Economies of Scale in Large Container Ships

Kevin Cullinane and Mahim Khanna*

Abstract
Liner shipping has recently experienced a surprising expansion in the size of the largest container ship. This tendency towards breaching the previously existing size barrier is explained by the potential economies of scale that can be reaped from utilising such ships. Model outputs provide an insight into optimal container ship size. Suggestions are made concerning the optimal deployment of the current fleet of such vessels, likely future trends in container ship size and deployment, and the impact this will undoubtedly have upon container operations, logistical systems, and ports.

1. Developments in Container Ship Size
The revolution in ports brought about by containerisation has allowed liner shipping companies to take advantage of greater productivity in cargo handling. Only to a certain extent, however, have they reaped the economies of scale associated with ship size. The first container ships of around 4500 TEU\(^1\) were built in 1984. Thereafter, the largest size for a container ship remained at this level for almost a decade. Despite this moratorium on maximum ship size, the average size of container ships has increased continuously over the years.

McLellan (1997) and Cullinane and Khanna (1997) provide detailed analyses which suggest that, since early 1995, liner shipping has entered a new phase; container ships with capacity larger than 4500 TEU and other post-Panamax\(^2\) designs have been rapidly deployed and a significant number are under construction today. In terms of the conceptual framework developed by Hayuth (1987), this can be hypothesised as Phase III in the evolution of containerisation; as in Phase I, the focus is again technological advancement, but it is now specifically aimed at reaping greater economies of scale in ship size. In a series of interviews with eight of the major container lines (Maersk, NYK, NOL, MOL, COSCO, P&O, Hanjin, and CSC) the following emerged as the most quoted reasons for this phenomenon:

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\(^1\) Twenty-foot Equivalent Unit; a standard size of container used for denoting the container-carrying capacity of ships.

\(^2\) The economics of the liner trades in recent years has meant that ships of between 2,500 and 4,500 TEU are increasingly built for optimal performance rather than the ability to transit the Panama Canal.
(1) Gaining a competitive advantage through economies of scale in ship size and forcing competitors to react in order to combat this advantage.
(2) Bigger alliances have made such ships operationally viable.
(3) There is an expectation of future growth in container volumes as the result of increased trade of containerisable cargoes and of container penetration.
(4) Developments in and improvements to port infrastructure (especially greater depths and better cranes) have facilitated the use of bigger ships.
(5) In many cases, this is the time for replacing old tonnage and so all possible sizes are being assessed.

2. Objectives

As the interviews revealed, the fundamental reason behind the current trend towards increasing ship size in the container trades is based on the economic relationship summarised by Pearson (1988) as “irrespective of ship type, as the ship size increases the ship costs at sea per tonne or TEU decrease”. The overall efficiency of a ship undertaking a voyage is also, however, closely related to total time spent on that voyage. The relevance of this is that the cargo handling rate for container ships does not increase directly in proportion to increases in ship size. Therefore, as Jansson and Schneeboom (1987) point out, the use of larger container ships implies that “economies of ship size are enjoyed at sea and diseconomies of ship size are suffered in port” and that, given the current trend, companies making such investments believe that the former outweigh the latter.

By developing a costing model that seeks to quantify this trade-off, the objective of this paper is to develop a powerful quantitative tool for assessing the net private economic benefits of using larger container ships and, on this basis, to compare different sizes of container ships under a range of scenario inputs. The purpose of developing this sort of quantitative model is not, however, to derive absolutely accurate costs of container ship operation but, rather, to provide a tool for the relative assessment of cost differences between ships of varying sizes. An important characteristic of such models, therefore, is that they are internally consistent and produce outputs that are representative of actual costs rather than absolutely definitive.

3. Methodology

3.1 Conceptual model

As the objective of this study is to examine the impact of increasing ship size on operating economies, it focuses only on those costs that are a function of ship size. To understand the behaviour of such costs, it is necessary to identify the factor(s) which lead to a cost being incurred or to change and then to analyse the specific relationship between the factor(s) and the cost. For sea transport, two factors that exert a strong influence over costs are the time taken and the distance travelled on a voyage. Studying the variability of costs with respect to these specific factors can highlight the behaviour of ship-related costs over a range of ship sizes.
Although, as Ryder and Chappell (1979) have pointed out, container ship costs can be calculated in a number of ways, the approach adopted in this study revolves around the development of three submodels that yield the following outputs:

(1) Daily Fixed Cost per TEU.
(2) Cost per TEU-Mile.
(3) Total Shipping Cost per TEU.

The first submodel analyses cost variability in relation to time and provides an input into the second submodel, which assesses cost variability in relation to distance travelled. The third submodel uses the output from both previous submodels to develop a composite picture of the total cost of a voyage. A possible further extension in order to model “door-to-door” costs is inappropriate since the additional costs that such an approach implies are unaffected by economies of ship size in container shipping. Figure 1 shows how the cost model elements are linked together, and the measures that were taken to test their validity.

3.2 Operationalising the model

The use of actual empirical data for studying economies of scale in ship size suffers from two major shortcomings:

(1) Cost comparisons between different ship sizes is difficult. This is illustrated in the work of Lim (1994) who compared the costs of container ships of different sizes using actual cost data provided by an Asian shipping company and concluded that, due to the effect of variations in vessel specifications, operational standards, and accounting methods, there was no general solution to the ship size optimisation problem. To evaluate economies of size, therefore, one prerequisite must be to ignore cost variations that are not a function of size alone.

(2) Actual cost data is commercially sensitive and, as such, difficult to obtain. In any case, since this paper addresses the latest and potential future generations of large container ships that have not yet been deployed, actual cost data will not be available even to prospective owners of such tonnage.

