24} \right) \right) \quad (\text{Eq. 3})$$

The equation consists of two terms, the first calculates cost at sea and the second calculates cost in ports. Here  $M$  is the weight of the cargo carried. During a roundtrip voyage, the sea conditions will vary and this is handled by dividing each voyage into sailing sections, with a distance  $D_i$  for each sea condition, and the total for the voyage is given by the summation of the sailing sections from zero to  $n$ . The second factor ( $D_i/v_i$ ) gives the hours in each section of the voyage. The hourly fuel cost per section is given by  $(K_f \cdot P_i \cdot C_{Fuel})$ ; where  $K_f$  is the fuel required per produced kWh,  $P_i$  is power required and  $C_{Fuel}$  is the cost per fuel unit. In addition to fuel, the cost of operating a vessel comprises depreciation, interest and operational cost expressed as  $E_{k_1 k_2 k_3}$ . Here  $k_1$  is the daily depreciation as a function of newbuilding price,  $Capexv$ ,  $k_2$  is the interest on the employed capital, and  $k_3$  gives the daily operational. Moreover it should be noted that the  $TCE$  calculated here

expresses what is required to pay back the new vessel over the given depreciation period, i.e. usually 15 or 20 years, cover all the operational cost and give the required return on both the borrowed and own capital. In the real shipping market, the achieved Time Charter (*TC*) will not be constant over a period of 15 to 20 year and it will periodically be both higher and lower than the *TCE*.

The second term calculates cost in ports when loading, discharging and waiting based on total days used  $D_{lwd}$ .

The fuel consumption per ton transported is given by equation 4.

$$F = \frac{1}{M} \sum_{i=0}^n \left( \frac{D_i}{v_i} \cdot ((K_f \cdot P_i)) \right) + \left( D_{lwd} \cdot ((K_f \cdot P_{aux})) \right) \quad (Eq. 4)$$

The equation consists of two terms: the first calculates fuel at sea and the second fuel in ports.

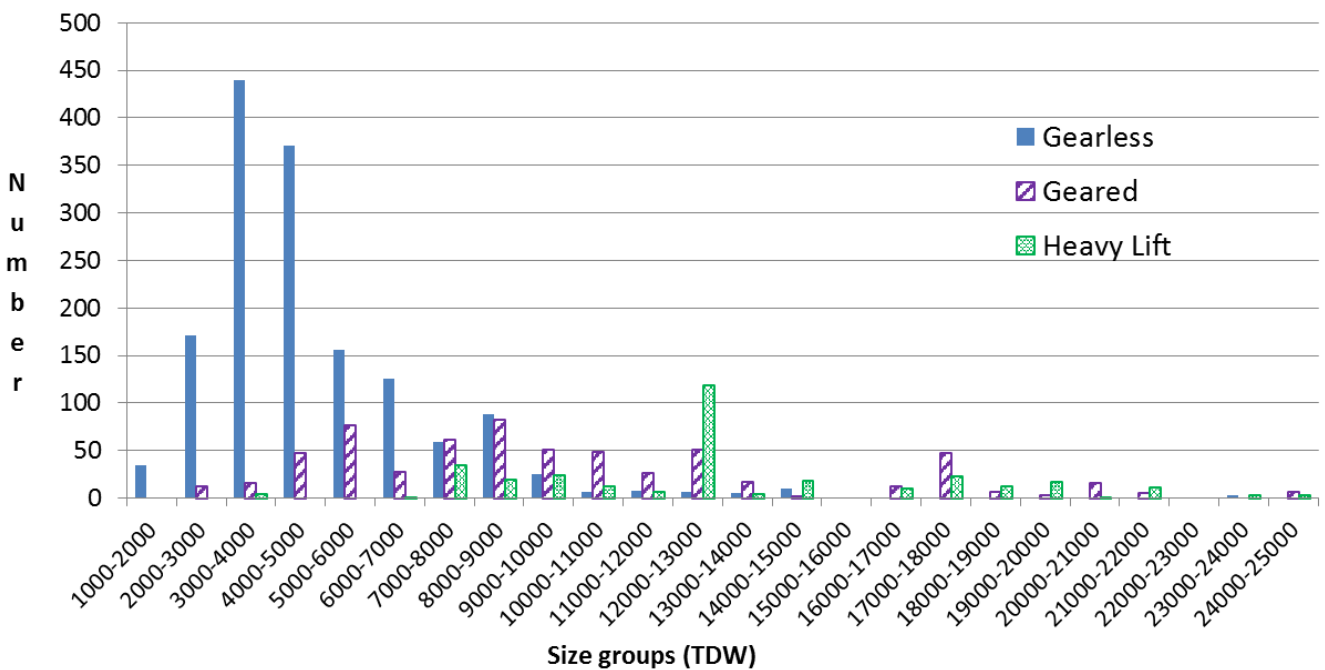
Emissions,  $\varepsilon$  per pollutant per ton transported are calculated as expressed by equation 5:

$$\varepsilon = \frac{1}{M} \sum_{i=1}^n \frac{D_i \cdot P_i \cdot K_{ep}}{v_i} \quad (Eq. 5)$$

Here,  $K_{ep}$  is the emission factor for the pollutant as a function of engine load. Emissions per kWh produced increase when engine load is reduced.

### THE EXISTING FLEET

In this study, the focus is on the North European General Cargo fleet, which trades in European seas and to and from Europe. This fleet consists of gearless vessels, geared vessels and heavy lift vessels. Fig 3 shows the size distribution of the vessels up to 25 000 dwt, built with North European specifications and design from 1990 to 2016 as obtained from the Sea-web database ([www.sea-web.com](http://www.sea-web.com)).



