# OPPORTUNITIES FOR IMPROVED EFFICIENCY AND REDUCED $CO_2$ EMISSIONS IN DRY BULK SHIPPING STEMMING FROM THE RELAXATION OF THE PANAMAX BEAM CONSTRAINT

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## SUMMARY

In 2014 the Panama Canal Authority is scheduled to bring into commission new locks that will eliminate the long standing Panamax beam constraint of 32.2m. The expansion of the canal is aimed at increased capacity for container transits but will clearly have consequences for all types of vessel. There is an emerging demand for dry bulk carriers that are larger than the current Panamax limit of around 85,000 dwt but smaller than the Capesize class of around 160,000 dwt and the expansion of the canal will facilitate this development. Larger vessels will permit economies of scale and greater efficiency in the dry bulk shipping sector compared to what is currently possible with conventional Panamax ships. The relaxation of the constraint will additionally permit the development of more efficient hull forms than is possible within the existing beam constraint and the expansion of the Panama Canal's locks will therefore (eventually) contribute directly to the reduction of $CO_2$ produced by dry bulk shipping. The use of the Panamax constraint is far wider than the dry bulk sector, however, and the potential for reduction in carbon emissions for other sectors currently constrained to 32.2m beam is recommended for further study to evaluate the total carbon reduction 'windfall' that could result from the expansion of the Canal.


## NOMENCLATURE

| | |
|---|---|
| dwt | Deadweight (tonnes) |
| TEU | Twenty-foot Equivalent Unit, being a single twenty foot standard shipping container. |
| Handysize | Smaller dry bulk carriers, typically between about 10,000 and 40,000 dwt. |
| Handymax / Supramax | Dry bulk carriers between about 40,000 and 60,000 dwt with Panamax beam. |
| Panamax | Limiting beam dimension of about 32.2m or a class of dry bulk carriers between about 60,000 and 85,000 dwt with Panamax beam. |
| U-Panamax | "Unconstrained-Panamax" being ships with deadweight similar to the "traditional" panamax class described above but without being restricted by the Panamax beam limitation. |
| GT | Gross Tonnage |
| Capesize | Dry bulk carriers too large to transit the Panama Canal, typically around 160,000 dwt. |
| Mini-Cape | Dry bulk carriers too large to transit the Panama Canal but smaller than the traditional Capesize class of vessels (typically between about 85,000 and 120,000 dwt). |
| PSD | Parcel Size Distribution function (tonnes). |
| $L$ | Length between perpendiculars (m) |
| $B$ | Breadth Extreme (m) |
| $T$ | Draught (m) |
| $C_B$ | Block Coefficient |
| $D$ | Depth (m) |
| $K_d$ | Deadweight / Displacement ratio |
| $GZ$ | Righting Lever (m) |
| $KM_t$ | Transverse metacentre (m) |
| $LCB$ | Longitudinal Centre of Buoyancy (m) |
| $\Delta$ | Displacement (tonnes) |
| $F_n$ | Froude number |
| $V$ | Volume of displacement ($m^3$) |
| $w$ | Taylor Wake Fraction |
| $t$ | Thrust deduction |

## 1. INTRODUCTION

To the designers of the Panama Canal in the first decade of the last century the limiting dimensions of the locks must have seemed very large indeed. Given that the size of a large dry cargo ship at the time was around 7,000 dwt [1] the chambers could have accommodated two ships abreast and almost three in line. Ships have become larger, however, and by the end of the twentieth century the limiting dimensions of locks had become an issue because of the limitations they impose on the capacity of the Canal, in particular the capacity for transit of containers. The justification for the expansion [2] indicated that the capacity for transit of containerised cargo will be exceeded by demand from 2011 and that unless the Canal expands, its relevance to shipping will erode to the detriment of the Panamanian economy.

After many years of study the funding for a \$5.8 billion expansion was announced in 2006, aiming to be completed in 2014 exactly one hundred years after the Canal first opened to shipping. The maximum size of container vessel that can transit the Canal will increase from around 4,800 TEU to around 12,000 TEU when the project is completed. It is not only container vessels that will benefit, however, the relaxed constraint also applying to bulk carriers and other vessel types that may benefit from the shortened route between the Atlantic and Pacific oceans.

 

The expansion of the Canal is based on the requirements of the container trades and the consequent effect on container vessel design has been well researched [2,3,4,5,6,7]. Little has been written to date about the potential effects on design in other fleet sectors, however. This paper considers the wider implications of the relaxation of the Panamax beam constraint for ship designers. This is not a purely technical issue and must take account of factors such as market demand for larger ships and other constraints, in particular in the capability of supporting infrastructure to handle larger dimensions. The case of the ubiquitous Panamax dry bulk carrier is used to illustrate the issues that will be faced in considering expansion of vessel size in response to the relaxation of the constraint.

## 2. DRY BULK SHIPPING THROUGH THE CANAL

Dry bulk carriers rank second in importance to container ships in terms of number of transits through the Canal but lead in terms of tonnage of cargo, as described in Table 1.

| Market Segment | Number of Transits | Cargo (thousand long tons) | Tolls (thousand Balboa[1]) |
|---|---|---|---|
| Container | 3,031 | 50,305 | 763,988 |
| Dry Bulk | 3,050 | 86,890 | 250,692 |
| Refrigerated | 1,718 | 4,811 | 61,722 |
| Tankers | 2,233 | 44,941 | 171,152 |
| General Cargo | 834 | 6,948 | 31,124 |
| Vehicle carriers | 607 | 2,664 | 118,770 |
| Others | 893 | 8,257 | 42,378 |
| Passengers | 225 | 0 | 40,727 |
| Total | 12,591 | 204,816 | 1,480,554 |

Table 1: Summary of Canal traffic by segment in 2010[8]

It is interesting to note that whilst dry bulk trades make up by far the largest sector in terms of tonnage (42% in 2010) the revenue received by the Panama Canal Authority is dominated by container shipping, hence the focus of the expansion on the container sector.

| | South-bound | North-bound |
|---|---|---|
| Number of laden transits | 1,410 | 865 |
| Number of ballast transits | 11 | 748 |
| Total transits | 1,421 | 1,613 |
| Total Cargo (thousand long tons) | 58,645 | 27,760 |

Table 2: Summary of dry bulk Canal traffic in 2010 [8]

Whilst the total number of dry bulk carrier transits is roughly equal in both directions about 70% of dry bulk cargoes move in the Southerly direction, that is from the Atlantic to the Pacific, with ballast voyages being mainly on North-bound routes. Dry bulk carrier traffic in 2010 is summarised in Table 2.

The predominance of South-bound traffic is due to the importance of Grain cargoes, for which the main flow is from the Atlantic to the Pacific. The main dry bulk flows are summarised by commodity and direction in Table 3.

| | South-bound | North-bound |
|---|---|---|
| Coal and Coke | 8,072 | 2,392 |
| Grains | 37,943 | 2,464 |
| Fertilizers | 4,463 | 1,987 |
| Ores | 3,051 | 3,380 |

Table 3: Summary of dry bulk cargoes transiting the Canal in 2010 (thousand Long Tons) [8]

There are a wide range of dry bulk routes served by the Canal but the following (Table 4) are the most significant, showing more than 1 million long tons transiting in 2010.

| | |
|---|---|
| N-bound | Grain: W. Coast Canada to E. Coast USA |
| | Ore (principally copper): W. Coast South America to Europe |
| | Coal: W. Coast Canada to Europe |
| S-bound | Grain: E. Coast USA to W. Coast South/Central America |
| | Grain: E. Coast USA to Asia |
| | Coal: E. Coast South America to W. Coast South America |
| | Ore (principally Iron): E. Coast South America to Asia |

Table4: Largest (>1m long tons) dry bulk trade routes through the Canal in 2010 [8]

## 3. PANAMAX

The complex set of regulations applying to ships transiting the Canal are set out in the Panama Canal Authority's notice to shipping generally referred to as the "Vessel Requirements" [9]. Inter alia the Vessel Requirements set out the limiting dimensions and the 2010 revision of the document for the first time refers to the limitations that will apply following expansion. The limits are summarised in Table 5.