In his pioneering investigation of the relationship between ship size and various cost elements, Thorburn (1960) proposes that the only feasible means of progressing is to build a quantitative model with what limited empirical data is available and then to supplement this with some generalisation. This methodology has been used in one form or another in several ensuing studies such as those by McKinsey & Co. Inc. (1967), Goss and Mann (1974), Ryder and Chappell (1979), Gilman (1980, 1983), Jansson and Shneerson (1987), Pearson (1988) and Talley (1990), most of which have focused primarily on liner shipping.

The model developed in this paper will draw on this body of previous work, synthesising relevant elements from each. In an effort to make the model more representative of present operating conditions in container shipping, however, for certain cost elements the chosen modelling methodology deviates from methods employed in the past. This is mainly necessary because the latest generation of vessels surpasses the maximum ship size considered in previous studies.
The major source of vessel data was the Fairplay computer database on CD-ROM (Fairplay, 1996). All vessels in the database classified as container ships having a capacity of more than 200 TEU, and which were delivered or under construction in the period between January 1995 and April 1996, were included in the analysis. This gave a total of 370 ships, including the twelve 6000 TEU vessels of Maersk lines. An advantage of this approach is that vessels of a similar age provide a comparable basis for cost evaluation, thus minimising the impact of intervening variables and supporting the objective of achieving internal consistency in the model.

3.3 Model assumptions
The two major physical constraints on containership size are port infrastructure and the availability of sufficient cargo to offer the desired frequency of service. In order to isolate and evaluate economies of scale in container ship size, however, these factors are assumed non-restrictive.
In the pursuit of parsimony, and as mentioned previously, only unit costs that are a function of ship size are included in the model. To this end, the following assumptions are made.

1. The deployment of larger ships is usually associated with lower service frequency and, in consequence, inventory size and associated total cost are likely to increase if improved service speeds do not fully compensate for this. However, despite constituting a significant proportion of the total cost of freight transport, since unit values are unlikely to be related to ship size (that is, to change with scale), costs associated with cargo handling, through transport, shore infrastructure, and container inventory are excluded from the model. This approach was also adopted in the studies of Thorburn (1960), Heaver (1968), Jannson and Shneerson (1987), and Pearson (1988).

2. Port entry charges (which include port dues, pilotage, towage, wharfage, and so on) are dependent on ship size and the amount of cargo handled. When they are assessed, however, on a “per TEU slot” basis there is little variation with ship size. In their analyses of ship size economies, Goss and Jones (1982), Thorburn (1960), and Pearson (1988) similarly chose to ignore these costs. While Jannson and Shneerson (1987) gave some small recognition to these costs, they too admit that they are relatively insignificant and could well be ignored.

In the evaluation of the costs of container ships larger than the currently existing size, it is assumed that the present technology, without major changes, can be extended to these ships. In support of such an assumption, Jannson and Shneerson (1987) extol the virtues of cost models based on ship size elasticities by stating that: “The ship size elasticities constitute ‘something to hold on to in a changing world’.” Our empirical results showed that the size elasticities found in shipping cost studies of quite different ages are of the same magnitude, which lends support to ... the relative constancy of size elasticities.”

A ship’s deadweight tonnage (DWT), that is, its cargo-carrying capacity in tonnes, is the principal measure of size for cargo ships. Jannson and Shneerson (1987) and Talley (1990), for example, used DWT as the basis for measuring container ship size. Ryder and Chappell (1979), Pearson (1988), and Lim (1994), on the other hand, used maximum TEU slot capacity as quoted by shipyards. The TEU measure of capacity is advantageous not only because costs can be disaggregated on a “per TEU” basis, but also because many costs are incurred on this basis. Although yard-denominated TEU slot capacity is the most frequently used basis for comparing container ship sizes, Meckel (1985) strongly criticises this practice because a ship’s carrying capacity, as determined by its TEU slots, may well be constrained by the highly variable influence of available DWT per TEU slot. Both he and Lloyds Shipping Economist (1996a) advocate using the nominal TEU (NTEU) measure of a container ship’s carrying capacity (and ultimately its slot costs), based on the standard assumption of 14 DWT per TEU. This standard is supported by the fact that the average payload per TEU is about 10 tonnes (Drewry Shipping Consultants, 1995), the tare weight of each container is about 2.3 tonnes, and some
part of the vessel’s total deadweight is allocated to bunkers, fresh water, spares, and supplies. A comparison of the NTEU of containerships is fundamentally, therefore, a comparison of DWT, except that a concept is used (that is, the number of containers that can be carried), which is much easier to relate to.

4. Disaggregate Model Components

4.1 Daily Fixed Cost per TEU

Daily Fixed Cost per TEU provides an aggregation of all time-related cost elements that would be incurred by the ship even while unemployed. The development of this sub-model begins with the calculation of the daily fixed cost per ship, which is found by summing the two components of Daily Capital Costs and Daily Operating Costs.

4.1.1 Daily Capital Costs

By applying a Cobb-Douglas function \( y = kx^e \), where \( e \) is the elasticity, Haldi and Whitcomb (1967) have calculated the elasticities of capital and labour costs in a wide range of industries. They found that the size elasticity of capital costs lay in the range 0.6 to 0.8, and that most of the calculated elasticities of labour cost were below 0.4.

In relation to the size elasticity of capital cost, by hypothesising that the capital cost of a ship is a function of area rather than volume, Thorburn (1960) obtains a result consistent with this:

\[
\begin{align*}
\text{Cost} & \propto \text{Surface area} \quad \text{and} \quad \text{Surface area} \propto \text{Volume}^{0.67}; \\
\text{Cost} & \propto \text{Volume}^{0.67} \quad \text{or} \quad \text{Cost} \propto \text{dwt}^{0.67}.
\end{align*}
\]

Subsequent studies have revealed only slight differences from this elasticity. Based on a sample of 50 observations, Jansson and Shneerson (1987), for example, derived an elasticity of 0.655 with an \( r^2 \) of 0.34.

