
Revealing the Impact of Increased Tanker Size on Shipping Costs

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Abstract:

Purpose: The research objectives refer directly to the key in maritime transport problem of cost economies related to the increasing scale (size) of ships. This article reveals the relationship between an increase in tanker size and shipping cost and its various categories.

Design/Methodology/Approach: Economies of tanker size are expressed in terms of the elasticity of daily and unit shipping costs relative to vessel size measured in deadweight. Functions of the shipping daily and unit costs concerning the tanker size were derived by regression, while the parameters were estimated with the ordinary least squares' method.

Findings: Elasticity values for daily and unit shipping costs estimated for tankers within the size range (dwt); 25,000 - 300,000. Tanker daily shipping mean elasticity estimates: another operating cost (labor cost included) (0.262), capital costs (0.407), port costs (0.449), fuel costs (0.575). Revealed tanker unit shipping mean elasticity estimates: full operating costs (-0.67), other operating cost (-0.835), capital costs (-0.690), port costs (-0.649), fuel costs (-0.523).

Practical implications: Elaborated models allow one to estimate savings in shipping costs resulting from handling larger tankers in seaports, which in turn is an important factor in terms of the calculation of the effectiveness of port capacity expansion, as well as in the analysis of competition between ports. The models may be used to study the impact of scale in tanker shipping on the remaining transport links (i.e., ports and hinterlands) and in the routing of sea-land supply chains.

Originality/Value: The models for daily and unit costs developed here allow calculating the shipping cost for any tanker size.

Keywords: Tanker, scale, shipping, cost, elasticity.

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1. Introduction

As the size of a business grows, increasing, constant, and decreasing returns with production scale may appear. These changes stem from the changing dependencies between the increase in the input of production factors and the increase in output. Average long-term production costs are directly related to variable returns with scale. Economies of scale are developed when average long-term production costs decrease with the development of business (Arvanitis *et al.*, 2012). On the other hand, economies of density arise when average short-term production costs decrease with increasing use of constant capital expenditure. An economy of scale is a long-term concept where a long-term production cost function is analyzed after all production factors have changed. An economy of density is a short-term concept where a short-term production cost function is studied with a constant capital stock (Caves *et al.*, 1981; Caves and Christensens, 1988). In maritime transport, economies of scale are primarily analyzed in terms of the increasing sizes of vessels (i.e., vessel size economies) (Button, 2010; Cowie, 2010; Thalassinos *et al.*, 2009; 2011; 2013). In a shipping context, an economy of scale refers to a situation where the full operating unit cost (i.e., cost/dwt or cost/slot) decreases as the ship size increases (Haralambides, 2019).

Economies of scale associated with the commissioning of ever-larger sea-going vessels are based on the fact that the costs necessary for their construction and some of the costs of production factors related to operation increase less than proportionally with the increase of deadweight/capacity. The increasing economies of scale of sea-going vessels mainly occur because of the factors given as follows:

- Specific technical relationships related to the construction of larger ships related to increasing lengths, widths, and heights of units, where the unit deadweight/capacity correspondingly increases. Larger ships require less investment per tonnage unit, and the cost of building a large ship decreases per ton of deadweight.
- The greater efficiency of large sea-going vessels is expressed by the fact that the commissioning and operation of sea-going vessels with increased capacity requires less proportional material and personal production factor inputs. The shipping costs of large vessels decrease per ton of deadweight.

Unit costs generally decrease as the ship size increases. This is because capital, operating, and voyage costs do not increase proportionally with cargo capacity. For example, a 330,000 dwt tanker costs only twice as much as 110,000 dwt vessel, but it carries three times as much cargo, i.e., the cost per ton for transporting 110,000 tons of oil is much higher than for transporting a 330,000-ton shipment (Stopford, 2009). It has been pointed out that economies of scale arise about sailing, i.e., the time spent by the ship at sea, while diseconomies of scale arise about transshipment, i.e., the ship's duration's stay in a seaport (Jansson and Shneerson, 1987). The larger the ship, the greater the mass of the delivered cargo. Larger ships also feature wider and deeper cargo holds, and therefore the work required for handling equipment takes longer.

For this reason, the unit costs for transshipment are increasing, as well as the durations for ships staying in ports (Haralambides *et al.*, 2002; Haralambides, 2017). Economies of density for a sea-going vessel apply when the operating cost (excluding capital cost) per dwt or slot decreases as the utilization of the vessel's capacity increases. In this case, the operating cost of shipping increases at a lower rate than the volume of a ship's transport performance. An economy of density is the short-term counterpart of an economy of scale where the short-term variable cost function is considered. Savings appear when the increase in the use of constant load capacity for transport is accompanied by a less than proportional increase in the variable costs for transport performance (Blauwens *et al.*, 2002).