The existing locks were specified in feet, being the reason for the unusually precise limiting dimensions. New Panamax dimensions are specified in meters, giving a more rounded constraint for metric designers. The new limiting lock internal dimensions are planned to be 427m x 55m x 18.3m. The reason for the increased beam clearance (6m in the new locks compared to 1.2m in the existing locks) is that ships will be taken through the new locks under the control of tugs. In the existing locks vessels are pulled through by locomotive engines on rails (known as "mules"), enabling vessels to be squeezed tightly between the walls.

[1] The Balboa is tied to the US Dollar at an exchange rate of 1.00.

 

| | Length (m) | Beam (m) | Draft (m) | Air draft (m) |
|---|---|---|---|---|
| Existing Panamax | 289.6[2] | 32.31[3] | 12.04[4] | 57.91[5] |
| New Panamax | 366 | 49 | 15.2 | 57.91 |

Table 5: Existing and New Panamax vessel dimensions[9]

The Panamax designation has come to mean more than a simple beam constraint, however, having evolved to designate classes of ship and, in particular, a class of dry bulk carrier. In the Sub-Panamax sector designers have also maximised the carrying capacity of Handysize ships, for which grain is an important cargo, by increasing beam to 32.2m. These ships are generally referred to as "Handymax" or "Supramax" ships. Typical dimensions for the main ship types are shown in table 6.

| | | *L* (m) | *B* (m) | *T* (m) | *L/B* |
|---|---|---|---|---|---|
| Dry bulk | Handymax | 190 | 32.2 | 10.0 | 5.9 |
| | Panamax | 225 | 32.2 | 13.9 | 7.0 |
| Tanker | Handymax | 182 | 32.2 | 11.75 | 5.7 |
| | Panamax | 228 | 32.2 | 13.4 | 7.1 |
| Container | Panamax | 260 | 32.2 | 12.3 | 8.1 |

Table 6: Existing typical Panamax ship dimensions[6]

These vessel types are not about to become extinct in the near future, not least because there are a significant number on order that, given the typical life expectancy of a ship, will be around for the next twenty five years or so. The relative sizes of existing fleets and orderbooks at mid-2010 is shown in Table 7.

| | | Existing fleet (No. ships) | Orderbook at 26.7.2010 (No. Ships) | % of existing fleet on order |
|---|---|---|---|---|
| Dry bulk | Handymax | 1,999 | 802 | 45.1% |
| | Panamax | 1,701 | 914 | 57.9% |
| Tanker | Handymax | NA | NA | NA |
| | Panamax | 393 | 84 | 22.0% |
| Container | Panamax | 928 | 98 | 10.5% |

Table 7: Panamax fleets and orderbook at mid-2010 [10]

[2] Equivalent to 950 feet. 294.13m (965 feet) is permitted for passenger and container ships.
[3] This is 106 feet, giving two feet clearance either side in the 110 feet locks. In some circumstances a beam of 107 feet may be permitted.
[4] Draft in Tropical Fresh Water (TFW), equivalent to 39 feet 6 inches.
[5] 190 feet clearance under the "Bridge of the Americas".
[6] All analysis of vessel numbers, dimensions and other characteristics presented herein is based on LR data published by Sea-Web.

The relative importance of Panamax dimensions to the dry bulk trades can be clearly seen in these statistics. Panamax dimensions are used for ship types much wider than this, however. Of 9,902 larger ships (over 20,000 GT) delivered since the start of 2000, 4,470 (45%) have had Panamax beam. The range of ship types adopting Panamax beam is illustrated in Table 8, based on ship deliveries between 2007 and 2009.

| **Ship type** | **No. ships** |
|---|---|
| Bulk Carrier | 526 |
| Container Ship (Fully cellular) | 305 |
| Chemical/Products Tanker | 276 |
| Products Tanker | 167 |
| Vehicles Carrier | 124 |
| Crude/Oil Products Tanker | 53 |
| Wood Chips Carrier | 24 |
| Open Hatch Cargo Ship | 20 |
| LPG Tanker | 10 |
| Passenger/Cruise | 9 |
| Replenishment Dry Cargo Vessel | 7 |
| Crude Oil Tanker | 3 |
| Bulk Carrier, Self-discharging | 1 |
| Crane Ship | 1 |
| FSO, Oil | 1 |
| Fruit Juice Tanker | 1 |

Table 8: Ships with Panamax beam delivered 2007 to 2009[6]

The Panama Canal Authority's 2010 Annual Report reveals that 49.5% of oceangoing transits over the year were by Panamax vessels, that is to say by the largest size of vessels that can currently pass through the Canal. The number of Panamax transits has increased by almost 60% since the mid-1990s, as shown in Figure 1, providing further impetus for the expansion.

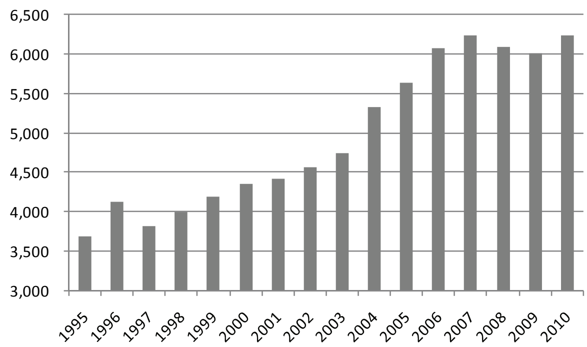


Figure 1: Number of Panamax vessel transits through the Canal (by financial year) [11]

## 4. HOW WILL THE EXPANSION OF THE CANAL AFFECT TRADING PATTERNS?

The short answer to this question is that it has not been possible to predict in advance. In an article published in Fairplay magazine ("The Post-Expansion Puzzle") on 1st July 2010 [12] the magazine states that "it is far too early to know how box carriers will reroute after the new canal debuts" and presents a number of conflicting views as to what may happen depending on assumptions on port limitations, demand growth and other variables. It appears pretty certain that container trades will grow but in what form it is not possible to say in definitive terms at present.

The implications for bulk carrier trades are even less certain and there are a number of key unknowns that make predictions difficult. Chief amongst these are the following.

- What will the cost of transit be? This clearly has a significant effect on the decision whether to route through the canal or around the Cape.
- How will demand for bulk shipping and fleet supply develop? The opportunity to add new capacity through the introduction of new large ships is constrained by existing committed capacity (see Table 7).
- What will fuel price and newbuilding price be? These two variables have a significant effect on the economy of scale that can be achieved by introducing larger ships and both are volatile. For example the price of a Panamax bulk carrier fell from a peak of \$55 million in 2007 to \$34.5 million at by mid-2010. [13]
- How well will infrastructure support the introduction of larger vessels?

Ultimately the market will decide by ordering new ships. Recent ordering statistics have shown an increase in demand for a new class of ship currently designated by the industry as "Mini-Cape" sized vessels, too large to transit the canal but smaller than the current Capesize class, which is typically around 160,000 dwt. The increase in the fleet and the distribution of size are shown in Figures 2 and 3.

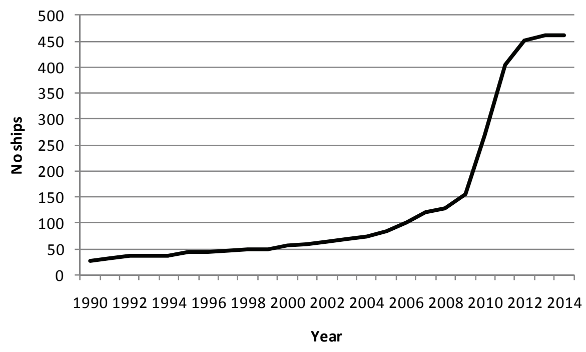


Figure 2: Growth in the "Mini-Cape" fleet sector[6]

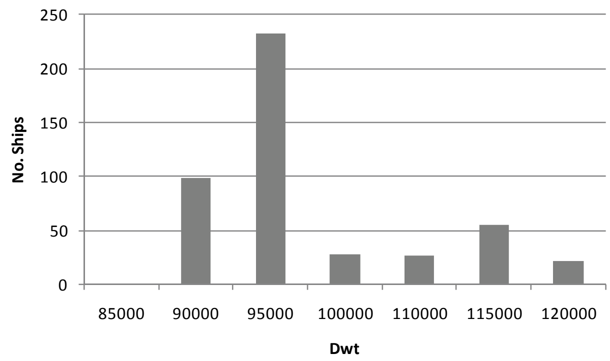


Figure 3: Distribution of size of "Mini-Cape" ships[6]

It can be seen from figure 2 that the fleet of Mini-Cape vessels is set to treble in terms of numbers of ships between 2009 and 2014. These ships are examples of "early adopters" in the new post-expansion Panamax dry bulk sector.