Since data on post-Panamax container ships now exist, it is appropriate to retest the original Thorburn hypothesis and the findings of later studies, which have generally tended to substantiate it. Therefore the current value of the ship size elasticity of capital costs was calculated by applying linear regression analysis to estimate the model \( y = kx^e \). Data on 153 vessel new-building contract prices and associated NTEU were available within the Fairplay database. After appropriate diagnostic checking, the model derived is as follows:

\[
\ln (\text{Ship Price}) = 4.8097 + 0.759 \ln (\text{NTEU}) \quad r^2 = 0.93
\]

Functionally dependent on ship size, modelled new-building contract prices are converted into an annual capital charge by applying a capital recovery factor, which assumes that the life of the vessel is 20 years, the interest rate is 10 per cent, and the residual value is zero. Dividing the annuity value by 360 days gives a ship’s daily capital cost. This approach contrasts sharply with that of Talley (1990) who, in developing a cost component for his analysis, applies the mean contract price (capital cost) per DWT of two vessels, one large and one small. In doing so, however, the size elasticity of capital cost is ignored, and the vital effect of economies of scale in capital costs is lost.

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4.1.2 Daily Operating Costs

The problem of ascertaining the operating costs of container ships is a difficult one because of the non-availability and commercial sensitivity of the data. The fact that such costs vary considerably under different registers and regimes compounds the problem. Past studies have dealt with the estimation of operating costs in two principal ways. Using a database of Zim line ships, Jansson and Shneerson (1987) empirically calculated the elasticity of operating costs with respect to size as 0.43 ($r^2 = 0.41$). Heaver (1968) and Goss and Mann (1974) adopted a similar approach. Ryder and Chappell (1979), Gilman (1983), and Pearson (1988) adopt an alternative approach, whereby different discrete crew numbers are assumed for different ship sizes in order to determine crew costs and then, since they are logically related to it, 3 to 5 per cent of the initial capital cost is assumed as an approximation to total expenditure on repairs and maintenance, insurance, and administration. Given the comparatively poor explanatory power of the former approach, in this analysis the latter approach was adopted. The total annual cost of repairs and maintenance, insurance and administration is taken as 3.5 per cent of initial capital cost. This figure yields representative operating costs that compare favourably with published data. Crew costs are calculated on the basis of the representative monthly crew expenses published by Lloyds Shipping Economist (1996b) for a vessel of about 1500 TEU under an open flag. For this analysis, all vessels of 800 TEU and over are assumed to have a crew size of 24 with the cost as given by Lloyds Shipping Economist (LSE). Vessels between 500 and 800 TEU and below 500 TEU are assumed to have crew sizes of 20 and 16 respectively. Crew costs for these vessels are calculated on a pro rata basis with respect to crew numbers.

As shown in Table 1, the resulting modelled daily operating costs are comparable to those published by Drewry Shipping Consultants (1996) and Fearnleys (1996). Similarly, Figure 2 shows that when the LSE figure for the operating costs of a 1500 TEU ship is used as the base value, they are also in line with Jansson and Shneerson’s method of modelling operating costs by applying an elasticity factor of 0.43.

The daily fixed cost per ship is divided by the NTEU capacity to give the Daily Fixed Cost per TEU, a level of aggregation that facilitates a test of the validity of the computations through a comparison with actual empirical data. Since capital and operating costs are borne by the shipowner when ships are hired out under time charter, in a well balanced and competitive charter market this total cost should be closely related to time charter hire rates.

The modelled Daily Fixed Cost per TEU for a range of ship sizes are compared with representative time charter rates for gearless ships as reported by Mentz Decker & Co. (1996). In January 1996, the charter market for container ships was purported to be reasonably stable and well balanced. During this month, reported rates rose from US$ 8 per TEU for a ship of 3400 TEU to US$ 21 per TEU for a ship of 200 TEU. The modelled Daily Fixed Cost per TEU is very similar to these reported time charter rates, with the equivalent figures rising from US$ 7.9 per TEU for a ship of 3400 TEU to US$ 21.4 per TEU for a ship of 200 TEU. On this basis, therefore, modelled Daily Fixed Cost per TEU would appear to be quite representative of actual observed data.
Figure 2
A Comparison of Modelled Estimates of Operating Costs

Table 1
A Comparison of Sample Modelled and Published Operating Costs per TEU

<table>
<thead>
<tr>
<th>TEU Capacity</th>
<th>Modelled Costs in US$ per Day</th>
<th>Published Costs in US$ per Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>600 TEU</td>
<td>3258</td>
<td>3000 (Fearnleys)</td>
</tr>
<tr>
<td>2440 TEU</td>
<td>616</td>
<td>6000 (Drewry's)</td>
</tr>
<tr>
<td>2500 TEU</td>
<td>6596</td>
<td>6500 (Fearnleys)</td>
</tr>
</tbody>
</table>


4.2 Cost per TEU-Mile
The time-related cost of a ship, encapsulated in the Daily Fixed Cost per TEU, is a useful measure but does not account for the transport capacity and the fuel costs at sea. By additionally including the fuel costs incurred during the sea voyage and comparing transport cost over a given distance, it is possible to gauge transport efficiency over a range of ship sizes. The Cost per TEU-Mile is calculated by adding the Daily Fuel Cost per TEU for a ship of a given size to its Daily Fixed Cost per TEU and then dividing by the Daily Distance, which is, of course, a function of service speed.