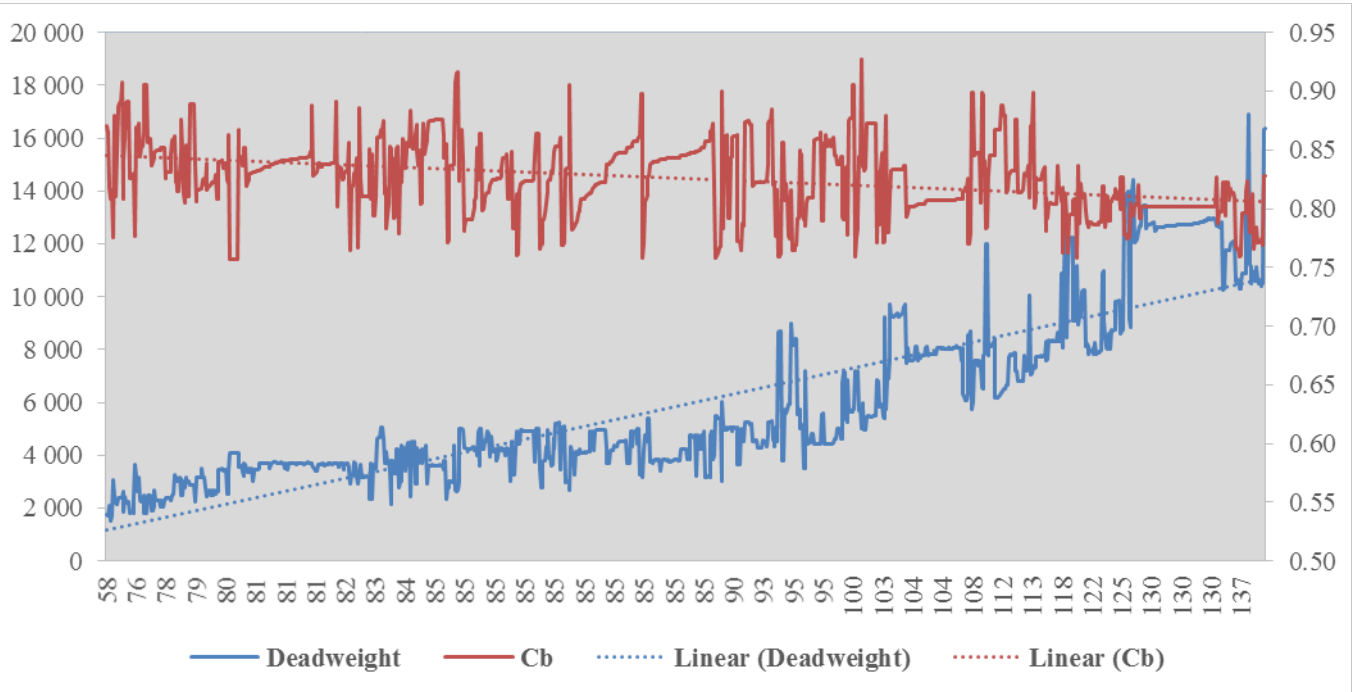
**Fig. 3:** North European General Cargo Vessels < 25 000 dwt built from 1990 – 2016 (source: Sea-Web database)

Main observations from Fig 3 is that the gearless vessels, i.e. 1509 vessels accounts for more than two third of these 2500 vessels. Moreover, gearless vessels in the size groups from 2000 – 7000 dwt add up to nearly 50 % of the whole fleet. The geared vessels built for the North European markets were mainly used as Container Feeder Vessels and Forest Products Carriers. The geared Feeder Vessels are now

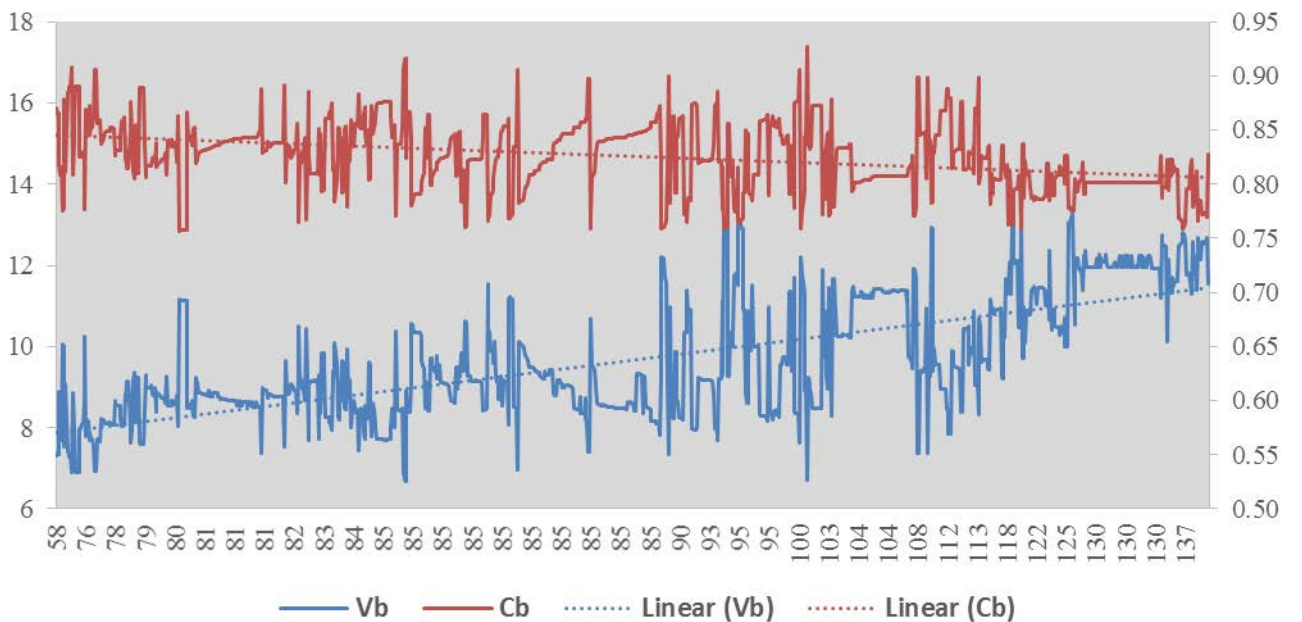
largely replaced by cellular container tonnage and only a few remains in Europe. Adding gear to a vessel increases the lightweight, and in addition, there are more than one gear solution available in the market. Due to this, the analysis from this point forward is based on the gearless vessels. Fig 4 shows deadweight and block coefficient  $C_b$  as a function of length and Fig. 5 shows boundary speed and

block coefficient  $C_b$  as a function of length for the whole fleet of gearless vessels (1000 – 25 000dwt). These two figures are plotted based on the values for the 1169 gearless

vessels for which displacement is stated in the Sea-web database (1509 vessels in total).



**Fig. 4:** Deadweight and Block coefficients as a function of vessel length



**Fig. 5:** Boundary Speed and Block coefficient as a function of vessel length

Main observations from Fig 4 and 5 are: The smallest vessels have the highest block coefficients, i.e. around 0.85. Second, when the vessel sizes increase the block coefficient is gradually reduced, i.e. to around 0.80 for the largest vessels. Third, there is a large spread, i.e. the block coefficients varies between 0.75 and 0.93. Fourth, since the smallest vessels are the shortest, the combination of short lengths and high block coefficients gives boundary speeds as low as 7 knots. Fifth high block coefficients give low boundary speeds for all vessel lengths. Sixth, the longest vessels have the highest boundary speeds due to the combination of block coefficients around 0.8 and their length advantage, where the latter is most important. Seventh, the boundary speed varies between 6.5 and 13 knots.

