5. ESTIMATION OF DISPLACEMENT AND MAIN DIMENSIONS

General design characteristics of a ship may be described in three main groups

- The displacement
- The main dimensions, and
- The hull form

In this chapter we will deal with the estimation of size and main dimensions during the early stages of ship design.

5.1. The Displacement of a Ship

The displacement is the weight of the ship, which is equivalent to the weight of water displaced by the ship as it floats. Light ship is the weight of the ship and its permanent equipment. Load displacement is the weight of the ship when it is filled with fuel and cargo to its designed capacity, that is, when it is immersed to its load line. The displacement tonnage is

$$\Delta = \mathrm{DWT} + \mathrm{LS}$$

Where DWT is the Deadweight tonnage and LS indicates the Lightship weight. Light ship displacement is the weight of the ship excluding cargo, fuel, ballast, stores, passengers and crew. The main components of the light ship are the weight of structure, outfit, main and auxiliary machinery, and other equipment.

Deadweight tonnage is the weight, in metric tons, of the cargo, stores, fuel, passengers, and crew carried when the ship is immersed to its maximum summer load line.

Cargo deadweight refers to the revenue generating cargo capacity of a ship and is determined by deducting the weight of fuel, water, stores, crew, passengers and other items necessary for voyage from the deadweight tonnage.

The ratio of the deadweight at the load draught to the corresponding displacement is termed the deadweight coefficient

$$C_D = \frac{\mathrm{DWT}}{\Delta}$$

Typical values of C_D for different ship types are presented in **Table 5.1.**

Table 5.1. DWT/Δ ratios for merchant ships

Ship type	C_D
Passenger ship	0.35
General cargo ship	0.62-0.72
Large bulk carrier	0.78-0.84
Small bulk carrier	0.71-0.77
Container ship	0.70-0.75
Oil tanker	0.80-0.86
Product tanker	0.77-0.83
Ro-Ro	0.50-0.59
Trawler	0.37-0.45
LPG carrier	0.62

Kafalı (1988) recommends the following formulae for small cargo ships and tankers

Tanker	$\frac{\mathrm{DWT}}{\Delta} = \frac{0.775\mathrm{DWT}}{\mathrm{DWT}+250}$
Cargo Ship	$\frac{\mathrm{DWT}}{\Delta} = \frac{0.750\mathrm{DWT}}{\mathrm{DWT}+300}$

5.2. Main Dimensions

The main dimensions (L, B, T, D) affect the many techno-economical performance characteristics of a ship. Therefore the proper selection of the main dimensions is vitally important in the early stages of design.

There may be an infinite number of combinations of length, breadth, depth and draught, which satisfy the main requirements, and restrictions of the design problem. The designer will attempt to find the best combination, however there are too many factors to be investigated within a limited time period. Therefore, the designer, most commonly, will use an iterative approach and the resultant main dimensions will be a compromise solution rather than the optimum values.

The estimation of main dimensions will require an iterative process based on the following order

- Estimate the design displacement.
- Estimate length based on displacement and speed
- Estimate breadth based on length
- Estimate block coefficient based on length and speed
- Calculate draught to satisfy $\Delta = LBTC_B$
- Calculate the required freeboard and hence the minimum required depth

Dimensional constraints may impose a limit on length, breadth, draught and air draught. A constraint on length may be set by the dimensions of canal locks or docks. It may also be set by a need to be able to turn the ship in a narrow waterway. The constrained length is usually the overall length but in some cases the constraint may apply at the waterline at which the ship is floating.

A limit on breadth is usually set by canal or dock lock gates, but the breadth of vehicle ferries is sometimes limited by the dimensions and position of shore ramps giving vehicles access to bow or stern doors. The outreach of other shore based cargo handling devices such as grain elevators or coal hoists can limit the desirable distance of the offshore hatch side from the dockside and thereby limit the breadth of the ship.

A draught limit is usually set by the depth of water in the ports and approaches to which the ship is intended to trade. For very large tankers the depth of the sea itself must be considered.

The air draught of a ship is the vertical distance from the waterline to the highest point of the ship's structure and denotes the ship's ability to pass under a bridge or other obstruction, which forms part of the projected route.