4.2.1 Daily Fuel Cost per TEU
Economies of scale in fuel consumption are enjoyed because of the physical property that the water resistance on a ship’s hull does not increase at the same rate as the volume of the hull. Thus, at any given speed, the horsepower requirement of the engine is less than proportional to ship size.
In marine engineering, the specific fuel oil consumption (SFOC) and the installed power of a ship’s engine are assumed to be proportional, with the former measure signifying the efficiency of the engine. Pearson (1988) used a figure of 120 grams per brake horse power hour (gms/bhphr) for calculating fuel oil consumption, and emphasised the improvement that had taken place since the late 1970s when a typical SFOC was 150gms/bhphr. In accordance with information derived from the Institute of Marine Engineers (1994), and *The Motor Ship* (1995 and 1996), an average SFOC of 125 gms/bhphr has been used in this study.

If, like Pearson (1988), we assume an 80 per cent utilisation of power to achieve designed service speed, daily fuel oil consumption (FO) in tonnes can be ascertained from bhp and SFOC as follows:

\[ FO = \text{Installed bhp} \times \text{SFOC} \times \text{Utilisation (80\%)} \times 24 / 1000000. \]

The ship size elasticity of installed bhp was estimated through a regression analysis using data for the vessels in the Fairplay database. The resulting estimated regression model has an \( r^2 \) of 0.94 and takes the form:

\[ \ln (\text{bhp}) = 2.6308 + 0.967 \ln (\text{NTEU}). \]

The combined “at sea” and “in port” daily diesel oil consumption (DO) for auxiliary engines was assumed to increase in regular steps from one tonne/day for a ship of 200 TEU to four tonnes/day for one of 6000 TEU. This element was incorporated into the model as the result of interviews held with company representatives, but has proved to be of comparatively little significance. The consumption rate of lubricating oil by the main engine at sea is usually taken as 1 gm/bhphr which, according to Gilman (1980), means that the cost of daily lubricating oil consumption (LO) represents approximately 3 per cent of FO cost. Gilman (1980) and Pearson (1988) have adopted a similar treatment of DO and LO, whereas Jansson and Shneerson (1987) and Ryder and Chappell (1979) elect to ignore these costs. By summing the products of the daily consumption of each type of fuel with their respective unit price per tonne, the *Daily Fuel Cost* is obtained for any given size of ship which, when divided by the respective NTEU, yields the *Daily Fuel Cost per TEU*.

4.2.2 Daily Distance

Clearly, the distance travelled by a ship in a day depends on the speed of that ship, a characteristic that in turn may be closely related to ship size. According to a time-honoured rule of naval architects, the design speed of a ship will increase by the square root of the length of the ship if the block coefficient and the Froude number are held constant. This implies a size elasticity of speed of 0.167, a value adopted by Thorburn (1960) in his analysis. In many cases, however, the theoretical speed given by this relationship is not consistent with actual performance. For bulk vessels, for example, it has been found that average speed does not increase much with size though, according to Evans and Marlow (1990), it is not altogether clear why this should be so.

In order to determine whether this theoretical relationship is valid for ships engaged in the liner trades, Jansson and Shneerson (1987) applied regression analysis to data re-
lating to three different sets of general cargo vessels. They estimated that the size elasticity of design speed was between 0.16 and 0.17, with $r^2$ varying from 0.35 to 0.54.

In the absence of empirical data for the even larger container ships of the future, it is imperative that a reliable relationship is drawn between service speed and ship size, so that the design speeds associated with ship sizes that do not currently exist can be inferred from an extrapolation of this relationship.

In analysing the economies of size in container ships, Gilman (1980) took speed as a key variable, even for ships of the same size. In our analysis, however, variations in design speed for the same size of ship are not considered; instead standard vessels of different sizes are compared. Although they used the actual service speed of vessels in evaluating economies of size in bulk carriers, a similar approach was adopted by Goss and Jones (1982), who highlighted the complex nature of attempting to cater for variations in design speed for a given ship size. Moreover, small variations in speed for a given ship size do not have a significant impact on the overall cost per mile. This is because fuel cost and time-related costs move in opposite directions as speed changes. This proposition has received support from Pearson and Fossey (1983), who commented that “the cost curve with respect to speed is very shallow near its minimum point”. Similarly, Gilman (1983) has calculated that for a ship size of 1500 TEU, any speed in the range of 16.5 to 24.5 knots gives unit costs within 2 per cent of the minimum.

To test the validity of the hypothesised relationship between ship size and design speed for the purposes of this study, a regression analysis is applied to data contained in the Fairplay database. Out of a total database of 370 container vessels, design service speed was available for 280. The estimated model takes the form:

$$\ln(speed) = 1.5747 + 0.192 \ln(TEU).$$

The estimated elasticity of 0.192 has a high $r^2$ of 0.90, supporting the hypothesis that the speed of a container ship is closely related to its size, and suggesting that an estimated design speed for a standard vessel can be predicted fairly accurately simply on the basis of its size denominated in TEU. This high explanatory power contrasts most dramatically with the empirical testing of the size-speed relationship undertaken by Talley (1990) who found an elasticity of 0.09 with an adjusted $r^2$ of only 0.09. The database he used, however, consisted of just 36 container ships that visited a port during a set period of time. In addition, the inadequacy of the yard-denominated TEU measure of container ship size, and the variability in the age of the vessels and in the unit price of fuel during the 1980s, may all help to explain his result.

For voyage calculations in bulk trades, the theoretical distance to be covered in any voyage from origin to destination port is normally increased to allow for the effect of the weather conditions and currents encountered (Gorton et al., 1990). This is usually done by increasing the distance by a fixed percentage, say 5 per cent, or by adding an extra day to the voyage duration, which has been estimated purely on the basis of distance. In this study, to account for inevitable weather and hull conditions, 95 per cent of the design speed is taken as the vessel’s achievable average sea speed. On this basis, the Daily
Figure 3
Container Ship Size vs Design Speed and Cost per TEU-Mile

Table 2
A Comparison of Sample Modelled and Published Cost per TEU-Mile
(US Cents)

<table>
<thead>
<tr>
<th>TEU Capacity</th>
<th>As Modelled</th>
<th>Published</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>2750 TEU</td>
<td>2.30</td>
<td>2.32</td>
<td>Evergreen Lines</td>
</tr>
<tr>
<td>4458 TEU</td>
<td>1.90</td>
<td>2.70</td>
<td>US Lines — US Flag</td>
</tr>
<tr>
<td>3000 TEU</td>
<td>2.24</td>
<td>4.50</td>
<td>CSR Consultants</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(includes port entry and handling cost)</td>
</tr>
</tbody>
</table>


Distance that it is possible to travel can be estimated for any given size of ship, thus enabling the calculation of Cost per TEU-Mile.