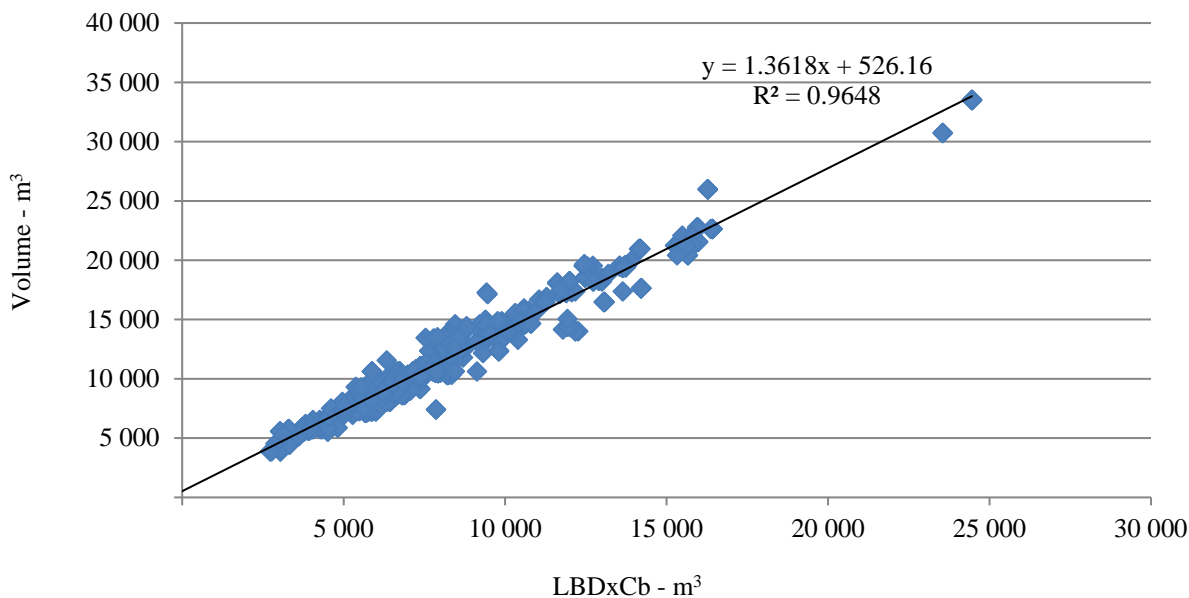
Low boundary speeds as such is not a problem if vessels are operated at that speed, but in reality most of the general cargo fleet are powered to operate at designs speeds 2 to 4 knots above their boundary speeds. In comparison, deep-sea bulkers and tankers are generally designed to operate at their boundary speeds, with power reserves to do no more than 0.5 – 1.5 knots higher. Historically marine fuel was cheap and even if consumption doubles compared to operating at the boundary speed, the additional fuel cost was less than the additional income due to more freight work produced. More recently, higher fuel prices due to the introduction of the 0.1% sulphur limits in the North Sea and the Baltic in combination with increased environmental concerns has challenged this practice. There is hence a need for

developing designs, which use less fuel per tons of goods transported.

## ANALYSIS

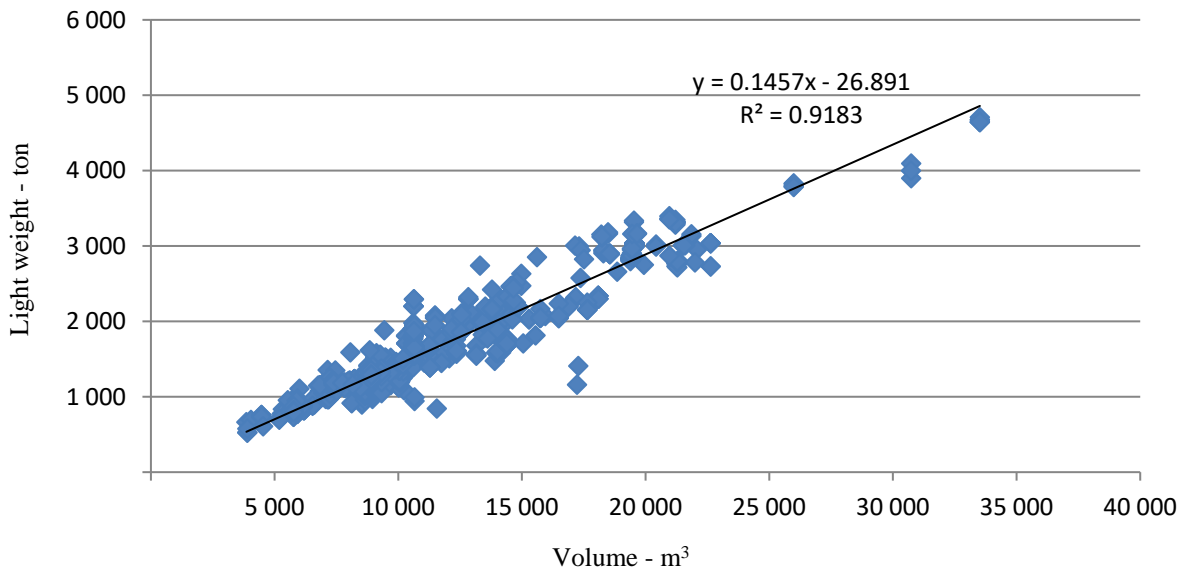
The purpose of this section is to investigate alternative designs with focus on varying vessel length and width, to enable more slender designs and hence lower fuel consumption and emissions per transported unit, compared to more full body conventional short sea designs operating at similar speeds.

First, we establish the regression lines for the existing fleet, which enables calculating of lightship weights, displacements and building cost for alternative designs based on the Volume (in cubic meters) calculated from the gross tonnage (GT) and the power from the required power for 12 knots with 35% sea margin. In fig 6 the volume from GT is plotted against  $LxBxD \times C_b$ , and in fig 7 lightship-weight versus Volume is plotted. These plots are based on 1169 out of the 1509 gearless vessels, i.e. the vessels for which displacement or lightweight is stated in the Sea-web database. We did not try to define and correct for the different ice classes as we were only aiming for the general trend, which we believe is the reason for the larger spread in Fig. 7. The predominant vessel in this size group has a dwt of 4500 ton, a draught of around 6 meter, a length of 84.99 meter, a beam of 14 meter, a block coefficient of 0.84 and a 12 knots design speed.