Economies of density for a sea-going vessel mainly occur due to the low marginal cost for carrying cargo within the capacity offered by the vessel, as this only covers the cost of handling an additional container/ton of cargo at a seaport. The marginal cost is much lower than the average cost of transportation; however, loading additional cargo extends the service time in a port. Increasing the use of the capacity/deadweight of sea-going ships presents barriers related to maintaining the regularity, frequency, and reliability of shipments. The cost disadvantages related to an extended stay in a port and the increased fuel consumption at sea can increase to the point where the related cost savings are offset by additional costs related to the maintenance of regularity, reliability, and frequency of sea transport after exceeding a certain level of deadweight utilization (Shneerson, 1984).

A tanker is a category of the ship designed with a single deck hull, which includes arrangements of integral or independent tanks specifically designed for the bulk carriage of cargo in liquid or gaseous forms. Cargo handling to and from the tanks is carried out via shore-based and/or ship-based pumping and piping equipment. The two main categories of liquid bulk cargo in shipping are crude oil and oil products. Crude oil is transported from oilfields to refineries, and oil products are transported from refineries to distribution centers and bunkering ports. This has led to the establishment of a worldwide network of tanker routes (Branch, 2007).

Crude oil is shipped in substantial parcel sizes, typically over 100,000 tons, while most oil products are shipped in parcels of 30,000, 40,000, or 50,000 tons (Stopford, 2009). Tankers are classified according to their carrying capacity and capability to be deployed in certain routes (Branch, 2007). Tankers under 60,000 dwt are often referred to as MRs, which stands for medium range. Tankers in the range of 60,000 dwt to 120,000 dwt (LR1-LR2) are often used for product transport and are referred to as LRs, long-range. The main principles of tanker shipping and the transportation of oil are given as follows:

- Crude oil transport is unidirectional (i.e., vessels return empty to the oil-exporting region), while this is not usual for product tankers, which can hence be better exploited by ship owners (Lyridis and Zacharioudakis, 2012),
- A typical 300,000 dwt Very Large Crude Carrier (VLCC) could carry about 2 million barrels of oil at a draught of about 22 meters, a speed of 15.8 knots,

and with a pumping capacity of between 15,000 and 20,000 tons per hour. Suezmax tankers typically carry 1 million barrels with a loaded draught of 15.5 meters and a discharge pumping capacity between 10,000 and 12,000 tons per hour (Stopford, 2009),

- Tankers evolved into VLCCs (over 200,000 dwt) work on long-haul routes. Suezmax tankers (199,999 dwt) are used for medium-haul crude oil shipping. Aframax tankers (80,000-120,000 dwt) are used for short-haul crude shipping. Panamax tankers (60,000-80,000 dwt) are used for very short-haul crude and dirty product shipping. Product tankers feature a deadweight tonnage between 10,000 and 60,000 dwt (Branch, 2007).

Large vessels require dedicated port infrastructure and the terminals used in the oil trade are often located in remote locations, consisting of a tank farm for temporary oil storage and a jetty or single buoy mooring that extends into deep water where large tankers can load cargo. From a discharge terminal, oil is delivered directly to a refinery or to a crude oil terminal linked to a refinery by a pipeline (Stopford, 2009).

2. Research Related to the Impact of Tanker Size on Shipping Costs

As a result of large ships' operation, economies of scale consisting of a decrease in the long-term cost of transporting a ton of cargo are achieved. As a result of increasing the use of deadweight of a ship, economies of density consist of a decrease in the short-term cost of transporting a ton of cargo. In terms of research related to economies of scale and economies of density in shipping, in the first place, the estimation of elasticity values about the distinguished types of daily operating costs for shipping is required. The value of elasticity below unity denotes the occurrence of economies of scale and economies of density, i.e., the distinguished categories of shipping costs increase less than proportionally to the size of a ship (carrying capacity) or the use of its deadweight, which indicates the existence of economies of scale and density. Values of elasticity above unity refer to shipping costs increasing more than proportionally to the carrying capacity of a sea-going vessel or its use, which means that there are diseconomies of scale and density.

The elasticities of shipping costs in terms of sizes of ships per day or ton of ship deadweight (dwt) are determined here for the total operating costs and/or for individual components, such as capital, operating cost, fuel, and port costs. The few studies on tankers have shown the following values of elasticity for daily costs about an increasing tanker load capacity (Heaver, 1968). For capital costs, the value is 0.6, for operating costs (without fuel), the value is 0.3, and for fuel, the value is 0.6. It should be emphasized that these are average values of elasticity determined for increasing tanker sizes based on statistical information from the end of the 1960s.

On the other hand, for various ranges of tanker sizes measured in dwt, i.e., <25,000, 25,000-35,000, 35,000-40,000, 41,000-51,000, 67,000-85,000, 114,000-124,000, and 188,000, the elasticity values for the average daily operating costs (without fuel) range from 0.351 to 0.892 (Talley *et al.*, 1986). This proves that savings in shipping

costs occur for all vessel size ranges, although they decrease as the deadweight increases, and it is likely that the cost savings become exhausted for the largest tankers. It has been found that the increase in the efficiency of transshipment in proportion to the size of a tanker results in that the impact of the costs associated with staying at seaports on the maritime shipment costs is negligible.