The general shape of the curve for sea voyage costs for varying ship sizes is very similar to other studies of liner ship costs by Gilman (1980), Ryder and Chapell (1979), Pearson (1988), and Jansson and Shneerson (1987). A precise comparison of results is more difficult for two main reasons.

1. Most past studies are now quite old and are not, therefore, directly comparable with the present situation.
2. Most studies have not quantified sea voyage costs but have derived generic relationships. The work by Gilman (1980) is an exception, although comparison remains difficult because this study incorporated the extremely high fuel oil costs prevailing at that time.
Thus, a comprehensive comparison of modelled Cost per TEU-Mile, either with the results of previous research or with actual current observed data, is not feasible, although a comparison with some available published figures is given in Table 2. It should be noted, however, that only fuel costs have been added to the validated daily fixed cost of ships to obtain the voyage cost at sea. Fuel expenses are, in principle, based on engineering fundamentals, and thus cannot deviate much from actual figures. The modelling of a ship's bhp and service speed could influence the aggregated costs for a sea voyage but, as previously shown, these have been statistically derived and validated.

The benefits of scale economies while a ship is at sea follows the shape of a negative exponential curve, where marginal savings in unit costs reduce progressively with increasing ship size. Cost per TEU-Mile and ship speeds for different ship sizes are shown in Figure 3, which illustrates that, quite apart from being more economical (because larger ships are also faster) they are potentially capable of providing a better utilisation of assets, and also a better service, as long as reductions in service frequency associated with their deployment do not mitigate this marketing advantage. This is important, since it has been argued by Brooks (1990) that the criterion of transit time, although less important than the price and frequency of service, is the determining criterion for carrier selection when the other two (ostensibly more important) determinants are not differentiable. This suggests that, through the provision of a better quality of service, a competitive advantage exists that not only leads to greater market share and revenue earning, but also creates the demand and load factors necessary to allow the reaping of the lower unit costs associated with economies of scale.

4.3 Total Shipping Cost per TEU

The two measures of cost considered thus far have not taken into account the time a ship spends in port while engaged on a voyage. In fact, this is an important influence on total shipping cost and on the overall efficiency of the shipping service. By summing elements relating to the cost of time in port per TEU (a product of time in port in days and the Daily Fixed Cost per TEU plus a small allowance for in-port Diesel Oil consumption), and the cost of time at sea per TEU (a product of Cost per TEU-Mile and voyage distance), the resulting Total Shipping Cost per TEU provides a much more valid basis for the comparison of economies of scale due to varying ship sizes.

Jansson and Shneerson (1987) have demonstrated that the economies of scale in container ships are determined by trading off the positive returns to scale from ship size earned at sea (during the line-haul operation) with the diseconomies of ship size accruing while in port (during the handling operation). In carrying out such an analysis, they acknowledge, however, the difficulty of estimating a ship's time in port as a function of the port's cargo handling rate.

Thornburn (1960) reasoned that the handling rate is proportional to the length of the ship and, assuming that the principal dimensions of a ship (length, breadth, and depth) are in a constant ratio, then length $\propto dwt^{1/3}$. Thus:

- Time in port $\propto dwt$/handling rate, or $dwt$/length,
- $\propto dwt^{1/3}$
- $\propto dwt^{2/3}$ or $length^2$. 

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While Goss (1970) criticised both the generality and simplicity of this formula, Jansson and Shneerson (1987) estimated that the size elasticity of a ship's time in port lies between 0.7 and 0.8. They suggested that their results were inconclusive, as they contradicted those reported by Robinson (1978), who found that the turnaround time for bigger ships in the port of Hong Kong was faster than for smaller ones. This latter analysis, however, neglected to control for the effect of handling part, as opposed to full, cargoes. Similar research by Edmond and Maggs (1976) did not reveal any significant relationship between container ship size and turnaround time, but did highlight the significant difficulties in attempting to establish such a relationship that are brought about by influential factors such as tides, the weather, and, especially, sailing schedules. More recently, statistical tests conducted by Tabernacle (1995) revealed no relationship between vessel size and individual crane moves (that is, the rate of handling per crane is not a function of ship size), and that there is only a very weak correlation between ship size and time at berth.

This review of past research indicates that perhaps a formal specification of the ship size elasticity of turnaround time cannot be defined. In fact, due to improving terminal productivities, the results of past research on turnaround time could certainly not be relied on to meet the objectives of this study.

In the absence of suitable container terminal data, a questionnaire was designed and targeted at container terminals to determine the average number of cranes that were employed on ships of different size categories. This information, together with the figure for average crane productivity produced by Containerisation International (1994), could be used to determine the approximate time spent in port for ships of a given size.

All the major container ports in various geographical regions were identified and the questionnaire sent to the top two or three terminals in each of these ports. This process resulted in the questionnaire being sent to 43 terminals world-wide with a total of 14 valid responses received. These had a very wide geographical spread and included terminals in Europe, the Mediterranean, the Gulf, Asia, and the USA. The response rate of 33 per cent was considered encouraging in view of the sensitivity of this type of information. The number of respondents was also considered sufficient to gauge the variability of container ship time in port in relation to size. Most previous research has based the measurement of the relationship between a ship's size and turnaround time on only one terminal, and although such an approach will be more precise for the port in question, the method adopted within this study means that more representative results are likely to emerge.