Table 5.2. Dimensional restraints

	Max length (m)	**Max breadth (m)**	**Max draught (m)**	**Air draught (m)**
Suez	-	74.0 48.0	11.0 17.7	-
Panama	289.6 (950 feet)	32.2 (106 feet)	12.04 TFW (39.5 feet)	57.91 (190 feet)
St Lawrence	228.6	22.86	8.0	35.5
Kiel	315	40	9.5	-

5.2.1. Length

The length of a ship will affect most of the technical and economical performance requirements. The following will be observed when two ships with the same displacement but with different length values are compared.

- The longer ship will have larger wetted surface area and hence higher viscous resistance. However, both the wave making resistance and the propulsive performance will improve with and increasing length. Therefore, fast ships should have higher lengths compared with slow speed vessels.
- Both the weight and building cost of ship will increase with length.

- Long ships may achieve the same speed with less engine power; hence the increasing length will reduce the operational costs.
- Increasing length with constant displacement may result in losses in capacity
- Increasing length may detoriate the intact stability characteristics.
- Increasing length will improve the directional stability but worsen the turning ability
- Increasing length will require a higher value of freeboard
- Increasing length will improve the vertical plane motions, including heave, pitch, vertical accelerations, deck wetness and probability of slamming

Many empirical formulae have been proposed to estimate the design length. These formulae are usually based on displacement and design speed.

Ayre ( )

$$L = \Delta^{1/3}\left(\frac{10}{3} + \frac{5}{3}\frac{V}{\sqrt{L}}\right)$$

where L[m], Δ[ton] and V[knot].

Posdunine ( )

$$L = C\left(\frac{V}{V+2}\right)^2 \Delta^{1/3}$$

where L[m], Δ[ton] and V[knot]. C coefficient is recommended as follows

	Watson (1962)	Parsons (1994)	Baxter (1976)
Single screw ships	7.15	7.1 – 7.4 (11-16.5 knots)	7.13
Twin screw ships (slow speed)	7.30	7.4 – 7.7 (15-20 knots)	7.28
Twin screw ships (high speed)	7.90	8.0 – 9.7 (20-30 knots)	7.88

Schneekluth reccommends C=7.25 for freighters with a trial speed of 15.5 to 18.5 knots.

Kafalı (1988) proposes the following values for C coefficient.

$$C = 3\frac{V}{\sqrt{L}} + 3.2$$ Passenger ship

$$C = 1.7\frac{V}{\sqrt{L}} + 4.4$$ Cargo ship - tanker

$$C = 0.75\frac{V}{\sqrt{L}} + 3.66$$ Tug

where V (knot) and L (m)

Gilfillan (1968) proposes the following formula for the length of a bulk carrier

$$L = 7.38\left(\frac{V}{V+2}\right)DWT^{1/3}$$

Völker ( ) proposes the following formula for dry cargo and container ships

$$L = \Delta^{1/3}\left(3.5 + 2.3\frac{V}{\sqrt{g\Delta^{1/3}}}\right)$$

Where L[m], Δ[ton] and V[knot] .

Schneekluth (1987) developed the following formula on the basis of lowest production costs.

$$L = C\Delta^{0.3}V^{0.3}$$

Where L[m], Δ[ton] and V[knot] . C is a coefficient which van be taken 3.2 if the block coefficient has the approximate value of $C_B = \frac{0.145}{F_n}$ within the range of 0.48-0.85. If the block coefficient differs from this value the coefficient C can be modified as follows

$$C = 3.2\frac{C_B + 0.5}{\frac{0.145}{Fn} + 0.5}$$

Where $Fn = \frac{V}{\sqrt{gL}}$ (L [m], V [m/s])

Benford[10] recommends the following formula for liner type general cargo vessels:

$$L = 6.31\left(\frac{V}{V+2}\right)\Delta^{1/3} \qquad\qquad V\ [\text{knot}]$$

Wright () proposes the following formula for the design length

$$L_{BP} = 5.58\,DWT^{1/3}$$

The relation between the term $\left(\frac{V}{V+2}\right)DWT^{1/3}$ and ship design length has been investigated for a large number of recent designs which resulted in a series of empirical formulae as given in the following table.