Research into economies of scale and density concerning tankers has rarely continued. This is probably due to the following reasons:

- In the case of tanker shipping, the disadvantages at seaports are limited as the transshipment technology based on a system of pumps and pipelines allows for a flexible increase in throughput depending on the size of a ship, so the stay duration for large tankers in seaports is not the critical element affecting the cost-effectiveness of sea transport.
- The sizes of tankers have been adapted to the demand, shipment size, transport routes (long-, medium- and short-range), ability to handle ships in ports, capacity for transshipment, and cargo types (crude oil and oil products).
- Tankers carry a full shipment of cargo in terms of the maximum quantity allowed by the ship's deadweight, so the possibilities for increasing the utilization of a ship's capacity are also slight. As a rule, tankers that carry crude oil and petroleum products are fully loaded.

Today, modern tankers vary in size according to their cargo and trade routes (Song and Panayides, 2012). The economies of scale and density for tankers have been largely exhausted and determined by sea trade conditions and the technology for the transportation and handling of crude oil and its products². In tanker shipping, there are still issues that should be studied, and this paper intends to make the following contributions:

- verify the historical results of research on the elasticity of shipping costs for tankers in the context of changed commercial and technological conditions for tanker shipping;
- reveal daily and unit elasticities for different operating cost categories;
- develop shipping cost models depending on the size of a tanker.

²*The largest supertanker ever built is the Knock Navis, formerly known as the Seawise Giant. The ship is 458-m-long and can carry 650,000 m³ of crude oil at a total displacement of almost 650,000 tons and has a capacity of over 560,000 deadweight tons. With its draft of 24.6 m, it is not able to navigate the English Channel. In 2004, it was refitted and became permanently moored in the Persian Gulf as floating storage and offloading unit (FSO). The Tankers International (TI) ship TI Asia and its three sister ships are currently the world's largest supertankers. The ship features a relatively high speed of 16.5 knots while laden and 17.5 knots in ballast. Its main particulars are Length; 380 m, Beam; 68 m, Depth; 34 m, Draft; 24.5 m, deadweight tonnage of 441,890 tons, and a maximum volume of 514,000 m³ for crude oil (Hopman and Nienhuis, 2009).*

The last of the mentioned issues is especially important due to the following reasons:

- studies on the function of shipping costs in the context of size and type of ship are scarce, and a rare example of this is the unit cost model for dry bulk carriers (Kasembe and Gang, 2011);
- such models could be used to study the impact of the development of infrastructure and handling of larger ships in ports on the efficiency of shipping and on changes in the competitiveness of ports and in the routing of sea-land supply chains;
- the cost of sea transport is an important component for cost calculation in the intermodal transport and logistic systems.

3. Aims and Methodology

This article aims to estimate values of elasticity for daily and unit shipping costs and develop models for daily and unit operating costs depending on tanker size. The article's objectives refer directly to the key maritime transport problem of cost savings related to an increasing ship scale. The contribution to research consists of providing revisited historical results for the elasticity values of daily shipping costs. Additionally, daily and unit cost elasticities for different operating cost categories are revealed, and shipping cost models for various tanker sizes are also developed.

The research questions here are the following:

- 1) How does the increase of tanker size influence the different shipping cost categories?
- 2) What is the impact of tanker size on the daily and unit shipping costs?

The subject of the analysis here is tankers for the transport of crude oil and its products. The cost advantages related to the size of a tanker are established here in two stages. In the first stage, the shipping cost per ship/day is compiled for ships of different sizes (dwt). Functional dependencies between the daily shipping cost (ship/day) and the tanker size (measured with deadweight, dwt) are determined. The values of elasticity for daily shipping costs are estimated. In the second stage, the shipping cost per ton-kilometer is determined, and the functional relationships between the cost of a ton-kilometer and tanker size are determined. Elasticity values of unit shipping cost about tanker size are estimated. The function of the unit shipping cost per ton-kilometer is determined for tankers of any size.

The analysis covers ships' shipping costs during a sea voyage in terms of the port to the port relationship. Shipping costs include the following (Stopford, 2009):

- operating costs (manning, stores and lubricants, repairs and maintenance, insurance, administration and gross margin);
- voyage costs (cost of fuel consumption, and port and canal dues);
- capital costs (capital repayments and interest).

Data for the shipping costs of tankers during a day of shipping were taken from the study by Delhaye *et al.* (2010), in which the average daily shipping costs for selected groups of tanker sizes were presented. The detailed structure for daily shipping costs is presented as values calculated for the average tanker size in a given vessel size group. The analysis was performed for tankers with guide deadweights (tons) of 35,000, 62,500, 160,000, and 260,000. On this basis, a function of the daily shipping costs concerning the tanker size (dwt) was derived by regression, while the parameters were estimated via the ordinary least squares method (OLS). Next, the elasticities of daily costs for the main categories of shipping cost were estimated.