## 5. THE ECONOMIC CASE FOR LARGER BULK CARRIERS

### 5.1 OVERVIEW

It is almost axiomatic that ships get larger over time, although occasionally the reverse happens as with very large tanker sizes in the 1980s [1]. Buxton states that "a view on future size trends depends on ones view of the causative factors". Ten possible causative factors are listed in Buxton's paper, of which one, "substitution for older type" applies in this case. The relaxation of the Panama Canal's constraint isn't in itself going to generate any new bulk trade, although it may lead to some modification of trading patterns. On this basis the development of a new Panamax class may be relatively slow, given that capacity for the new ship type may be generated by relatively modest trade growth and substitution for ships in a fleet sector that is relatively modern: almost 60% of the existing fleet is currently on order as shown in Table 7.

The choice of class of bulk carrier (Handymax, Panamax or Capesize) is determined "principally according to the commodity shipped, the length of the trade route and the depth of water in the ports served" [14]. In summary iron ore and coal tend to be carried in Capesize parcels and all other bulks (grain, bauxite and so on) tend to be carried in Panamax or smaller parcels. Substitution is possible between cargoes in the upwards direction, however, that is to say Panamax ships can carry Capesize cargoes but the reverse is not generally true. This is termed "intra-marginal substitution" by Engelen and Dullaertzx: "Capesize can not enter all ports due to draft restrictions" but "most ports can receive Panamax vessels". The resulting conundrum for ship owners is that they can obtain a lower unit cost with Capesize ships but they tend to be inflexible and this does not therefore tend to lead to improved profitability for Capesize vessels. Panamax vessels, on the other hand, can be more flexible between trades conferring better access to cargoes[7].

For this reason the demand for smaller ships is not likely to disappear with the relaxation of the Panamax constraint. The question is, however, are class sizes likely to be optimised upwards to take advantage of the relaxation and, if so, by how much?

### 5.2 THE PARCEL SIZE DISTRIBUTION FUNCTION

Ship size categories are not random; they develop to accommodate the size and type of cargo parcels that shippers want to transport. This can be examined through analysis of the Parcel Size Distribution Function (PSD) [15]. This examines the size of shipments fixed in the charter markets. A review of how the PSD has developed in the dry bulk sector is shown in Figure 4, comparing spot market dry bulk fixtures in 2008/9 with fixtures in 2001/2[8].

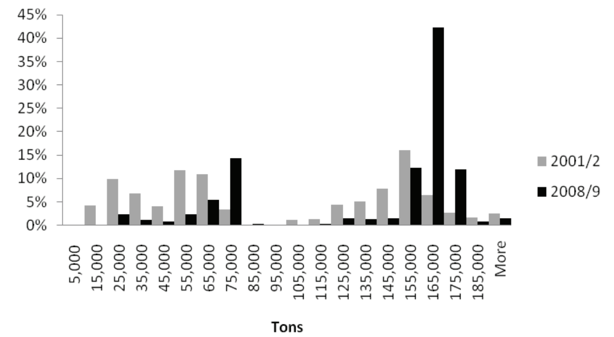


Figure 4: Development of dry cargo PSD (proportion of number of spot market fixtures recorded by Clarkson)

The two parts of the distribution represent the market for parcels below 85,000 tonnes (including Panamax, Handymax and Handysize cargoes) and the market above 85,000 tonnes (Capesize cargoes). A number of trends can be seen in this comparison:

- Capesize cargoes have increased in importance over the past decade.
- The size of Capesize cargoes has increased, peaking now in the range 155,000 to 165,000 tonnes as opposed to 145,000 to 155,000 tonnes in 2001/2.
- The spread of Sub-Panamax parcels has reduced and skewed significantly towards the upper end of the Panamax sector.
- The peak of Panamax parcel sizes has increased from between 45,000 and 65,000 tonnes previously to concentrate in the 75,000 to 85,000 tonne range currently.

The implications of the changes in the Sub-Panamax sector are that parcel sizes are now skewed towards the maximum size that the Panama Canal can accommodate suggesting that further increases in parcel sizes are constrained by the Canal. This, coupled with the increasing use of Capesize rather than Panamax or Sub-Panamax vessels, strongly suggests that there is pressure from the market for parcel size in the Panamax sector to increase.

### 5.3 ECONOMY OF SCALE

The underlying reason for increasing ship size over time is found in the sea transport unit cost function [15]:

$$\text{Unit cost} = (LC + OPEX + CH) / PS$$

In this equation LC represents the capital cost of the ship, OPEX the operating costs, CH the cargo handling costs and PS the parcel size. As Stopford states "The unit cost generally falls as the size of the ship increases because capital, operating and cargo-handling costs do not increase proportionately with the cargo capacity".

The change in capital cost of dry bulk carriers with size is shown in figure 5, showing prices per dwt at the peak of the market in 2007 and prices prevailing in 2010.

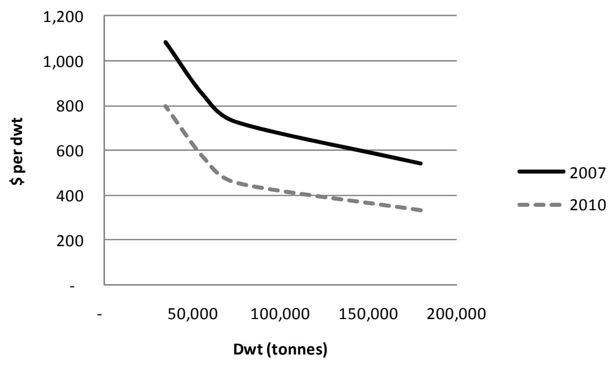


Figure 5: Newbuilding price for dry bulk carriers [13]

On this basis the unit capital cost of a 110,000 dwt vessel is about 11% lower than an 80,000 dwt vessel, assuming 110,000 dwt to be a possible typical size for a post-expansion Panamax ship.

The most significant difference in operating costs will be felt in Fuel. Figure 6 shows the change in fuel consumption of modern dry bulk carriers (post-2005 build only) as size increases.

[7] This flexibility may be reflected in freight rates. The average earnings for trip charters at 04.03.2011 was $5,500 per day for a capesize compared to $15,900 for a panamax bulk carrier. [Clarksons "Shipping Intelligence Weekly" 04.03.2011]

[8] Sourced from Clarkson's Shipping Intelligence Network, http://www.clarksons.net/sin2010/

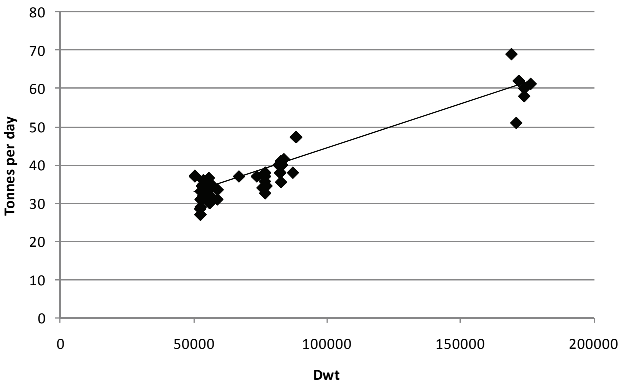


Figure 6: Total fuel consumption of modern dry bulk carriers[6]

This data suggests that the fuel consumption for a 110,000 dwt ship is around 43.4 tonnes per day, equivalent to 0.39 kg/dwt/day compared to around 0.47 kg/dwt/day for an 80,000 dwt ship, a reduction of 16% in the larger ship.