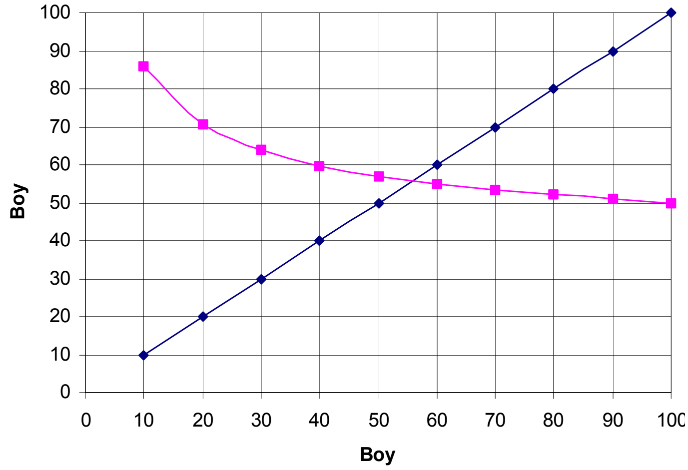
Ship type	Design length (m)	Ship type	Design length (m)
Container	$8.13\left(\frac{V}{V+2}\right)DWT^{1/3} - 33.975$	General Cargo	$5.54\left(\frac{V}{V+2}\right)DWT^{1/3} + 12.041$
Tanker	$5.31\left(\frac{V}{V+2}\right)DWT^{1/3} + 14.743$	Bulk carrier	$5.38\left(\frac{V}{V+2}\right)DWT^{1/3} + 15.461$
Chemical tanker	$5.11\left(\frac{V}{V+2}\right)DWT^{1/3} + 16.945$		

Example 5.1. Estimate the length of a ship with a displacement of 1000 ton and a design speed of 10 knots by using the Ayre formula.

Solution: The Ayre formula will require and iterative approach as shown in the following table

Displacement	Speed	L	$\Delta^{1/3}\left(\frac{10}{3} + \frac{5}{3}\frac{V}{\sqrt{L}}\right)$
1000	10	100.0000	50.0000
1000	10	50.0000	56.9036
1000	10	56.9036	55.4276
1000	10	55.4276	55.7198
1000	10	55.7198	55.6610
1000	10	55.6610	55.6728
1000	10	55.6728	55.6705
1000	10	55.6704	55.6709
1000	10	55.6709	55.6708
1000	10	55.6708	55.6708

This process can also be carried out graphically as shown below.

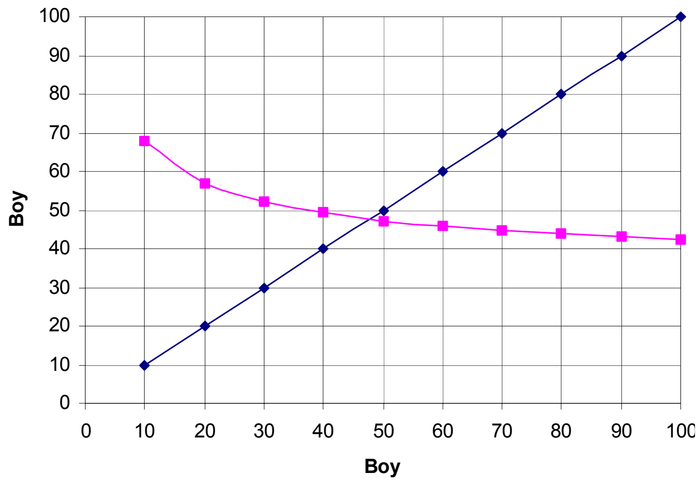


Example 5.2. Estimate the length of a ship with displacement 1000 t and speed 10 knots by using Posdunine's formula. C will be taken as $C = 1.7\dfrac{V}{\sqrt{L}} + 4.4$

Solution

Displacement	**Speed**	L	$C\left(\dfrac{V}{V+2}\right)^2 \Delta^{1/3}$
1000	10	100.000	42.361
1000	10	42.361	48.694
1000	10	48.694	47.474
1000	10	47.474	47.690
1000	10	47.690	47.651
1000	10	47.651	47.658
1000	10	47.658	47.657
1000	10	47.657	47.657