The daily shipping cost (€/day) is defined as below:

$$DSC = DOC + DVC + DCC \quad (1)$$

where:

DSC denotes daily shipping cost (€);
 DOC denotes daily operating cost (€);
 DVC denotes daily voyage cost (€);
 DCC denotes daily capital cost (€).

The benefits related to ship size can also be expressed as a function of the unit shipping cost of a tanker relative to its size (Jansson and Shneerson, 1987). In the second part of the article, the unit costs of shipping for the selected sizes of tankers per ton-kilometer were estimated. The calculations were made with the following assumptions:

- full use of the ship's capacity (in tons of cargo);
- constant sailing speed for a given ship size, where consequently the journey distance (in km) that the ship can cover in a 24-hour period is constant;
- the average ship size (dwt) for a given size range was assumed.

The unit shipping cost (€/tkm) is defined in the following way:

$$USC = \frac{DSC (DOC + DVC + DCC)}{FCW \times DD} \quad (2)$$

where:

USC denotes unit shipping costs (€/tkm);
 DSC denotes daily shipping cost (€);
 DOC denotes daily operating cost (€);
 DVC denotes daily voyage cost (€);
 DCC denotes daily capital cost (€);
 FCW denotes full cargo weight (ton)/vessel;
 DD denotes maximum daily distance (km);
 S denotes speed (km/h, constant);
 DD = S × 24 h.

Ton-kilometer unit costs were calculated for tankers with the aforementioned guide deadweights. The shipping cost per ton-kilometer function was derived by regression for the entire range of vessel sizes, while the parameters were estimated with the OLS method. Next, the elasticities for the main unit shipping cost categories were estimated.

4. Economies of Scale Related to Tanker Size

The daily shipping costs for tankers are presented in Table 1.

Table 1. Daily shipping cost for tankers (€/day) (2010).

Vessel size	Medium range (MR) 1	Long range (LR) 1	Suezmax	VLCC
Scale range	25,000- 45,000	45,000- 80,000	120,000- 200,000	200,000- 300,000
Guide deadweight tonnage	35,000	62,500	160,000	260,000
Manning	2369	2369	2600	2808
Insurance	554	592	1038	1377
Repairs and maintenance	1408	2108	2777	3108
Stores and lube oil	585	654	885	1131
Administration	1031	1292	1523	1723
Capital repayments	5748	6684	9358	13,368
Interest	4725	5495	7692	10,989
Gross margin	2791	3263	4398	5866
Port	2500	3025	4445	6286
Fuel (ton/day)	29.0	35.0	60.0	92.5
Fuel (€/day)	9242	11,154	19,122	29,480
Speed (knots)	12.0	15.0	15.0	15.0
Full cargo weight (ton)	34,763	59,404	158,078	256,626
Shipping route	European	Via Panama	Via Suez	Via Cape
Total daily shipping cost (€/day)	30,953	36,636	53,838	76,136

Source: Delhaye et al., 2010.

The shipping costs for a tanker mainly include marine fuel costs and capital costs (installments and interest on capital allocated to financing the purchase of ships). In total, they account for between 63.8% for a tanker with a deadweight of 35,000 tons to 70.7% for a tanker with a deadweight of 260,000 tons. For the analyzed tanker sizes, the share of capital cost in the total cost decreased from 33.9% (for MR1 with 35,000 dwt) to 32.0% (for VLCC with 260,000 dwt). The share of fuel costs increased the most, from 29.9% to 38.7%. Port costs, including port dues and channel charges, remained at the constant level of 8.3%. Personnel costs related to a ship's manning decreased as tanker size increased and were, about the total cost, in the range of 7.7% for a ship of 35,000 tons to 3.7% for large VLCC tankers. The relationship of the daily shipping cost of a tanker about its size measured in deadweight (tonnes) has been described using the following model (Bernacki and Lis, 2016):

$$C_i = \beta_1 DWT_i + \beta_0 + U_i, \quad (3)$$

where:

C_i denotes the average daily shipping cost of the i -th tanker size;

DWT_i denotes the i -th size of tanker expressed in terms of a guide deadweight (dwt);

β_1 and β_0 are structural parameters of the model;

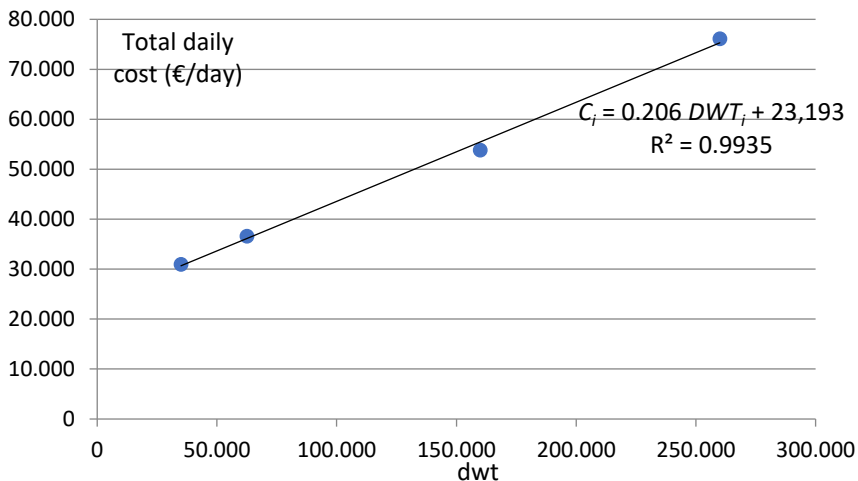
and U_i is a random component.