The importance of these cost elements will change over time and will obviously be more significant when capital costs and fuel costs are high. Assuming the analysis of daily running costs given as an example by Stopford [15] an approximation can be given of the effect of the improvement in capital and fuel costs as shown in Table 9.

| | 80,000 dwt | 110,000 dwt |
|---|---|---|
| Operating costs | 0.14 | 0.14 |
| Maintenance | 0.04 | 0.04 |
| Fuel costs | 0.30 | 0.26 |
| Other voyage costs | 0.10 | 0.10 |
| Capital costs | 0.42 | 0.37 |
| Total | 1.00 | 0.91 |

Table 9: Example of potential reduction in unit cost due to an increase in Panamax size

On this basis the unit cost reduction is 9% and this suggests, as with the parcel size evidence, that economy of scale will also tend to a larger size of bulk carrier following the relaxation of the Panama Canal constraint.

## 6. INFRASTRUCTURE

### 6.1 THE IMPORTANCE OF INFRASTRUCTURE

The development of new ship types is a function not only of the market demand for larger ships but also the capability of shore-side facilities to accept larger ships, the latter factor acting to some degree as a brake on the speed of development. Shore-side facilities include both port facilities for loading and discharge and drydocking facilities for maintenance. These two key facilities are examined below.

### 6.2 PORT INFRASTRUCTURE

The loading and discharge ports used in the Panamax trades are widely spread. Based on analysis of ports named in Clarkson fixture reports in 2008 and 2009[9] around 112 separate loading ports and 117 separate discharge ports are noted for bulk cargoes. A relatively small number of ports dominate, with 13 discharging ports and 15 loading ports accounting for 50% of the total weight of bulk cargoes included in the database. Some of these ports can handle capesize tonnage but many are restricted to Panamax dimensions or smaller. This includes some of the larger (in terms of quantity handled) ports such as Mobile, Kamsar, Samarinda, Ghent and Ijmuiden. For ports that can handle larger ships, such as Kaoshiung, Rotterdam, Dunkirk, Hampton Roads and Richards Bay, Capesize berths make up only part of the capacity to handle bulk cargoes and smaller ship visits will inevitably continue to be important to maintain throughput, at least until infrastructure developments take place.

It may be concluded that the need for development means that port infrastructure will act to some degree as a brake on the development of the mini Cape fleet, with port constraints acting to reduce owners' potential to take advantage of increased economies of scale. It does not necessarily follow, however, that development in bulk terminal infrastructure will be an inevitable consequence of the potential for larger ships afforded by the canal expansion.

Further review of terminal data [16] reveals that above Panamax size there is no coherence between terminals that will lead to a single optimum Mini-Cape-sized ship, unlike the rigid constraints that led to the emergence of Panamax vessels. A spectrum of ship sizes, as seen in the distribution presented in Figure 3, is likely to emerge, to suit the specific requirements of trades. In the bulk carrier sector, therefore, there is unlikely to be a single class of ship, the "New Panamax" bulk carrier, which will emerge in response to the relaxation of the canal constraint. Within this spectrum it is likely that sub-classes may develop to serve specific trades. A good existing example is the existing "Kamsarmax" sub-class of bulk carrier designed to transport bauxite from the port of Kamsar in Guinea. Limitations in the port permit a slightly longer and deeper version of what would normally be regarded as Panamax, with dimensions 229m x 32.26m x 14.4m ($L$x$B$x$T$) [17].

In the bulk sector it is most often draft that restricts port entry and, on this basis, naval architects may see some scope in maximising volume by increasing beam whilst maintaining draft at lower levels. This should be done with caution, however, in particular due to restrictions in

[9] Sourced from Clarkson's Shipping Intelligence Network, http://www.clarksons.net/sin2010/

drydocking capacity discussed in the next section of this paper.

### 6.3 DRYDOCKING INFRASTRUCTURE

An assessment has been made of drydock capacity for Panamax and larger ships, in terms of number of drydocks (floating and graving docks) available for repair in 2011 [18]. A total of 550 drydocks capable of stemming panamax vessels or larger has been analysed[10]. The distribution of dock width is shown in figure 7.

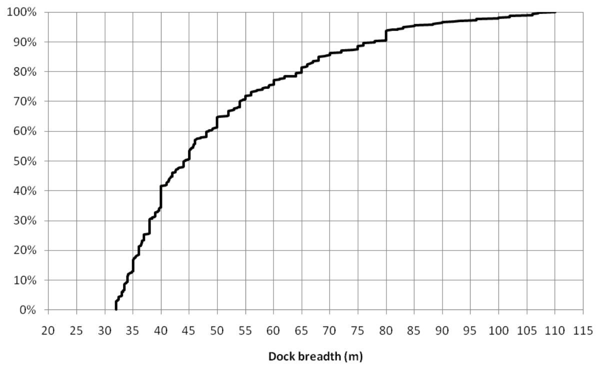


Figure 7: Distribution of dock width over 32m

"Conventional" panamax docks can be seen on the steepest part of the curve, between 32m and 40m. A minimum of 1m clearance either side of the ship would normally be regarded as the requirement for working space around the ship, although ships can be "squeezed" into docks if necessary. It can be seen from Figure 7 that a ship requiring a drydock greater than 40m width (that is for a ship greater than about 38m beam) the available docking capacity is around 40% less than for conventional panamax vessels and for a beam of 43m (requiring 45m dock width) the available dock capacity is halved.

Restriction of dock capacity will have an impact on drydocking costs. An enlarged Panamax vessel will be committed to competing for dock space with much larger, and for the shipyard more lucrative, ships. The revenue that a shipyard can earn per day of dock occupancy will typically be 10% to 25% higher for a large tanker (aframax, suezmax, VLCC) when compared to a large bulk carrier (Panamax or Capesize). Shipyards will inevitably choose the higher value vessels where available and the competitive position of the bulk carrier will be weakened.

Analysis of docking capacity by region, Table 10, suggests that the issue will be greatest for ships operating in the Baltic Sea and Mediterranean. For ships confined to those waters the availability of capacity for drydocking above Panamax size is limited and increase of beam above 32.2m should be very carefully considered. For vessels trading East, on the other hand, and in particular trading within the vicinity of China, the limitations are slight.

[10] Docks over 180m length and 32m width have been included in this analysis.

| | Total no. Drydocks | Panamax | Post-panamax |
|---|---|---|---|
| China Sea | 197 | 39% | 61% |
| Atlantic Ocean | 147 | 56% | 44% |
| Mediterranean | 97 | 67% | 33% |
| Indian Ocean | 55 | 49% | 51% |
| Pacific | 44 | 50% | 50% |
| Japan Sea | 36 | 39% | 61% |
| Baltic Sea | 39 | 72% | 28% |
| Black Sea | 19 | 53% | 47% |
| Arabian Sea | 5 | 20% | 80% |
| Great Lakes | 2 | 50% | 50% |
| Arctic Ocean | 2 | 50% | 50% |

Table 10: distribution of larger drydocks by region

For dry-dock designers the decision on what beam limitation to set depends on the type of dry-dock. For steel floating docks where the design life would typically be expected to be around thirty years (although much older docks remain in use) the maintenance of the existing Panamax capability could be justified, given the likely persistence of Panamax ships in the fleet for the next twenty five to thirty years at least. For graving docks, however, where the design life will typically be expected to be between fifty and one hundred years, the existing Panamax constraint may be regarded as obsolete and New Panamax dimensions are more appropriate for dock design.

## 7. DESIGN IMPLICATIONS

### 7.1 DIMENSIONS AND KEY RATIOS

Removal of the beam constraint will clearly allow naval architects more freedom in choice of key dimensional ratios for vessels around the limiting size. The existing Panama Canal beam and draught constraints limit the design deadweight for dry bulk carriers to around 80,000 to 85,000 tonnes. To achieve the displacement required for vessels approaching this limit, length has to be increased resulting in a length to breadth ratio, $L/B$, of typically 6.75 to 7.1. For a beam of 32.2m this results in a length between perpendiculars of typically around 225 to 229 m. This is well within the length constraint set by the existing Panamax limits but is constrained by stability and strength considerations. The required displacement is also achieved by maximising block coefficient, $C_B$. In keeping with the beam and draught constraints the breadth to draft ratio, $B/T$, is typically 2.2 to 2.7.