**Fig 6:** Volume versus LBD x Cb (1169 gearless vessels)





**Fig 7:** Lightweight versus Volume for the fleet (1169 gearless vessels)

These regression lines combined with detailed data on specific vessels enables us to calculate weight, volume, resistance and power requirements for alternative designs, where length, beam, block coefficients and dwt are varied. Combined with published new-building prices, and known operational cost and capex structures for specific vessels, it also enables us to calculate the daily and yearly cost for each of the alternative designs. Table 2 shows the main characteristics for the reference vessels and the alternative designs. The smallest reference vessel is called A and she has a length of 64.99m, and a beam of 14m, a draught of 6m and a depth of 7.1m and with a block coefficient of 0.84 this give a dead weight of 3 582 ton. First we increase length stepwise with 10 m and keep the beam and the block coefficient constant, stopping vessel G with a length of 124.99m which gives a dead weight of 6 848 tons. Second, we increase beam with 3 meter for all these designs (except the longest) and labels them A-1 to E-1. Third, we

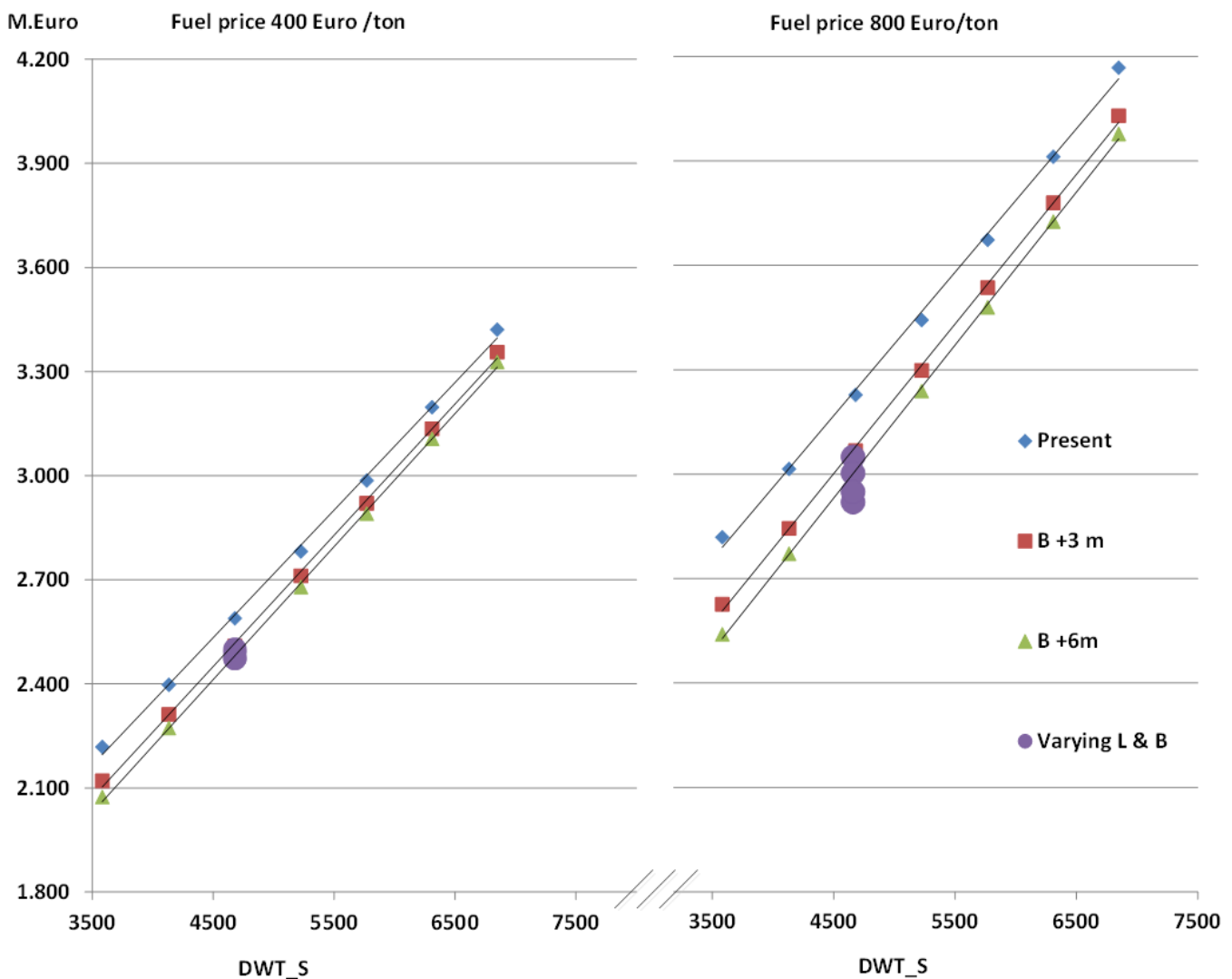
increase the beam with an additional 3 meter, i.e. 6 meter in total and labels them A-2 to E-2. Fourth, we keep the beam at 20 meter and then we adjust the block coefficient so that the vessels which are compared gets equal carrying capacity, i.e. 4680 dwt and labels them A-3 to E-3. For fuel prices, two prices are used in the assessment, 400 Euro per ton, which reflects the current distillate prices (2016) with a crude oil price around 50 USD per barrel. And 800 Euro per ton, which reflects distillate prices in 2012 – 2014 when the oil price was above 100 USD. It is outside the scope of this article to make any predictions for future crude and distillate prices, however if prices drops further, the transport cost for all the vessels will be reduced, but it will not change the ranking compared to the 400 Euro level. And opposite if, the prices increases above 800 Euro it will only make the slender designs which benefits from the 800 level already even more competitive.