Using the statistical data for the daily shipping costs and the guide deadweight tonnage values for the specific size groups, the parameters for the daily cost model were estimated with the OLS method and then the following model of the daily shipping cost was obtained:

$$\hat{C}_i = \underset{(0.012)}{0.206} DWT_i + \underset{(1802.930)}{23,193.404} \quad (4)$$

where 0.206 is the estimate of the parameter β_1 of the cost model and 23,193.404 is the estimate of the parameter β_0 of the cost function model in relation to the ship deadweight. The parameters were found to be statistically significant. The goodness of fit (R^2) of the equation was found to be 0.9935 and the standard errors are presented in parentheses. The evolution of relationship between the daily shipping cost and the size of a tanker (dwt) is shown in Figure 1.

Figure 1. Daily shipping cost curve with respect to tanker ship deadweight tonnage (€/day)



Source: Own study.

The daily shipping cost function indicates constant scale economies for tankers within the size ranges between 25,000 and 300,000 tons. The daily shipping costs grow at a similar rate to deadweight tonnage growth for tankers. On the other hand, the elasticity values for the main types of shipping costs calculated at the next stage of

the research indicate increasing economies of scale, i.e., a lower increase rate for daily posts about the growing size of a tanker. The likely reason for this paradox is that the size elasticities for shipping costs can vary widely according to a ship's given size. As proven by Talley *et al.* (1986), the larger the studied tanker, the higher the daily shipping cost elasticity value. For 188,000 dwt tankers, the shipping cost elasticity value was found to be 0.892. In the conclusion of the cited study, it was stated that shipping cost economies might become exhausted for larger sized tankers. In our case, the research also covered large and very large tankers of the Suezmax (120,000-200,000 dwt) and VLCC (200,000-300,000 dwt) classes, and the cost savings for these size classes may likely become depleted, and therefore constant and perhaps even diminishing economies of scale may arise. The regression model parameters were estimated based on the entire analyzed range of vessel sizes. As a result, the daily shipping costs' function estimated for the entire group of tankers of the leading size from 35,000 dwt to 260,000 dwt (max. 300,000 dwt) presented a linear form.

Based on scatter plot analysis, a model was adopted for individual types of daily costs with the following functional form.:

$$C_{mi} = a_{m1} \cdot DWT_i^{a_{m0}} e^{U_{mi}} \quad (5)$$

where:

C_{mi} denotes the m -th category of average daily shipping cost of the i -th tanker size;

DWT_i denotes the i -th tanker size in terms of the guide deadweight tonnage (dwt);

a_{m1} denotes an intercept parameter for the m -th cost category;

a_{m0} denotes the elasticity of the average daily shipping cost for the m -th cost category;

U_{mi} is a random component for the m -th cost category.

Table 2. Estimated function parameters in terms of the daily cost categories in relation to tanker size.

C_{mi}	Dependent variable	Coefficients	Estimate s	Standard errors	t -Stat	R^2
C_{1i}	Other operating costs	a_{10}	0.262	0.006	42.944	0.998
		a_{11}	383.538	1.073	84.553	
C_{2i}	Capital costs	a_{20}	0.407	0.058	7.055	0.942
		a_{21}	140.995	1.944	7.446	
C_{3i}	Port costs	a_{30}	0.449	0.047	9.590	0.968
		a_{31}	21.966	1.714	5.732	
C_{4i}	Fuel	a_{40}	0.575	0.068	8.511	0.960
		a_{41}	21.069	2.176	3.920	

Source: Own study.

Using the model for the daily costs for tanker shipping (Eq. 5), estimations were made for the following costs categories: (C_{1i}) other operating costs (manning, insurance, repairs and maintenance, stores and lube oil, administration), (C_{2i}) capital costs

(capital repayments and interest), (C_{3i}) port costs (port and canal dues), and (C_{4i}) fuel. The estimated results of the model are presented in Table 2, where parameter a_{m0} is the mean elasticity of the m -th category of daily shipping cost.

By comparing the estimated values for the daily shipping cost elasticities, the following can be concluded:

- for other operating costs (labor cost included), the ship size elasticity value of 0.262 is very low, meaning that the cost economies are great;
- for capital, port and fuel costs, the ship size elasticities are higher, with respective values of 0.407, 0.449, and 0.575, meaning that economies of ship size are substantial.

The cost savings for an increased tanker size are large, although they will vary for each type of shipping cost. The calculations show that with a double deadweight increase for a tanker (i.e., by 100%), the other operating costs will increase by only 26.2%, capital costs will increase by 40.7%, port costs by 44.9%, and fuel cost by 57.5%. Input estimates for the daily shipping costs of tankers are presented in Table 3.