If these values are compared to Capesize vessels, where no such constraints apply, then corresponding ratios of between 6.0 to 6.5 for $L/B$ and 2.5 to 3.2 for $B/T$ are common. In some instances at the lower end of this size class designs have an *L*/*B* ratio as low as 5.5 with a corresponding increase in the *B*/*T* ratio to achieve the design deadweight. This is not simply a function of size however, with Handysize and Handymax vessels (20,000 to 55,000 tonnes deadweight) having very similar dimensional ratios to the unconstrained Capesize vessels. The variation by class of ship is shown in Figure 8 and Figure 9.

Relaxing the beam constraint will allow vessels of the existing typical Panamax deadweight to be achieved with different and generally more conventional dimensional ratios, in addition to facilitating larger ships. The release of the beam constraint allows the *L*/*B* ratio for ships in this size range to reduce to a more contemporary value, namely providing the ability to carry more deadweight through increased beam rather than length, which is a more cost effective means of doing so even if not required for stability purposes. Of particular interest is the cluster of vessels in the new Mini-Cape deadweight range that have a beam of between 36.5m and 43.0m. The reason for this upper constraint, 6m less than the new Panamax limit, is not clear but may simply be a consistent with an appropriate design solution for vessels of this deadweight and possibly also reflecting production constraints in the producer shipyards. It is also apparent that the largest of these vessels also approach the new Panama Canal draught constraint of 15.2m but that some classes have a reduced operating draught to a level comparable to existing Panamax ships or even less. This dimensional data is shown in Figures 10, 11 and 12.

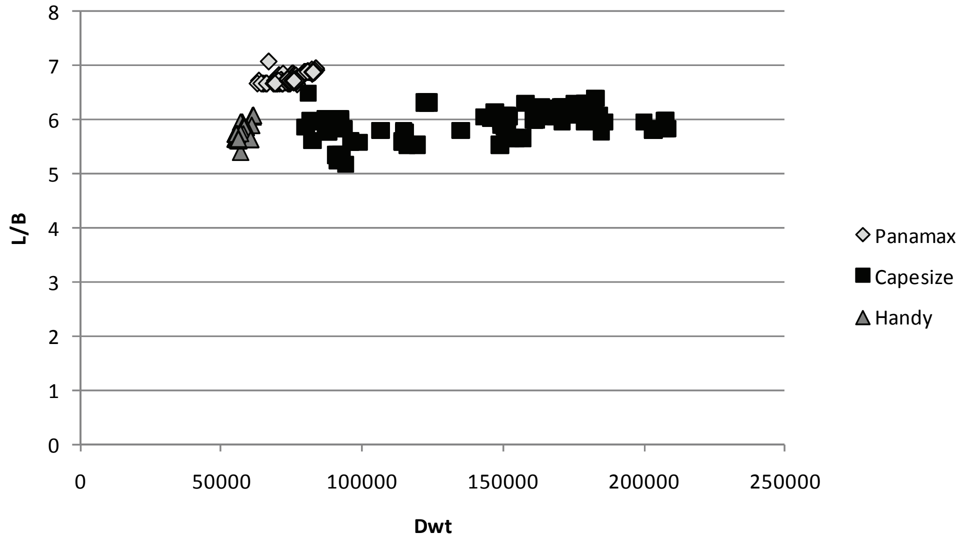


Figure 8: Length to Beam ratio for modern bulk carriers[6]

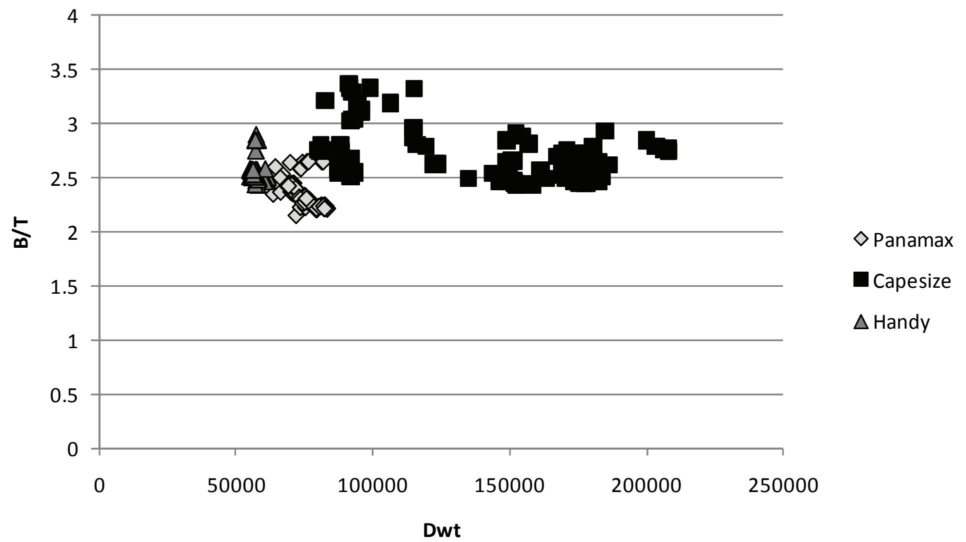


Figure 9: Beam to Draught ratio for modern bulk carriers[6]

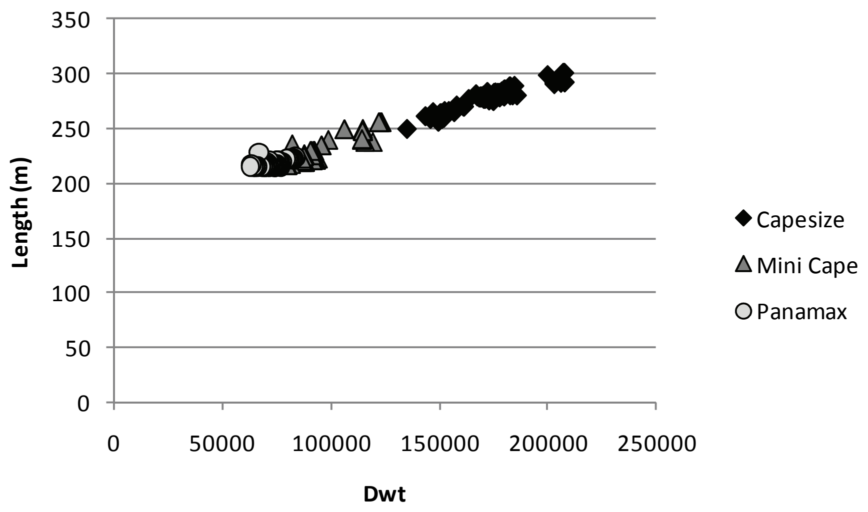


Figure 10: Distribution of Length of modern bulk carriers[6]

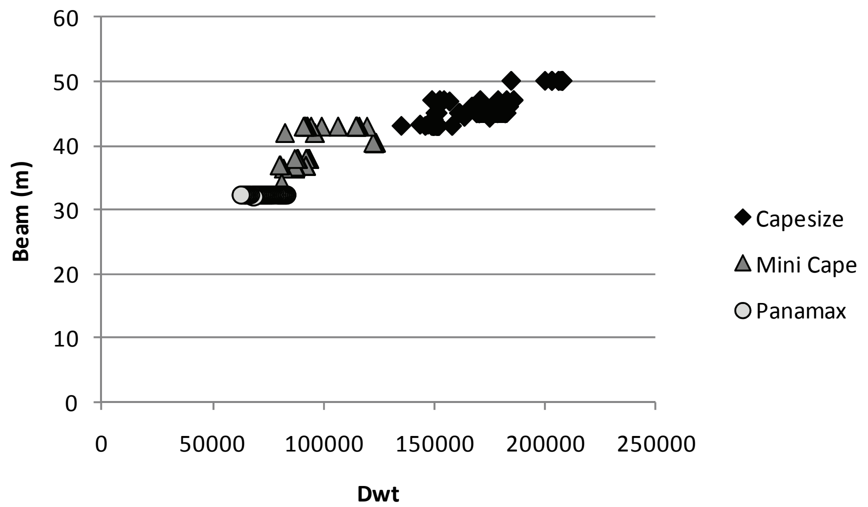


Figure 11: Distribution of Beam of modern bulk carriers[6]