**Table 2: Design characteristics and daily cost figures as a function of vessel size (200 days at sea)**

Design characteristics										Daily Cost - 12 knots (Euro - €)						Daily Cost per DWT (€/t)						
Alt	Length BP (m)	Beam (m)	Draught (m)	Depth (m)	Cb	Dead weight Dwt_s (ton)	New-built cost V <sub>d</sub> =12 knots (M.€)	Depreciation & Interest	Operation	Opex & Capex	Power 12knots	Power 16knots	Fuel/hour	LDT	DEPL	L/B	Fuel 400 €/ton	Fuel 800 €/ton	Capex & Opex	Capex Opex Fuel (400€/t)	Capex Opex Fuel (800€/t)	Capex Opex Fuel (400€/t) Vd=16 knots
A - 1	64.99	17.0	6.0	7.20	0.70	3 582	6.5	2 234	2 249	4 483	1 341	4 052	0.260	1156	4738	3.8	1 388	2 777	1.25	1.64	2.03	2.63
A - 2	64.99	20.0	6.0	7.30	0.59	3 582	6.4	2 213	2 252	4 464	1 228	3 369	0.240	1162	4744	3.2	1 281	2 562	1.25	1.60	1.96	2.39
A - 3	64.99	20.0	6.0	7.20	0.77	4 680	8.5	2 909	2 374	5 326	1 611	4 925	0.309	1462	6142	3.2	1 646	3 292	1.14	1.48	1.83	2.40
B	74.99	14.0	6.0	7.15	0.84	4 132	7.6	2 634	2 309	4 942	1 659	4 862	0.317	1302	5434	5.4	1 691	3 382	1.20	1.61	2.01	2.62
B - 1	74.99	17.0	6.0	7.25	0.70	4 132	7.6	2 620	2 322	4 942	1 415	4 001	0.274	1335	5467	4.4	1 459	2 919	1.20	1.55	1.90	2.37
B - 2	74.99	20.0	6.0	7.35	0.59	4 132	7.5	2 602	2 325	4 926	1 321	3 483	0.257	1341	5474	3.7	1 369	2 739	1.19	1.52	1.85	2.22
B - 3	74.99	20.0	6.0	7.20	0.67	4 680	8.5	2 953	2 383	5 336	1 477	4 075	0.285	1486	6166	3.7	1 519	3 037	1.14	1.46	1.79	2.20
C	84.99	14.0	6.0	7.20	0.84	4 680	8.7	3 007	2 380	5 387	1 663	4 625	0.318	1479	6159	6.1	1 695	3 390	1.15	1.51	1.88	2.35
C - 1	84.99	17.0	6.0	7.30	0.70	4 680	8.7	3 019	2 395	5 414	1 492	3 985	0.287	1516	6196	5.0	1 532	3 064	1.16	1.48	1.81	2.19
C - 2	84.99	20.0	6.0	7.40	0.59	4 680	8.7	3 001	2 398	5 400	1 407	3 544	0.272	1523	6203	4.2	1 451	2 902	1.15	1.46	1.77	2.07
C - 3	84.99	20.0	6.0	7.40	0.59	4 680	8.7	3 001	2 398	5 400	1 407	3 544	0.272	1523	6203	4.2	1 451	2 902	1.15	1.46	1.77	2.07
D	94.99	14.0	6.0	7.25	0.84	5 225	9.9	3 435	2 453	5 888	1 784	4 673	0.339	1658	6883	6.8	1 810	3 620	1.13	1.47	1.82	2.21
D - 1	94.99	17.0	6.0	7.35	0.70	5 225	9.9	3 431	2 470	5 901	1 571	4 004	0.301	1700	6925	5.6	1 607	3 215	1.13	1.44	1.74	2.06
D - 2	94.99	20.0	6.0	7.45	0.59	5 225	9.9	3 414	2 473	5 888	1 493	3 620	0.287	1708	6933	4.7	1 533	3 066	1.13	1.42	1.71	1.97
D - 3	94.99	20.0	6.0	7.46	0.53	4 680	8.8	3 025	2 406	5 430	1 374	3 256	0.266	1541	6221	4.7	1 420	2 841	1.16	1.46	1.77	2.00
E	104.99	14.0	6.0	7.30	0.84	5 769	11.2	3 856	2 527	6 383	1 857	4 664	0.353	1840	7608	7.5	1 880	3 760	1.11	1.43	1.76	2.08
E - 1	104.99	17.0	6.0	7.40	0.70	5 769	11.2	3 857	2 545	6 402	1 652	4 004	0.316	1886	7654	6.2	1 685	3 369	1.11	1.40	1.69	1.95
E - 2	104.99	20.0	6.0	7.50	0.59	5 769	11.1	3 840	2 549	6 389	1 579	3 712	0.303	1895	7663	5.2	1 615	3 230	1.11	1.39	1.67	1.89
E - 3	104.99	20.0	6.0	7.54	0.48	4 680	9.0	3 124	2 426	5 550	1 368	3 117	0.265	1591	6271	5.2	1 415	2 829	1.19	1.49	1.79	1.99
F	114.99	14.0	6.0	7.35	0.84	6 309	12.4	4 293	2 601	6 894	1 936	4 695	0.367	2023	8333	8.2	1 955	3 909	1.09	1.40	1.71	1.99
F - 1	114.99	17.0	6.0	7.45	0.70	6 309	12.4	4 296	2 622	6 918	1 735	4 124	0.331	2074	8383	6.8	1 763	3 527	1.10	1.38	1.66	1.89
F - 2	114.99	20.0	6.0	7.55	0.59	6 309	12.4	4 280	2 626	6 906	1 665	3 819	0.318	2084	8393	5.7	1 697	3 394	1.09	1.36	1.63	1.83
F - 3	114.99	20.0	6.0	7.63	0.44	4 680	9.2	3 179	2 437	5 615	1 371	3 043	0.266	1618	6298	5.7	1 417	2 834	1.20	1.50	1.81	1.99
G	124.99	14.0	6.0	7.40	0.84	6 848	13.7	4 750	2 677	7 426	2 027	4 815	0.383	2210	9057	8.9	2 042	4 083	1.08	1.38	1.68	1.93

Main observations: First, the daily cost per dwt goes from 1.71 for the smallest vessel down to 1.38 Euro per ton for the largest vessel, which means that when cargo carrying capacity is doubled the cost increases by 2/3 and the costs per tonmile work declines. Second, increasing beam with 3m reduces cost compared to the reference designs, and increasing the beam further to 6m gives additional reductions compared to the reference designs. Third, increasing speed from 12 to 16 knots increases cost with 33% - 60% and freight work with 33%. This implies that the

D-3 and E-3 designs (long and slender) can increase speed without increasing cost per ton nm. Fourth, the largest cost reduction compared to the reference design is achieved for the most unconventional design, i.e. the shortest vessel with 20 meter beam, rather than 14. In fig. 8 the annual cost, i.e. capex + opex + fuel is plotted for the assessed designs to enable a better visualization of the main results presented in the table 2. First, with a fuel price of 400 Euro per ton on the left side of the figure, and second, for a fuel price of 800 Euro per ton on the right side.