Table 3. Average daily shipping costs by tanker size (EUR/day; 2010)

Tankers size	MR 1	LR 1	Suezmax	VLCC
Guide deadweight tonnage (DWT_i)	35,000	62,500	160,000	260,000
Daily average total cost (EUR/day) (C_i)	30,953	36,636	53,838	76,136
Other operating costs (C_{1i})	5947	7015	8823	10,147
Capital costs (C_{2i})	10,473	12,179	17,050	24,357
Port costs (C_{3i})	2500	3025	4445	6286
Fuel (C_{4i})	9242	11,154	19,122	29,480

Source: Delhaye et al., 2010.

The unit shipping costs of tankers per ton-kilometer were calculated as (Equation 2):

- using the cruising speed of a vessel, then converting it from sea knots to a speed expressed in km/h, the maximum distance of a sea voyage that a vessel can cover in 24 hours was established. The daily shipping cost was divided by the maximum voyage distance per day, whereby the cost of operating the ship per kilometer was obtained.
- by dividing the operating cost accruing for one kilometer of a ship's voyage by its full cargo weight in ton, the cost of one ton-kilometer for a tanker was calculated.
- the operating cost data for tankers were gathered in 2010, and they have been updated for 2019 by using the nominal GDP indexation for the EU-28 countries, which amounted to a 1.2807-fold increase overall.

The cost of one ton-kilometer for the different sizes of tankers is presented below in Table 4.

Table 4. Total unit shipping costs for tanker ships per tkm (€/tkm) in 2019.

Vessel size	MR 1	LR 1	Suezmax	VLCC
Guide deadweight tonnage	35,000	62,500	160,000	260,000
Total daily shipping cost (€/day)	30,953	36,636	53,838	76,136
Full cargo weight (ton)	34,763	59,404	158,078	256,626
Voyage speed knots (NM/h)	12.0	15.0	15.0	15.0
Converter knot/km/h	1.85	1.85	1.85	1.85
Voyage speed (km/h)	22.22	27.75	27.75	27.75
Max. voyage distance (km/day)	533.28	666.0	666.0	666.0
Unit shipping costs (EUR/km)	58.04	55.01	80.84	114.32
Total unit shipping costs 2010 (EUR/tkm)	0.00167	0.00093	0.00051	0.00045
Nominal GDP indexation indicator (EU-28) for 2010-2019 (via Deflator PKB)			1.2807	
Total unit shipping costs in 2019 (EUR/tkm)	0.002138	0.001186	0.000655	0.000571

Source: Own study.

In the analysis, the unit cost model with the following functional form was adopted:

$$c_i = b_1 \cdot DWT_i^{b_0} e^{U_i} \quad (6)$$

where:

c_i is the average total unit shipping cost of the i -th tanker size;

DWT_i is the i -th size of tanker, expressed as the guide deadweight tonnage (dwt);

b_1 and b_0 are structural parameters of the model;

U_i is a random component.

The model of the total unit cost for tanker shipping in relation to ship deadweight, derived by the regression and parameters estimated with the OLS method, is given as follows:

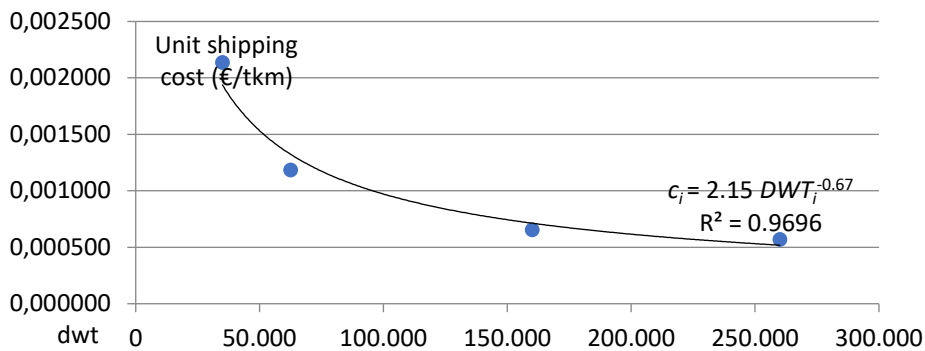
$$\hat{c}_i = 2.150_{(2,623)} DWT_i^{-0.67_{(0.084)}} \quad (7)$$

where 2.150 is the estimate of parameter b_1 of the cost model, -0.67 is the estimate of parameter b_0 , i.e., the elasticity of the average total unit shipping cost in relation to the i -th ship deadweight tonnage (dwt). Standard errors are presented in parentheses and the goodness of fit (R^2) of the equation was 0.9696. The evolution of relationship between the unit shipping cost and the size of a tanker (dwt) is shown in Figure 2.

The mean elasticity of the total unit shipping cost in relation to the growing size of tankers is (-0.67).