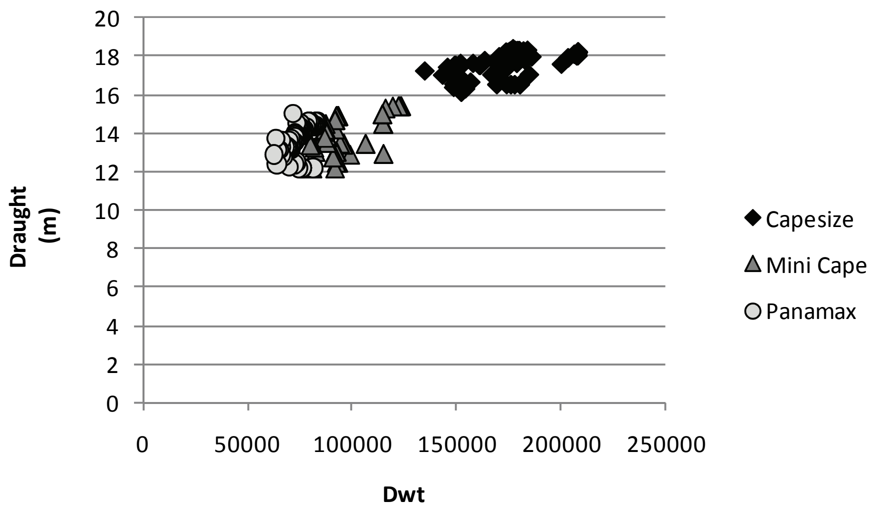


Figure 12: Distribution of Draught of modern bulk carriers[6]

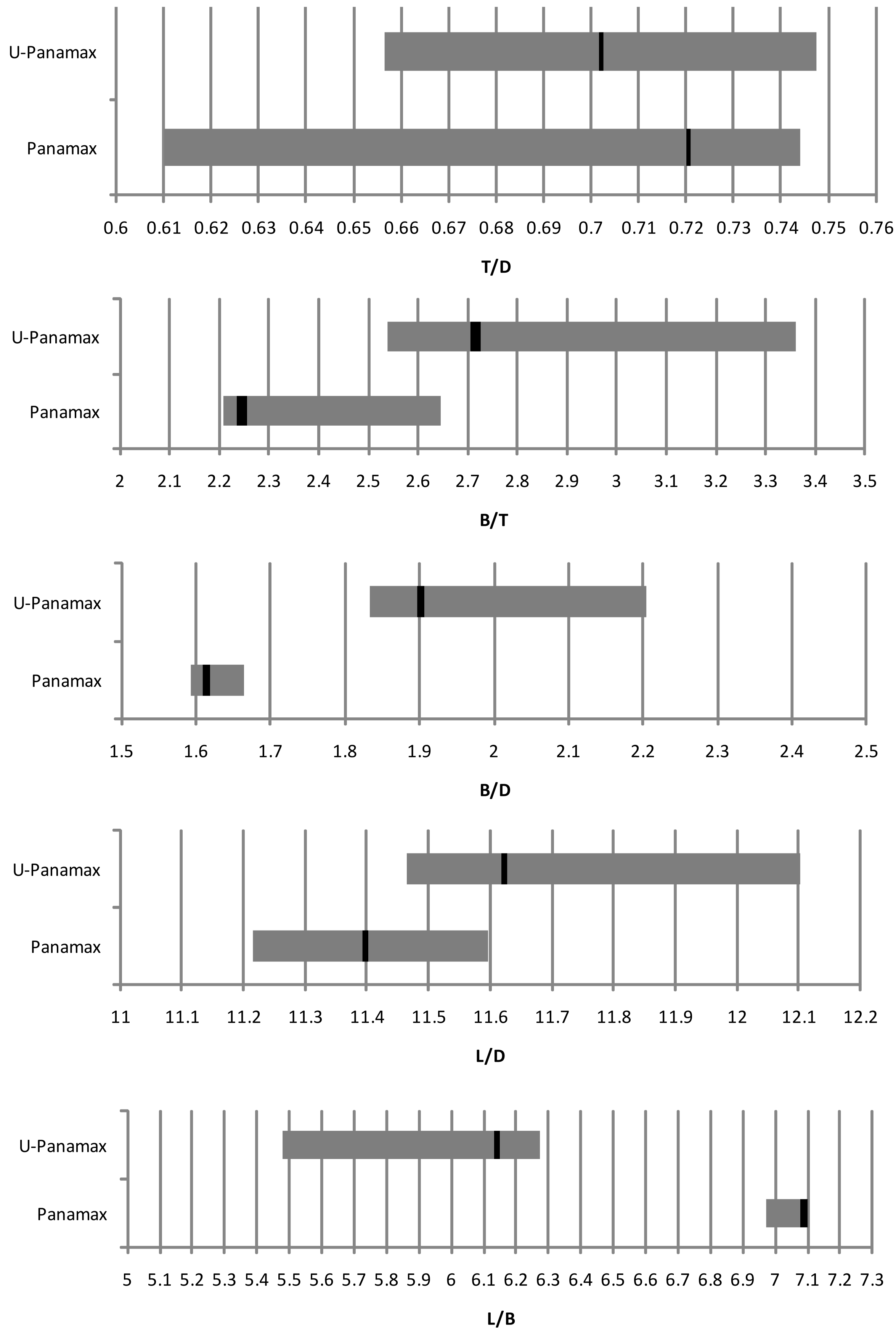


Figure 13: Changes in key ratios reflecting the relaxation of the constraint in the Panamax bulk carrier sector[6,11]

[11] The range of values in the sample is represented by the bars and the average value by the black lines

 

The influence of the relaxation of the beam constraint is of greatest significance for ships at the bottom end of the new Mini-Cape class where it overlaps with the Panamax sector at a deadweight of around 85,000 tonnes. This is effectively the unconstrained version of the traditional Panamax[12] class of ship whereby increase in displacement is achieved predominantly by increasing beam with only a modest change in length, up to only 236.0m in the longest case with potentially more flexibility in terms of block coefficient selection. Analysis of this sector enables the effects of the relaxation of the constraint on hull form and performance to be isolated from the additional effects of increased deadweight with larger Mini-Capesize ships. In the analysis below these unconstrained vessels are referred to as "U-Panamax".

Figure 13, summarises the dimensional ratios observed in a sample of 223 recent (built since 2000) bulk carriers between 80,000 and 90,000 deadweight, divided into traditional Panamax (155 vessels) and U-Panamax (68 vessels). Analysis of the implications of these changes is presented in Section 7.2

## 7.2 IMPLICATIONS OF THE CHANGES IN RATIOS

It is of interest to give a broad appreciation of the influence of these changes in dimensional ratios with respect to ship cost, performance and operation; the principal interest being resistance and propulsion given that most other performance criteria, such as stability and strength, are likely to be equally met by both designs.

### 7.2(a) Influence on first cost

The observed values of $L/B$ and $B/T$ all fall within generally accepted values, such as those given by Watson [19]. It is worth noting the influence that length has on the first cost, however. Fisher [20] estimates the relationship between a 1% change in principal dimensions and block coefficient with the percentage change in capital cost. The order of the influence of length, beam, depth (draught) and block coefficient is the same as that noted by Watson. Namely that as a means to increase deadweight and displacement, increasing beam is a cost effective course where draught and fullness cannot be increased further.

The depth in the U-Panamax designs remains largely unchanged. The $L/D$ ratio is increased slightly in the case of the largest beam designs due to the increase in length. As the design bending moment will be slightly increased due to the length and displacement increase in these designs there is a slight increase in the steel mass and lightships that results in a marginal reduction in deadweight displacement ratio, $K_d$, from 0.87 to 0.86 from the data collected; especially as the increase in beam also provides a less structurally efficient value of $B/D$. This has attendant implications for first cost.