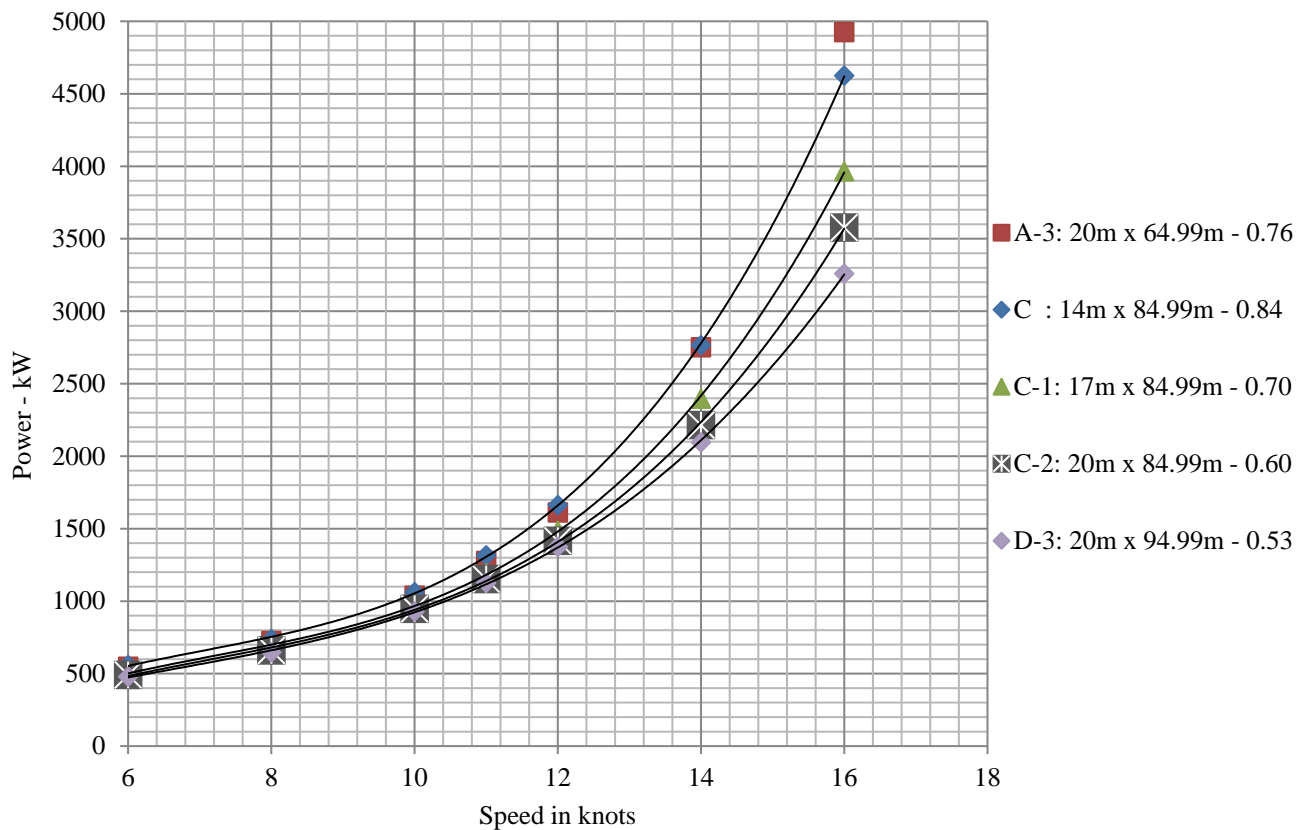
**Fig 8:** Annual cost (Capex + Opex +Fuel) with fuel prices of 400 and 800 Euro per ton for the investigated designs

Main observations from Fig 8: First, the cost advantage of increasing the beam with 3 or 6 m are higher under higher fuel prices (also carbon prices, which work the same way) both in absolute values and in percent. Second, even at 12

knots, a more slender design is rewarded, so therefore we will investigate what happens at both higher and lower speeds. The designs which will be further assessed are: First, A-3 which is short and wide with a length beam ratio of 3.3;

Second is C which is the reference vessel with a block coefficient of 0.84; Third is C-1 with a beam of 17m and a block coefficient of 0.70; Fourth is C-2 (equal to C-3) with a beam of 20m and a block coefficient of 0.60; Fifth is D-3 which is long and slender with a block coefficient of 0.53. And sixth is E-3 which is long and even more slender with a

block of 0.48. The first step of this assessment is to compare required power to gain additional insight about the optimal speed areas for each of the designs. Fig. 9 shows required power as a function of speed for these six alternative designs for speeds from 6 to 16 knots.