Using the model of the unit cost of tanker shipping as below:

Figure 2. Unit shipping cost curve with respect to tanker ship deadweight tonnage (€/tkm) in 2019.



Source: Own study.

$$c_{ni} = b_{n1} \cdot DWT_i^{b_{n0}} e^{U_{ni}} \tag{8}$$

where:

- c_{ni} is the n -th category of the average unit shipping cost of the i -th tanker size;
- DWT_i is the i -th size of tanker expressed in terms of a guide deadweight (dwt);
- b_{n1} is the intercept parameter for n -th cost category;
- b_{n0} is the elasticity of the average unit shipping cost for n -th cost category;
- U_{ni} is a random component for n -th cost category model,

Estimates were made for the following costs categories: (c_{1i}) other operating costs (manning, insurance, repairs and maintenance, stores and lube oil, administration), (c_{2i}) capital costs (capital repayments and interest), (c_{3i}) port costs (port and canal dues), and (c_{4i}) fuel. The model's estimated results are presented in Table 5, where parameter b_{n0} is the mean elasticity of the n -th category of the unit shipping cost.

The cost savings resulting from the increase in tanker size appeared for all unit shipping costs types. The greatest effects were obtained as the result of decreases in other operating costs (-0.835), capital costs (-0.690), port costs (-0.649), and fuel costs (-0.523).

Table 5. Estimated function parameters per unit cost categories in relation to tanker size.

c_{ni}	Dependent variable	Coefficients	Estimates	Standard errors	t-Stat	R^2
c_{1i}	Other operating costs	b_{10}	-0.835	0.040	-20.835	0.993
		b_{11}	2435.946	1.586	16.897	
c_{2i}	Capital costs	b_{20}	-0.690	0.094	-7.380	0.947
		b_{21}	895.497	2.936	6.312	

c_{3i}	Port costs	b_{30}	-0.649	0.083	-7.789	0.952
		b_{31}	139.514	2.609	5.150	
c_{4i}	Fuel	b_{40}	-0.523	0.107	-4.876	0.884
		b_{41}	133.815	3.437	3.966	

Source: Own study.

Input estimates for calculations of the unit shipping costs for tankers are presented in Table 6.

Table 6. Average unit shipping costs by tanker size (EUR/1000 tkm; 2019)

Tankers size	MR 1	LR 1	Suezmax	VLCC
Guide deadweight tonnage (DWT_i)	35,000	62,500	160,000	260,000
Total average unit cost (c_i)	2.138	1.186	0.655	0.571
Other operating costs (c_{1i})	0.411	0.227	0.107	0.076
Capital costs (c_{2i})	0.724	0.394	0.207	0.183
Port costs (c_{3i})	0.173	0.098	0.054	0.047
Fuel (c_{4i})	0.638	0.361	0.233	0.221

Source: Own elaboration based on Delhaye et al., 2010.

5. Discussion and Conclusions

The lowest value of the daily shipping cost's elasticity about the size of a tanker pertains to other operating costs (0.262). This indicates a large cost-saving advantage with an increasing tanker deadweight. In this case, the economies of scale mainly result from savings in the manning costs for a tanker's crew and costs related to administration. Along with an increase in the dwt of a tanker, there are slight changes in the number of crew on a ship and the expenditure related to shipping management. On the other hand, the savings in insurance, repairs, maintenance, and stores and lube costs are lower, as they are more dependent on the value of the ship, which increases with the size of the tanker.

The estimated value of elasticity for daily capital costs includes the effects of technical progress related to tankers' construction and fitting them with ship equipment. The material intensity of building modern tankers is reduced per dwt, and at the same time, the efficiency and effectiveness of transport and transshipment increases (i.e., with more efficient propulsion, more efficient pump systems, etc.). Strong competition in shipbuilding markets reduces both price increases for new tankers and the costs of financing ships' purchase. The estimated value for the elasticity of daily capital costs (0.407) indicates high-cost savings related to an increased tanker size.

Fuel consumption is primarily a function of a tanker's deadweight and sailing speed. For the sea transport of crude oil and its products, a tanker's speed during its voyage primarily depends on the shipping distance. For short- and medium-range shipping, vessel speeds are within 12 knots, while tanker voyage speed increases to 15-16 knots for ocean shipping. The elasticity value for the daily fuel costs for a tanker was 0.575,

and this is large because an increase in its voyage speed accompanies an increase in tanker size. It is presumed that the larger the tanker is, the lower the economies of scale associated with fuel consumption are.

The value of elasticity for port costs about tanker size was estimated to be 0.449, which was higher than expected. It is assumed that the diseconomies of scale in seaports are inconsiderable, as in seaports, it is possible to flexibly adjust the efficiency of transshipment to the size of a single delivery of crude oil and its products, and thus the length of stay of large tankers in ports does not change significantly; however, it should be remembered that port costs include port charges and channel fees incurred by large tankers on ocean shipping routes (e.g., the Suez Canal and Panama Canal), which depend to a greater extent on the size of a tanker. The estimated elasticities of the daily shipping costs confirm large cost savings related to the ship size (i.e., economies of scale), although the impact of tanker size on individual types of shipping costs varies.