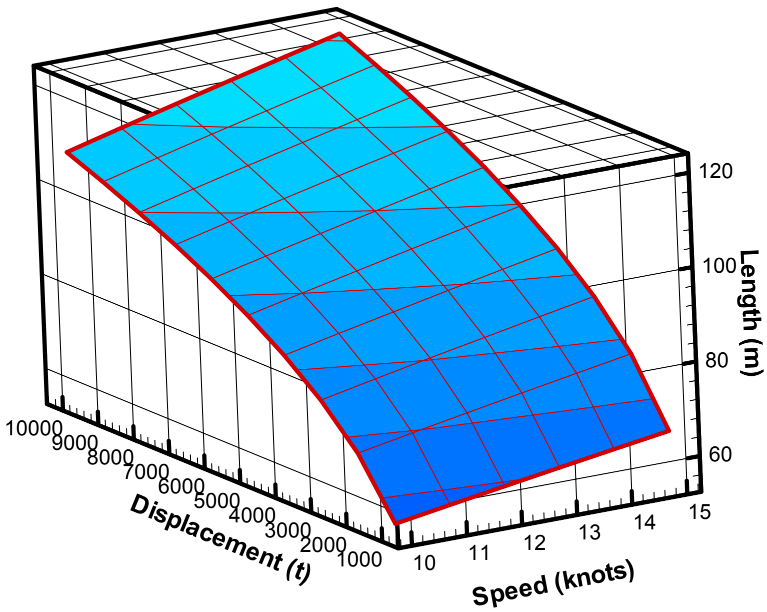
The same result can be obtained graphically as follows:



Example 5.3. Estimate the length for ships with displacement between 1000-10000 t and design speed 10-15 knot by using Ayre, Posdunine, Völker and Schneekluth formulae.

Solution:

Δ	Speed	Ayre	Posdunine	Schneekluth	Völker
1000	10	55,6708	47,6567	50,7166	58,2258
1000	11	57,5088	50,3682	52,1877	60,5484
1000	12	59,3042	52,9278	53,5679	62,8710
1000	13	61,0608	55,3590	54,8698	65,1936
1000	14	62,7817	57,6802	56,1033	67,5161
1000	15	64,4694	59,9062	57,2766	69,8387
2000	10	67,5472	58,0241	62,4394	70,1673
2000	11	69,6706	61,2461	64,2506	72,7743
2000	12	71,7464	64,2814	65,9498	75,3813
2000	13	73,7786	67,1593	67,5526	77,9884
2000	14	75,7704	69,9029	69,0713	80,5954
2000	15	77,7249	72,5302	70,5158	83,2024
3000	10	75,7021	65,1614	70,5158	78,3715
3000	11	78,0116	68,7276	72,5612	81,1607
3000	12	80,2703	72,0831	74,4802	83,9500
3000	13	82,4824	75,2611	76,2903	86,7393
3000	14	84,6513	78,2878	78,0054	89,5286
3000	15	86,7802	81,1840	79,6368	92,3178
4000	10	82,1103	70,7791	76,8720	84,8217
4000	11	84,5611	74,6127	79,1017	87,7480
4000	12	86,9589	78,2165	81,1937	90,6743
4000	13	89,3077	81,6271	83,1670	93,6005
4000	14	91,6114	84,8731	85,0367	96,5268
4000	15	93,8730	87,9771	86,8151	99,4531
5000	10	87,4715	75,4845	82,1942	90,2206
5000	11	90,0376	79,5400	84,5783	93,2578
5000	12	92,5488	83,3497	86,8151	96,2949
5000	13	95,0093	86,9528	88,9250	99,3321
5000	14	97,4229	90,3801	90,9242	102,3692
5000	15	99,7929	93,6560	92,8257	105,4064
6000	10	92,1241	79,5718	86,8151	94,9078
6000	11	94,7882	83,8185	89,3333	98,0386
6000	12	97,3958	87,8055	91,6959	101,1695
6000	13	99,9512	91,5743	93,9244	104,3003
6000	14	102,4584	95,1576	96,0359	107,4312
6000	15	104,9207	98,5812	98,0444	110,5620
7000	10	96,2600	83,2080	90,9242	99,0759
7000	11	99,0097	87,6238	93,5615	102,2883
7000	12	101,7016	91,7674	96,0359	105,5006
7000	13	104,3401	95,6826	98,3700	108,7129
7000	14	106,9290	99,4035	100,5814	111,9253
7000	15	109,4719	102,9574	102,6850	115,1376
8000	10	100,0000	86,4982	94,6405	102,8463
8000	11	102,8260	91,0662	97,3856	106,1309
8000	12	105,5929	95,3507	99,9612	109,4155
8000	13	108,3054	99,3974	102,3906	112,7001
8000	14	110,9672	103,2420	104,6925	115,9848
8000	15	113,5820	106,9129	106,8820	119,2694
9000	10	103,4253	89,5133	98,0444	106,3004
9000	11	106,3202	94,2201	100,8883	109,6501
9000	12	109,1550	98,6330	103,5565	112,9998
9000	13	111,9343	102,7995	106,0732	116,3496
9000	14	114,6622	106,7568	108,4579	119,6993
9000	15	117,3420	110,5342	110,7261	123,0491
10000	10	106,5935	92,3034	101,1929	109,4960
10000	11	109,5514	97,1381	104,1281	112,9051
10000	12	112,4483	101,6694	106,8820	116,3142
10000	13	115,2887	105,9463	109,4796	119,7233
10000	14	118,0769	110,0072	111,9408	123,1324
10000	15	120,8162	113,8826	114,2819	126,5415