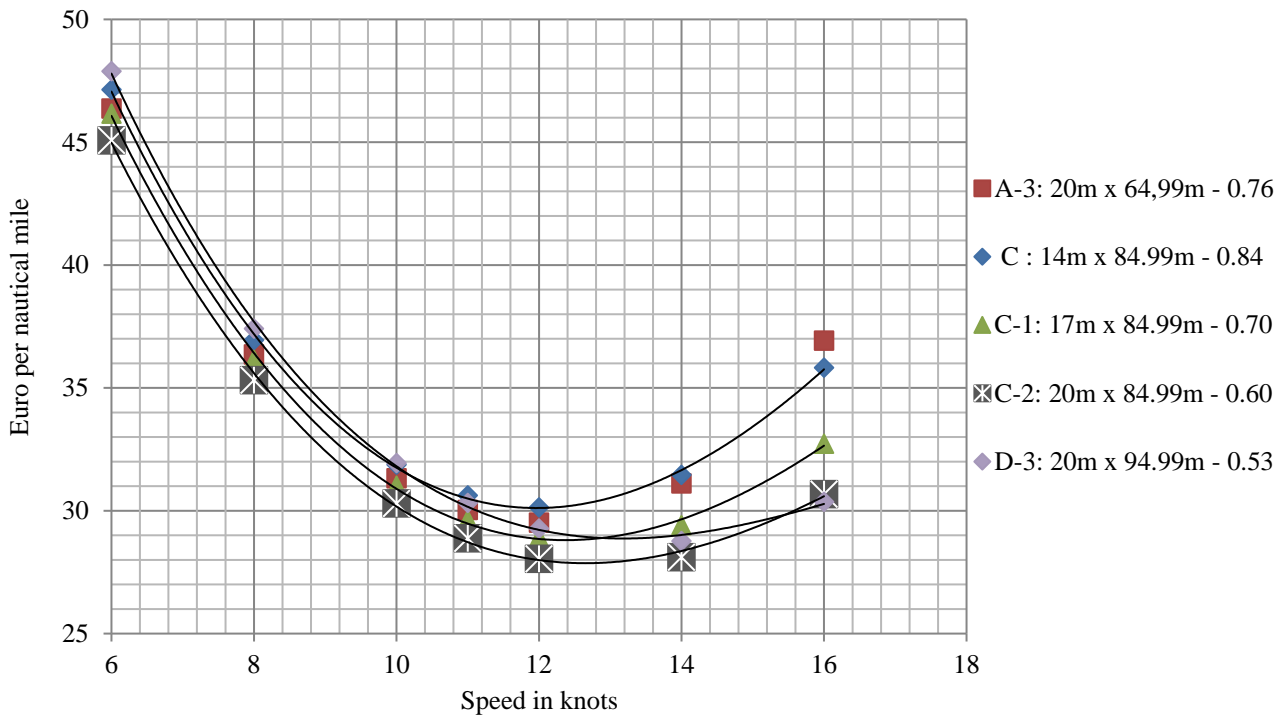


**Fig. 9:** Required power as a function of speed

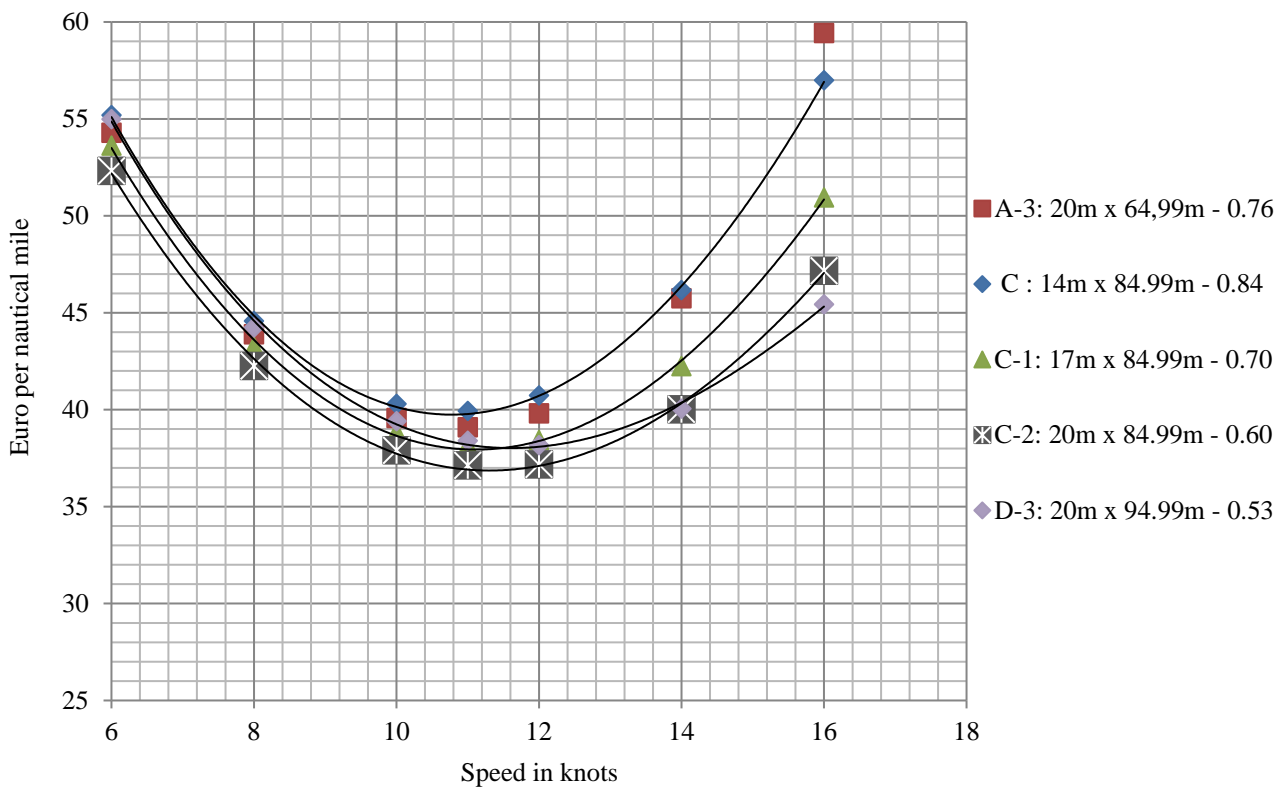
Main observations from Fig 9 are: First, at low speeds, i.e. less than 10 knots the differences in fuel consumption between the designs are marginal; Second at 12 knots the difference is 20 % between the lowest consumers and C the highest; Third for speeds up to 14 knots the short and wide, i.e. A-3 (unconventional) has a lower consumption than C, the reference vessel. Fourth at speeds above 12 knots the benefits of length and slenderness gives significantly lower consumption than shorter and more fullbodied designs. Fifth at 16 knots, the difference in fuel consumption has increased to 50 % between the lowest consumer E-3 and A-3. Sixth, for additional speed increases above 16 knots this difference will increase further, due to the high boundary speeds of D-3 and E-3 and D-3, i.e. 16.9 knots and 18.9 knots compared to

14.6 knots for C-2 and 12.2 for C-1 and around 9 knots for C and A-3.

Fig. 10 shows cost per nautical mile for each of these six alternative designs for speeds from 6 to 16 knots based on 50% dwt utilization on a roundtrip basis based on a fuel price of 400 Euro per ton and the same in Fig 11 based on a fuel price of 800 Euro per ton. There are certainly trades where the cargo carrying capacity is fully utilized both ways, however these vessels typically operate in trades with a mix of: fully loaded, partly loaded and ballast voyages. Lindstad et al. (2012a) has found that this mix of trades (for general cargo vessels) gives yearly dwt utilization in the range from 46 – 56 % , where the smallest vessels have the lowest figure.



**Fig. 10:** Cost per nautical mile (nm) as a function of speed 400 Euro per ton of fuel (50% dwt utilization on a rountrip basis)