As shown in Figure 4, the survey revealed that, on average, just over one crane is used for ships less than 700 TEU. Thereafter, the number of cranes used rises quite rapidly to about 2.6 cranes for a ship size of 1500 TEU, and then for larger ships the marginal increase in crane density (the number of cranes per ship) reduces progressively. This is explained by the fact that a ship's length does not increase much after this size.

Although crane productivity can vary considerably, Containerisation International has ascertained the approximate average measure of crane productivity in Asia and Europe as about 22 moves per hour (Containerisation International, 1994). This crane pro-
ductivity, together with the estimate of cranes used given a certain size of ship, were combined to calculate approximate time in port per voyage for cargo handling.

The results of the questionnaire and the calculation of total time in port for a voyage were compared with the actual time spent in port by the ships of a major consortium on the Europe-Asia run, and were also discussed with personnel from shipping companies and from terminals in the UK.

It emerged that this method of multiplying crane density and average crane productivity underestimates the time in port. Probable reasons for this discrepancy and the methods which the study adopts to account for it are as follows.

(1) The shipping company personnel interviewed were of the opinion that although the crane densities used were a good reflection of the number of cranes employed for 80 to 90 per cent of a ship’s cargo, because of an imbalance in the distribution of cargo onboard the ship, one last crane usually performed the remaining 10 to 20 per cent of the work alone. This was incorporated into the modelled calculation of time in port by assuming that an average crane density applies for 85 per cent of the cargo carried and that the remaining 15 per cent of the cargo is worked by only one crane.

(2) Since the itineraries of ships are established well in advance, port working plans are adjusted to account for itenary-dictated sailing times. Port times that are longer than predicted, therefore, perhaps reflect the inevitable imperfections in the scheduling of long-distance sea voyages.

After incorporating the adjustments in the model as discussed above, a comparison of modelled port time was again made with actual scheduled port time for four Europe-Asia services of a major alliance. The total round-voyage port time for 14 to 17 ports (excluding pilot time) was between 10.2 and 13.2 days. Time in port calculated using
the model, however, yielded a port time of only 9.8 days, assuming one hour per port for lashing and preparing for cargo work. Thus the error varied somewhere between 5 and 30 per cent.

No adjustment has been made for this bias in the predictions produced by the model. This is because the nature of the model is normative, the objective being to compare the operating economies of different sizes of container ships. It focuses on what operating costs of ships can be, rather than attempting to explain what they are in practice. The bias appears to be consistent across the whole size range and should not, therefore, undermine a comparison of economies of scale.

Container ship schedules are more and more commonly designed to minimise time in port. This is especially critical for the new generation of post-Panamax tonnage. In such an environment, the question of what precisely constitutes "time in port" is a debatable one, as is the increasing influence exerted by various factors other than merely cargo handling time in port. These are issues that should be addressed by empirical research that aims to develop accurate predictions of total "time in port" based on a range of potential explanatory factors (some controllable and others not), perhaps just one of which will be size of ship.

5. Sensitivity Analysis

The modelling of total shipping cost, composed of the cost of time in port and the cost of time at sea, must assume some voyage and port characteristics such as voyage length, cargo handling rate, time for port entry, and so on. There can be considerable divergence in these characteristics and, therefore, a sensitivity analysis to cater for this has been undertaken. The assumptions underlying this sensitivity analysis are: (a) the total cargo handled per voyage (one leg of a round voyage) was taken as twice the NTEU capacity of the ship (that is, once each for loading and discharging); (b) the time attributable to cargo handling on any voyage is deduced by assuming that 85 per cent of the cargo is worked by the average crane density as determined from the survey, and the remaining 15 per cent is worked by a single crane — this has been incorporated to account for an inevitable imbalance in cargo distribution onboard the ship and is relevant at any port; (c) a total of 24 hours per voyage is taken as the time used for port entry, securing containers, cargo documentation and port clearance; (d) port charges have been excluded from the analysis as these are not variable when assessed on a per TEU basis; and (e) cargo handling costs have not been included, since on a unit basis these too are independent of ship size.

5.1 Cost of Time in Port

Gauging the effect of varying port times on the cost of a ship’s time in port is especially important given the model’s systematic underestimation of between 5 and 30 per cent of the actual scheduled port time of four Europe-Far East services operated by a major alliance. The following five variations of time in port have been used in the sensitivity analysis:
Figure 5

*Container Ship Cost of Time in Port per Voyage (US$ per TEU)*

1. As modelled.
2. 50 per cent less time than modelled.
3. 50 per cent more time than modelled.
4. 100 per cent more time than modelled.
5. Time is calculated with maximum crane density per ship fixed at only three for all ships larger than 2500 TEU. This crane density is again used to work 85% of the cargo per voyage with the balance of the cargo worked by only one crane.

The cost of time in port expressed in US$ per TEU per voyage for these scenarios is given in Figure 5. Under all scenarios, it shows that for ship sizes up to about 1500 TEU there are no diseconomies of ship size in port, and that for ships larger than 1500 TEU there are diseconomies of ship size in port, but the magnitude of these diseconomies is quite small.

Past research in this area, however, suggests that container ships suffer significant diseconomies of size in port. Gilman (1980) concluded that “cost of time in port is very important and also that at any given handling rate there are important diseconomies of size”. Similarly, Jansson and Shneerson (1987), in their detailed investigation of economies of container ship size, hypothesised that container ships show diseconomies of size in port, although they admitted that empirical evidence was inconclusive. Thus, our findings for ship size less than 1500 TEU contradict earlier studies. For container ships of capacity greater than 1500 TEU, however, the findings conform to those of past studies in the sense that diseconomies of size in port do exist, although the magnitude is not as large as has been estimated in the past.