### 7.2(b) Influence on stability

From a stability perspective if the draught is restricted then the beam is normally larger than would otherwise be required so bulk carriers tend to have higher stability than required due to other design considerations. It is worth noting that for an increase in beam for the same depth then there will be a reduction in the angle at which deck edge immersion occurs with a corresponding reduction in the angle of maximum righting lever, $GZ$, but that the increase in beam will have the benefit of increasing the transverse metacentre, $KM_T$, and initial stability even if the range of stability is reduced.

The modest increase in length will result in an increase in the required rule freeboard but U-Panamax ships, relative to Panamax vessels of similar size, exhibit a reduction in depth in order to meet this freeboard requirement as the design draught is reduced from around 14.5 to under 14.0 and as low as 12.8 m for the largest beam designs explaining the reduction in $T/D$ previously observed.

### 7.2(c) Influence on resistance and propulsion

Resistance is influenced by principal dimensions, form parameters such as $C_B$ and $LCB$, as well as more detailed issues regarding section shape and features such as bulbous bows. The discussion here is limited to trying to assess the influence of the noted changes to principal dimensions and form characteristics.

The value of circular M, or length to displacement ratio, $L/\Delta^{1/3}$ for both classes of ship is 5.0 which is consistent with the general guideline that there is no advantage to increase this quantity above 5.2 for $C_B$ over 0.75. The increase in beam results in reduced values of $L/B$ consistent with benefitting resistance at Froude numbers, $F_n$, around 0.15, where frictional resistance predominates, about 65% of total resistance, and residuary resistance accounts for the remaining smaller proportion of the total still water resistance, namely about 35% of total resistance. Therefore the reduction of wetted surface area afforded by a lower $L/B$ and a deep ship is of benefit. This is partly mitigated by an increase in $B/T$ that has generally a detrimental effect on resistance although the influence of changing $B/T$ in this range for fuller slower ships is less than for faster finer ships. For an average $B/T$ value of 2.4, an increase to around 3.0 would increase resistance in the order of around 3% for a full bodied ship with Froude number around 0.14 and $C_B$ approaching 0.85, so the increase in beam and reduction in draught observed is not beneficial. For lower $L/B$ ratios there would be expected to be a reduction in $C_B$ to compensate and if some of the data for U-Panamax vessels is studied then it does appear that the

[12] Panamax in this context referring to a specific size class of bulk carrier, rather than the limiting dimensions of the Canal.

block coefficient drops, reducing from an average value of 0.82 or more for existing Panamax ships to around 0.79 for the larger ships. This reduction in $C_B$ is likely to be of particular benefit in reducing the relative fullness of the aft lines so help to minimise regions of high curvature and so reduce separation resistance and potentially improve flow to the propeller disc as well as benefitting shipbuilding cost.

In combination with these influences on resistance it is interesting to also consider the corresponding influences on propulsive efficiency. Given that the influences on propulsive efficiency are complex and include the main characteristics of the propeller and blade section as well as the influence of aft body hull shape and local features on propeller–hull interaction [21] the discussion here will be again simply limited to the potential influence of the noted changes in main particulars.

Propulsive Efficiency, $\eta_D$ or *QPC*, is the product of Open Water Efficiency, $\eta_O$, Hull Efficiency, $\eta_H$, and Relative Rotational Efficiency, $\eta_R$. Open Water Efficiency depends on propeller diameter, pitch ratio ($P/D$) and propeller revolutions. Generally the larger the diameter with accompanying values of $P/D$ and propeller revolutions, the greater the value of $\eta_{O,}$ Propeller diameter is limited by draught and suitable propeller tip clearances. Where the draught is increased there is obvious benefit but, as has been noted, this is not always the case.

It is of interest to see the potential influence on the latter two terms, namely $\eta_H$ and $\eta_R$, as these are influenced by dimensions and form although there is uncertainty in their estimation.

Hull efficiency accounts for the interaction between the hull and propeller. $\eta_H$ is defined as $(1-t)/(1-w)$. Therefore to achieve beneficial values the Thrust Deduction, $t$, value should be minimised and the Taylor Wake Fraction, $w$, maximised.

With respect to $t$ as a consequence of the propeller's influence on the aft body, this is generally benefited by larger $L/B$ ratios and finer forms with the longitudinal centre of buoyancy, *LCB*, forward to improve the flow of water into the propeller. However, these requirements are difficult to meet with fuller ships but, with the reduction in $C_B$ suggested, such an approach might be available again in reducing the fullness of the aft body through moving *LCB* forward. The influence of $C_B$ is apparent as this is the parameter that most empirical estimates of $t$ are based upon, with reduction in fullness being beneficial. The estimation of $t$ proposed by Holtrop and Mennen [22] also includes the product of beam and draught and more beneficial values of $t$ are achieved by reductions in both. A reduction in propeller diameter is also beneficial and in the case of the larger ships with a reduced draught this will be the case but such a reduction will likely be outweighed with respect to loss in Open Water Efficiency, $\eta_O$, so may not provide benefit to the overall Propulsive Efficiency.

Similarly, a comparison of typical relationships for estimating $w$ show a dependence on $C_B$ with conversely beneficial values achieved as fullness, $V^{1/3}$ and $B/T$ increases. If again the formulae proposed by Holtrop and Mennen are considered, although these relationships are too complex to generalise, it is apparent that there is a further dependence on length and breadth with a reduction in $L/B$ being potentially beneficial. This is also suggested by Schneekluth and Bertram [23] where a reduction of propeller diameter in proportion to the draught is also beneficial. The complexity of the Holtrop and Mennen relationships reflect the influence of the detailed form of the ship, particularly the aft body lines and propeller clearance, have on the propulsion fractions which are therefore obviously not adequately represented by arguments simply based on simple main parameters. Hence it is difficult to suggest the overall influence of the parameter changes observed but it is likely that with form optimisation values of $w$ around 3 are likely to be achievable.

Relative Rotational Efficiency takes into account the difference between the propeller in the open water condition and when behind the ship. Relative Rotational Efficiency is benefitted by increased propeller diameter relative to length and with respect to increasing $C_B$, both of which may not be the case in the ships discussed. $\eta_R$ also increases with $L/\Delta^{1/3}$ and $B/T$ so some overall benefit is possible.

## 8. IMPLICATIONS FOR FUEL CONSUMPTION AND $CO_2$ PRODUCTION

It follows from the above analysis that the relaxation of the Panamax beam constraint will provide the opportunity to reduce fuel consumption and therefore make a contribution to the reduction of $CO_2$ production by shipping. This opportunity stems from two effects: firstly by virtue of the more efficient new hull forms (without the beam constraint) that are possible for the existing Panamax parcel size (around 80,000 to 85,000 tonnes) and, secondly, by virtue of the larger vessel sizes that may in future constitute the Panamax class of ship (section 5.3 above). These two effects are considered separately below. In making these estimates the methodology and consensus factors proposed in IMO's "Second Greenhouse Gas Study" have been used [24].

### 8.1 REDUCTION DUE TO IMPROVED HULL FORMS

As a simple key performance indicator, Table 11 shows the average total installed power per knot of service speed per deadweight for recent, built 2007 to 2010, Panamax and U-Panamax vessels in the 70,000 to 90,000 deadweight range.

| | Average Dwt | Average kW/knot/Dwt |
|---|---|---|
| Panamax | 78,910 | 0.00938 |
| U-Panamax | 86,896 | 0.00891 |

Table 11: Total installed power per knot per deadweight in modern bulk carriers[6]

In crude averages the new class permits 10% greater deadweight to be carried for a 5% reduction in powering requirements [13].

IMO undertook analysis of ships' operations to obtain data on actual service speed compared to design speed. For bulk carriers with a design speed of around 14 knots the actual service speed was found to be 12.8 knots. Assuming this service speed the required main engine power for the two ships listed in Table 11 can be estimated by multiplying the factor shown in the table by speed and deadweight, with the results for average ships as follows:

| | Average Dwt | ME Power kW |
|---|---|---|
| Panamax | 78,910 | 10,362 |
| U-Panamax | 86,896 | 10,839 |

Table 12: Estimated average main engine power for Panamax bulk carriers

The relationship between power and fuel consumption has been analysed using data from LR, as presented in figure 14.