A comparison of the results for the elasticity of daily shipping costs about ship size is presented in Table 7.

Table 7. Comparative analysis of ship size elasticities of daily capital costs, other operating costs, and fuel costs.

Ship type	Capital cost	Other operating cost (except fuel)	Fuel cost
<i>Tankers</i> (Heaver, 1968)	0.6	0.3	0.6
Tramps (Thorburn, 1960)	0.67	0.4	1.0
Tankers, dry bulk carriers, and container ships (Jansson and Shneerson, 1987)	0.6	0.4	0.72
Tankers (Talley <i>et al.</i> , 1986)	Elasticities of operating costs (without fuel) according to the size of tankers (dwt): <25,000; 25,000-35,000; 35,000-40,000; 41,000-51,000; 67,000-85,000; 114,000-124,000 and 188,000		
	in the range of values from 0.351 to 0.892 (188,000 dwt)		
<i>Tankers</i> <i>Author's estimate</i>	0.41	0.26	0.58

Source: Sources as cited otherwise own elaboration.

The other operating costs (except fuel) for tankers were at similar levels (0.26 vs. 0.3). Similar elasticity values were also obtained for fuel costs (0.58 vs. 0.6). Differences appeared for capital cost elasticities, which were lower than those estimated in other studies (0.41 vs. 0.6). In previous studies concerning tankers, the capital cost categories used for calculation have been unknown. The existing research has also used cost data from the 1960s (Heaver, 1968) and 1980s (Talley *et al.*, 1986).

In our calculation of capital cost elasticity, only capital repayments and interest costs were considered. The results also reflect modern shipbuilding and shipbuilding

financing conditions. Factors related to this may be the source of lower capital cost elasticities compared to historical calculations. In other words, lower values of elasticity for daily capital costs indicate that prices for increasingly larger tankers are rising less today than in the past.

The regression-derived function of the daily total shipping cost for tankers of a size between 25,000 tons to 300,000 tons indicates constant economies of scale, i.e., the daily total shipping cost increases at a rate like that of an increased deadweight tonnage. On the other hand, the calculated elasticity values for the main types of shipping costs indicate increasing economies of scale, i.e., the rate of increase for daily costs is lower than the rate of increase for tanker size. For large and even the largest tankers, this means that cost savings may become depleted. Determining the "threshold" size of tankers for which economies of scale cease to increase requires additional studies for individual sizes of ships; however, it seems that the current tanker fleet size structure is not determined by economies of scale but by factors such as the demand and sizes of shipments in given specific markets, journey distance and route characteristics, and types of cargo (crude oil or oil products). It can be assumed that the threshold size of a tanker for which the economies of scale are exhausted is in the range of 250,000-300,000 dwt. This is indicated by the course of the estimated function of a tanker's unit shipping cost (Fig. 2), which ceases to decrease for this size range of tankers. Tankers of the VLCC type, with a deadweight of 300,000 tons, show constant economies of scale, and the terms of commercial contracts determine their use.

With a value of elasticity of (-0.67), this study confirms the substantial decrease of unit shipping costs in line with an increase in tanker size. The estimated elasticity values prove large economies of ship size in terms of shipping unit costs, including other operating costs (-0.835), capital costs (-0.690), port costs (-0.649), and fuel costs (-0.523).

The developed model of the unit cost of shipping for a tanker can be used for research on the microeconomic effectiveness of infrastructure investments in seaports and cost calculation in sea-land transport systems. The primary factor enabling the achievement of cost benefits related to the increase in the size of a sea-going vessel is the sufficiently high transport accessibility from a sea to a seaport. Port accessibility for sea-going vessels is determined by the depths of fairways and the port water area (i.e., port canals, basins, and the depths at quays). Increased depths at seaports enable large ships to be handled there. The unit cost's estimated function can be used to calculate the shipping cost savings resulting from the dredging of a port water area. Studies with the use of the unit shipping cost allow the estimation of the savings in shipping costs resulting from handling larger tankers in seaports, which is an important factor for the calculation of effectiveness for port investments and the analysis of competition between ports.

The cost-effectiveness of sea transport, supplemented with analysis of transport time costs, is a factor that determines the routes of transport chains and competitiveness

between transport systems. Using the model developed here, it is possible to calculate a unit cost of sea transport depending on the single delivery volume. Moreover, in comparative analyses of transport systems, this type of variable may be used to determine the impact of scale in maritime transport on the remaining links in a transport system (i.e., ports and hinterland transport) of the routes of transport systems and their modal configurations.

This study's limitations result from the data on operating costs, which represent average values for four tanker size ranges, and additionally, the average cost has been assigned to the leading load capacity in a given range. Consequently, the determined estimates include mean elasticities for the entire group of tanker sizes and not for various sizes of that given type of ship. Further research should focus on elaborating a model for analyzing the operating cost incurred by various tanker ship capacities. In this case, it is indispensable to have shipping cost data for individual sizes of ships.

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