There are two possible reasons for the disparity between the results of this and earlier research. First, there has been a significant improvement in average crane productivity...
in recent years. Second, as ship size increases, there is now a greater propensity for an increase in the average number of cranes employed on the ship, though this greater crane density is not proportional to the increase in ship size. Most significantly, greater crane density is particularly the case for ships of less than 1500 TEU; the average number of cranes employed on a ship increases rapidly from an average of 1.1 to 2.6 as ship size increases from 200 TEU to 1500 TEU.

Although Gilman (1980) did show significant diseconomies of size in port, the handling rate was assumed to be the same for different ship sizes, and also the maximum handling rate considered was only 1000 TEU/day. At present, crane density is definitely increasing as ship size increases. This was evident from the replies to the questionnaire discussed earlier. At the same time, terminal productivities are also much higher. The shipping companies interviewed reported average terminal handling rates of around 1400 to 1600 containers/day or 2130 to 2400 TEU/day in Europe; a figure that may be still higher in Asia. Similarly, Jansson and Shneerson (1987) assumed that two cranes will have a productivity of 350 tons/hour or 25 TEU/hr. At present, two cranes are likely to achieve 66 TEU/hr (assuming a box mix of 67 per cent TEU and the rest FEU). Thus, since the corpus of previous empirical research was actually carried out, there has been a considerable change in port productivity, and it is this which fundamentally explains the disparity in findings.

Jansson and Shneerson (1987) admitted themselves that the deployment of a 4400 TEU ship by APL in 1987 is explained by the fact that these ships employ six cranes for cargo operations instead of two as assumed in their model. They have further stated that the "tremendous increase in [container] ship size is by and large to be explained by the rise in productivity in ports".
Table 3
Total Shipping Cost per TEU
(US$)

<table>
<thead>
<tr>
<th>NTEU</th>
<th>Port Time used on Trans-Atlantic Voyage of 4000 Miles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>As modelled</td>
</tr>
<tr>
<td>1000</td>
<td>164</td>
</tr>
<tr>
<td>2000</td>
<td>124</td>
</tr>
<tr>
<td>3000</td>
<td>109</td>
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<td>4000</td>
<td>100</td>
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<td>6000</td>
<td>91</td>
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<tr>
<td>7000</td>
<td>89</td>
</tr>
<tr>
<td>8000</td>
<td>87</td>
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</table>

<table>
<thead>
<tr>
<th>NTEU</th>
<th>Port Time used on Trans-Pacific Voyage of 8000 Miles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>As modelled</td>
</tr>
<tr>
<td>1000</td>
<td>312</td>
</tr>
<tr>
<td>2000</td>
<td>231</td>
</tr>
<tr>
<td>3000</td>
<td>199</td>
</tr>
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<td>4000</td>
<td>180</td>
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<td>5000</td>
<td>168</td>
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<td>6000</td>
<td>159</td>
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<tr>
<td>7000</td>
<td>152</td>
</tr>
<tr>
<td>8000</td>
<td>48</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>NTEU</th>
<th>Port Time used on Europe-Far East Voyage of 11500 Miles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>As modelled</td>
</tr>
<tr>
<td>1000</td>
<td>441</td>
</tr>
<tr>
<td>2000</td>
<td>325</td>
</tr>
<tr>
<td>3000</td>
<td>277</td>
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<td>4000</td>
<td>250</td>
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<td>5000</td>
<td>232</td>
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</tr>
<tr>
<td>7000</td>
<td>208</td>
</tr>
<tr>
<td>8000</td>
<td>201</td>
</tr>
</tbody>
</table>

5.2 Total Shipping Cost per TEU
The cost of time in port and the cost of time at sea are aggregated to give the total shipping cost (excluding port charges and cargo handling charges). As port and terminal infrastructure can vary considerably, a detailed sensitivity analysis of the Total Shipping Cost per TEU was carried out by varying the input port time per voyage away from that modelled. In order to assess model robustness, the extreme deviations previously described were deliberately selected as the basis for evaluating Total Shipping Cost per TEU for each of three sample voyage lengths which conform approximately to the three main east-west routes (that is, Europe-Far East, trans-Pacific and trans-Atlantic).
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![Graph showing reduction in voyage cost per TEU slot for different route lengths.

Figure 7
Comparison of Economies of Scale and Route Length

The resulting Total Shipping Cost per TEU for each of the three sample routes is shown in Table 3. As expected, higher levels of port productivity (that is, reducing time in port) lead to greater economies of ship size in total shipping cost. Conversely, declining port productivity means reaping smaller benefits from economies of scale.

Based on the “as modelled” time in port, Figure 6 illustrates the Total Shipping Cost per TEU for the three selected route lengths and, for all three, the results suggest that economies of ship size are enjoyed till about 8000 TEU.

By comparing Figures 5 and 6 it can be seen that, for these three voyage lengths, the diseconomies of ship size in port are outweighed by economies of size at sea. More specifically, under all port productivity scenarios, the results of the sensitivity analysis show that for the Europe-Far East and trans-Pacific liner routes, economies of scale are enjoyed at ship sizes beyond 8000 TEU. In contrast, for the shorter trans-Atlantic route, when port times are 100 per cent more than initially modelled, or if ships are serviced by a maximum of only three cranes, then the optimal size for a container ship is only somewhere in the range 5000-6000 TEU (taking into consideration only the total shipping cost associated with the voyage).

Table 3 also demonstrates that the benefits from scale economies in ship size decline as route lengths shorten. Figure 6 also shows that the shorter the route length, the flatter is the line graph showing Total Shipping Cost per TEU. As one would expect, this implies that the economies of ship size are of greater benefit on longer routes.