The resulting estimate for fuel consumption and fuel consumed per tonne mile is shown in Table 13.

| | Average ME fuel consumption (tonnes per day) | Average fuel consumed per tonne mile (kg) |
|---|---|---|
| Panamax | 33.1 | 0.00125 |
| U-Panamax | 34.5 | 0.00118 |

Table 13: Estimated main engine fuel consumption for panamax bulk carriers

The resulting reduction in fuel consumption per tonne mile for the U-Panamax ship is 5.4%, achieved by virtue of the improved hull form.

The IMO estimated that bulk carriers of this class consumed 13.314 million tonnes of fuel oil for main engine power in 2007 and on the basis of the saving above the sector could have saved around 714,000 tonnes (5.4% of the total). The emission factor for the production of $CO_2$ proposed by IMO is 3.13 tonnes of $CO_2$ produced for every tonne of residual fuel oil burned and on this basis the amount of $CO_2$ that could have been saved over the year is around 2.23 million tonnes. This is equivalent to around 0.26% of the total estimated production of around 870 million tonnes $CO_2$ by international shipping over the year. Reduction in other pollutants will be pro rata according to their relevant emission factors [24]. This saving is from dry bulk carriers alone and it should be kept in mind that this is only one of a range of ship types constrained by Panamax beam, as discussed earlier in this paper. The total saving from all types due to improved hull forms is clearly likely to be considerably higher than this.

[13] Looking more closely the potential savings depending on the efficiency of design could be significantly greater than this. A more detailed study to confirm this finding is currently underway as well as assessing the implications with respect to the IMO Energy Efficiency Design Index, EEDI.

### 8.2 REDUCTION DUE TO INCREASED SHIP SIZE

The greater saving in dry bulk carrier fuel consumption will stem over the longer term from the potential to increase the average size of ships operating in this sector, as discussed in Sections 5.2 and 5.3 above. The 110,000 dwt vessel postulated as a future possible size of "Panamax" dry bulk carrier yields a 16% saving in ME fuel consumption per tonne mile over today's conventional Panamax. This would yield a saving of 6.7 million tonnes of $CO_2$ based on fuel used in 2007, around 0.8% of the total produced by international shipping over the year. Again this is the potential from the dry bulk sector only and other ship types will also yield gains.

### 8.3 TOTAL POTENTIAL CARBON SAVING

This is recommended for further study, taking into account all ship types and trades. Savings will stem in total from:

- improved hull forms for the ship types listed in Table 8, reducing fuel consumption;
- larger ships being deployed on the shortened route, reducing the carbon production per tonne-mile of cargo carried;
- Greater quantities of cargo moved through the canal, reducing the total tonne-mile sum in global trade.

## 8. CONCLUIONS

There are clear signs from the market that shipping advantage will be pursued in the dry bulk sector through increasing ship size. The relaxation of the beam constraint for bulk carriers transiting the Panama Canal presents an opportunity to construct larger ships with more efficient hull forms, gaining both economy of scale and significantly improved fuel efficiency.

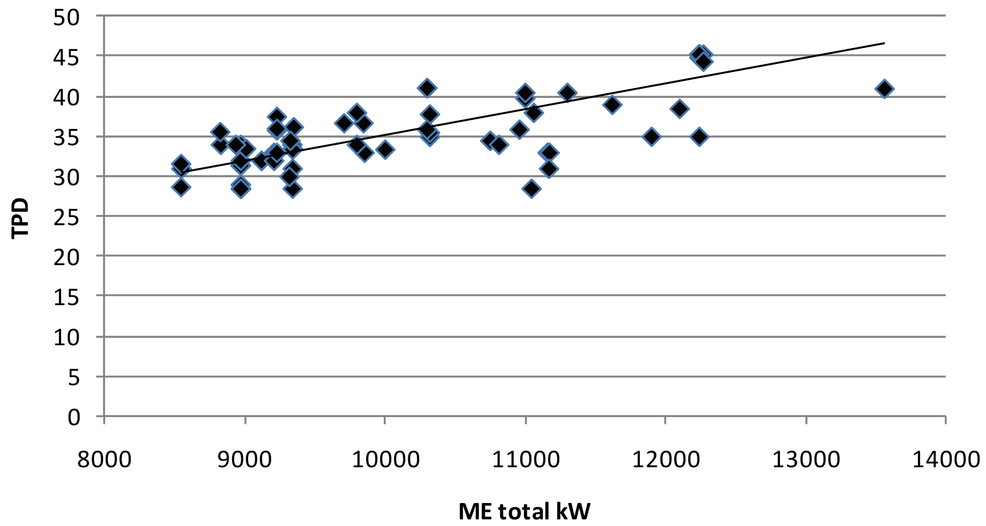


Figure 14: Fuel consumption (tonnes per day) against main engine power for modern[14] dry bulk carriers[6]

For handymax ships the market demand for the ship size remains, in particular for grain cargoes. The temptation to seek further commercial advantage through expansion of beam to achieve greater cargo volume should possibly be resisted, with ship repair capacity limitations providing a justification for the maintenance of the existing Panamax dimension even though the vessel's route may permit larger dimensions. Dry-docking a 65,000 dwt ship in a 300,000 dwt dry-dock is relatively inefficient and will be unattractive to shipyards where the option for larger ship dockings are available. This will have a time and cost implication for the owner, narrowing the range of possible repair locations. For ships in the larger Panamax sector the advantages of economy of scale and operation may offset the disadvantages of reduced choice of drydock location and increased drydocking costs, unless the ship will be operationally constrained to the Mediterranean or Baltic Seas, where the supply of docking capacity for larger ships is relatively limited. For drydock designers the existing Panamax constraint for dock design should be regarded as obsolete.

For the existing Panamax class of ships it seems inevitable that dimensions will increase over time to meet the new constraint but the dynamics of this development are uncertain. It is unlikely that a single coherent new class of bulk carrier, such as the existing Panamax class, will emerge, because of the specifics of trades and terminals. Change will also take time, given that there is a significant volume of "traditional" Panamax tonnage in process of delivery at the time of writing this paper and the Panamax fleet is relatively young. Increased capacity in the longer term, however, will inevitably be pursued through increased beam whilst preserving the draught requirements presented by many loading and discharge ports.

The ability to increase beam presents the opportunity to produce a lower first cost than is possible with the increase in length that is required for a conventional Panamax ship to maximise capacity within the beam constraint. It also presents the opportunity to reduce operating costs. A "Mini-Cape" vessel of around 85,000 dwt can offer on average a 10% increase in deadweight with a 5% reduction in power requirement compared to a traditional Panamax. A 110,000 dwt dry bulk carrier offers an estimated potential 9% unit cost reduction over a traditional 80,000 dwt Panamax ship.

Fuel consumption, and therefore $CO_2$ production, will benefit from the improved efficiency of hull forms that the relaxation of the beam constraint will permit. Capacity in Panamax vessels is achieved primarily by increasing length, which results in less efficient hull designs than could be achieved through increase in beam rather than length. The removal of the beam restriction will remove the need for this compromise in ship design. First estimates presented in this paper indicate a fuel saving of 5.4% due to the improved hull form. When combined with the potential to increase ship size it is estimated that a 110,000 dwt vessel offers a 16% saving in fuel per tonne-mile of cargo carried, and therefore pro rata saving in $CO_2$ production compared to a traditional Panamax ship.

The Panamax constraint has been applied far wider than in the dry bulk sector, however, and there is potential for carbon reduction in other sectors, through the optimisation of hulls that may previously have been

[14] Built after 2000.

constrained to 32.2m. Additionally to the above the expanded canal will permit a greater proportion of world trade to pass through the shortened route, reducing the total volume of sea trade in terms of tonne-miles, further reducing $CO_2$ production. This subject is recommended for further study to fully identify the carbon reduction windfall that may be generated by the Canal's expansion.

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