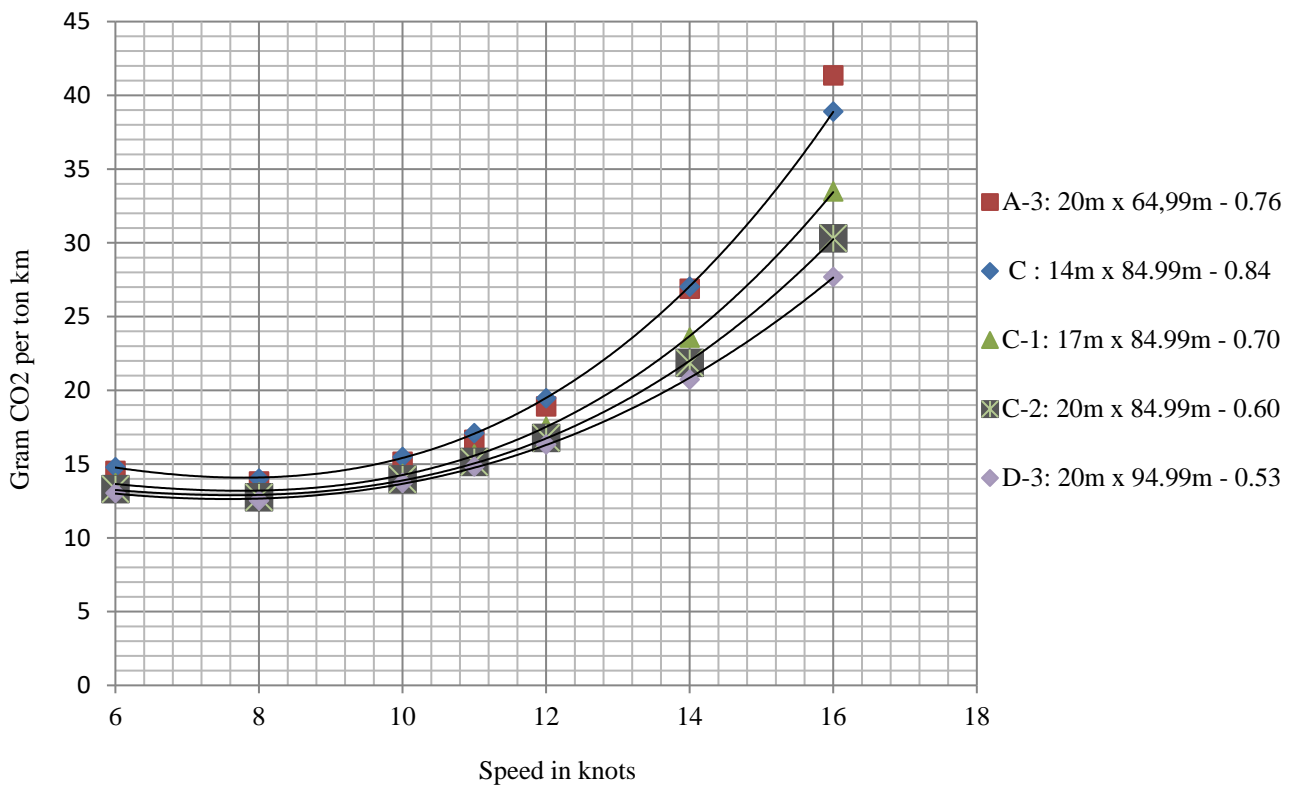


**Fig. 11:** Cost per nautical mile (nm) as a function of speed 800 Euro per ton of fuel (50% dwt utilization on a rountrip basis)

Main observations from Fig 10 are: First, the reference design C has the highest cost per nautical mile for speeds up to 14 knots while A-3 has the highest cost at 16 knots. Second, 12 knots is the cost minimizing speed for A-3 and C, i.e. the speed which gives the lowest cost. A 12 knot speed is 3 knots above the their boundary speed and 2 to 3 knots higher than the cost minimizing speed for a Panamax bulker (for this fuel price), which carries 15 to 20 times more cargo, i.e. 80 000 dwt (Lindstad, 2015). The simple explanation is that while fuel cost will account for more than half of the capex+opex+fuel for the Panamax dry bulker it will account for around a third of the cost on these General cargo vessels. Third, the slenderest designs, i.e. D-3 and E-3 have cost minimizing speeds around 14 knots which is significantly lower than their boundary speeds of 17 – 19 knots. Fourth, if the fuel price increases from 400 to 800

Euro per ton, the cost increases with a third for speeds around 12 knots, i.e. the cost minimizing speeds. Fifth, for lower speeds, i.e. from 6 to 10 knots a fuel price increase makes the slender designs a little bit more competitive, but the difference are still small. Sixth for speeds above 12 knots a fuel price increases makes the slender designs even more competitive versus the more full bodied and full bodied designs, i.e. C-1, C and A-3.

Fig. 12 shows gram CO<sub>2</sub> per ton kilo meter (km) for each of these six alternative designs for speeds from 6 to 16 knots based on 50% dwt utilization. The explanation for using km here is that it enables comparison with road transport, based on figures which are well known for the road transport sector.



**Fig. 12:** Gram CO<sub>2</sub> per ton km as a function of speed (50% dwt utilization on a roundtrip basis)

Main observations are that the lowest emissions per ton km are achieved, for speeds in the 6 to 10 knots area. In this speed area, the curves are nearly flat. When speed increases to the cost minimizing speeds the emissions increases to a 20 gram per ton km level for the A-3 and C (12 knots ) and the same emission level for D-3 and E-3 when they operates at 14 knots which is their cost minimizing speed. In comparison, recently published figures for road transport

(European Environmental Agency, 2013; Persson and Zanganeh, 2012; Cefic and ECTA, 2011) indicate direct emissions levels in the range from 50 – 70 g CO<sub>2</sub> per ton km when the same cargo is transported in by road. These figures indicate that these general cargo vessels emit less than half of road transport based on the published road transport figures. In addition except when both the producer and the customer are based next to sea and ports, the sea transport

option will have to include hinterland transport either at point of departure or at point of arrival or both which will increase the gram CO<sub>2</sub> emitted. However, the additional emissions from the hinterland transport will in general be less than the sea-transport emissions, which implies that the sea transport solution will give lower emissions than the truck only solution, even when neither the producer nor the customer is based close to the port.

## DISCUSSION AND CONCLUSIONS

This feasibility study has investigated the opportunities for development of new short-sea vessels which use significantly less fuel per unit transported and which can be built at a modest cost. The initial results compared with existing vessels indicate that fuel cost and emissions can be reduced significantly.

The study is an attempt to show what is possible with a single hull displacement vessel having no other restrictions. The next step will be to establish the restrictions.

These ships are built to carry bulk cargoes as well as timber packages and some are suitable for containers. Cargo handling is mainly by land-based equipment or by excavators fitted with scopes or other suitable equipment depending on cargo/trade. In order for the cargo handling to work, they have to be fully open hatch and with double skin. As the lines become finer, to achieve a practical design with these criteria becomes more and more difficult. Also as an example the steel weight could increase do to possible wider side skin.

The directional stability due to low L/B ratio will also set limits, as well as for some cargoes, too high GM's and cargo shifting moments. Some of the alternatives are outside the range of the database, i.e. 0.63 – 0.93, L/B min 4.6 – max 8.8 and these designs must be further analysed. Still they, serves a purpose defining what could be achievable.

Next step of the project will be to further investigate and develop the designs of the most promising of these concept, i.e. A-3 the short and wide, C-3 wide and slender, D-3 long wide and slender and E-3 long, wide and most slender. Moreover, to compete with trucks we will investigate if these concepts can be scaled down from 4680 dwt, to less than 3000 dwt without increasing daily cost per dwt compared to the 4680 ton vessels.

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