The parametric relationship between economies of scale and route length is shown in Figure 7 which illustrates that positive returns to scale decline as ship size and route length increase.
Table 4

Deployment of Container Ships on Primary Liner Routes

<table>
<thead>
<tr>
<th>Route</th>
<th>Number of Vessels in Size Ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Under 2500 TEU</td>
</tr>
<tr>
<td>Trans-Atlantic</td>
<td>14</td>
</tr>
<tr>
<td>Trans-Pacific</td>
<td>66</td>
</tr>
<tr>
<td>Europe-Far East</td>
<td>27</td>
</tr>
</tbody>
</table>

Note: This table includes only operators using vessels of 2500 TEU and above or operators who are prime candidates for upgrading to this size range within the next two years.

The actual deployment of vessels on these three routes by the major operators validates the findings of the model. This is depicted in Table 4 which shows that the biggest ships are employed on the longest route (that is, Europe-Far East). This is despite the fact that by far the largest route in terms of volume of traffic is the trans-Pacific route.

6. Conclusions

In developing the model presented within this paper, many of the estimates of the ship size elasticities of various component costs have largely concurred with those of previous studies. This is a necessary condition for justifying the common methodology adopted and is a helpful contribution to the validation of the final model. This is especially so since the input data for this study is independent of that used in previous research.

In contrast to earlier studies, however, the output from the model reveals that there are no diseconomies of scale in port for ship sizes of less than 1500 TEU. In addition, although such diseconomies of scale do indeed exist for ships larger than 1500 TEU, this analysis finds them to be less significant than suggested in previous studies. This disparity in results can be attributed to a fundamental change in the container shipping environment between the times at which the studies were undertaken. Most influential has been the dramatic improvements in port productivity (especially as manifest in both improved crane productivity and density), which have been implemented in recent years and which have greatly benefited the container shipping industry.

A further important conclusion of this research is that the disaggregate modelled relationships hypothesised within this study have tended to possess much greater statistical strength than those already present in the existing body of literature. Without a detailed re-examination and comparison of the datasets that have provided the basis of these previous studies, it is simply not possible to identify precisely the reasons why this should be the case. It is, however, feasible to speculate on two possible causes of the disparity, which appear to be potentially fruitful areas of further investigation.
Compared to the existing body of research, this study has used a larger dataset for analysis. Other things being equal, therefore, one might naturally expect a deterioration in the explanatory power of the modelled relationships that are estimated. In fact, the significant improvements achieved in the explanatory power of the various modelled relationships suggest that there must exist a fundamental difference in the nature of the datasets used. Since it is not unreasonable to assume that there is a very close relationship between the age of a ship and its costs, any analysis of ship size and costs is inevitably undermined by the use of a dataset that possesses any significant variation in the age of the ships that comprise that dataset. This points to the desirability of analysing a dataset, such as that utilised in this study, where the age of ships cannot constitute an intervening variable.

In evaluating ship size elasticities in the container trades, the input data for the ship size variable has typically been derived from yard-denominated TEU capacity. Since container ship costs are likely to vary with changes in the true container carrying capacity (assuming ships are fully loaded), it is important that the variable selected to represent ship size adequately reflects this capacity. This work posits that the results of previous studies suffered from the inappropriateness of yard-denominated TEU as a proxy for carrying capacity, and that the NTEU measure provides a much more accurate basis for the ship size variable in an analysis of this type.

The results from the model point to the fundamental conclusion that the economics of container ship operation are crucially dependent on port productivity. This is indicated not only by the comprehensive impact of recent general improvements in port productivity on container ship economies of scale, but also, as revealed through the sensitivity analysis, by the effect on optimum ship size when time in port deviates from the original best estimate input into the model.

Almost irrespective of voyage distance, by using best estimate input data that most accurately reflect the current shipping environment, the results of this study suggest an optimum ship size of approximately 8000 TEU. Clearly, on routes where expected time in port is greater than the best estimate inputs applied in this study (which are based on the average productivity of a set of large, mainline ports), diseconomies of scale in port will have a relatively greater significance, thus reducing the optimum ship size for the route. Equally, continued general worldwide improvements in port productivity will so fundamentally alter the container shipping cost environment that, in the absence of any technological constraint, ship size optiums for all routes will continue to increase as they have done in the past. As McLellan (1997) points out, however, for operational reasons and with the objective of risk minimisation, periods of pushing back the boundaries in maximum container ship size are likely to be followed by periods of consolidation. Actual investment in ships, therefore, is likely to constantly lag behind the optimum containership size as it continues to increase, primarily through improvements in worldwide port productivity.

Currently and in the future the results of this study suggest, not unsurprisingly, that the deployment of large container ships is likely to depend most crucially on voyage dis-
tance; a conclusion supported by the current deployment of existing post-Panamax tonnage. The objective of such deployment patterns is clearly to maximise time at sea reaping economies of scale and minimising time in port suffering diseconomies. This will be the case even if port productivities continue to improve in the future.

One further conclusion to be drawn from the results of this study is, therefore, that the adoption of the load centre concept by container ship operators and the continued proliferation of hub ports as the foci for container operations, is a trend that is unlikely to cease in the short to medium term. Indeed, given the highly positive correlation between the operation of post-Panamax vessels, company size and membership in a worldwide container shipping alliance, both industrial and hub concentration is likely to be self-perpetuating. Such a conclusion is supported all the more by the empirically established relationship between port productivity and throughput and the greater attractiveness of a port as a hub when feedership services abound.

Although the implications for ports are contentious (see Baird, 1997, and Notteboom et al., 1997), in the absence of appropriate financial incentives, the results of this study imply that the economics of container ship operation are now, and are likely to continue to be, such that operator and port specialisation will become more common, and that certain ports currently considered mainline will find themselves having to reposition themselves to the market as specialist trans-shipment ports. As Baird (1996) points out, there are likely to be a few surprises as to which ports will be most directly affected.

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