5.2.2. Breadth

The effects of breadth on techno-eceonomic performance characteristics of a ship can be summarized as follows.

- Increasing breadth will increase the resistance and hence the engine power and operating costs
- Increasing breadth will improve the initial stability characteristics.
- The weight and cost of hull will increase with increasing breadth
- Roll period will reduce with increasing breadth

The breadth of conventional ship types may be estimated based on the length as shown in the following formulae

Ship Type	Formula	Proposed by
Passenger ship	$\frac{L}{9}+6.1$	
General cargo	$\frac{L}{9}+4.27$	
	$0.125L+2.45$	
	$\frac{L}{9}+6 \quad \text{to} \quad 7.5$	(Munro-Smith)
Tanker	$\frac{L}{7.5}+1.98$	
	$0.125L+2.45$	
	$\frac{L}{9}+4.5 \quad \text{to} \quad 6.5$	(Munro-Smith)
VLCC	$\frac{L}{9}+12 \quad \text{to} \quad 15$	
	$\frac{L}{5}-14$	(Munro-Smith)
Bulk carrier	$0.146L-1.04$	
Containership	$0.150L+2.45$	
RoRo	$\frac{L}{10}+8$	
Tug	$0.200L+2.45$	
	$0.220L+1.50$	

The breadth of containerships can be estimated on the basis of the number of containers located transversely in the ship. The standard ISO container has a width of 2.44 m. However, each container requires an allowance for clearence, guides etc. of about 240 mm so that each container requires a width of 2.68 m.

Thus the number n of cells located transversely in the ship require 2.68n metres. Since the width available for containers is about 80 percent of the ship's breadth, then B=3.35n.

5.2.3. Draught

Draught of a ship is less effective on technical and economical performance compared with length or breadth. Therefore the draught is usually selected to satisfy the displacement equation $\nabla = LBTC_B$. The draught may be limited due to the depths of port, harbour and canals. Low draught increases the risk of bow slamming in rough seas.

5.2.4. Depth

Depth of a ship may be estimated as the sum of design draught and the freeboard. The weight and cost of the ship will increase with increasing depth. Classification Societies may impose certain limits on L/D ratio due to the longitudinal strength characteristics. However lower values of L/D may result in buckling problems. The depth will increase the height of centre of gravity which will affect the stability and seakeeping characteristics of the vessel. The following formulae may be suggested for an initial estimate of depth.

Ship Type	**Formula**	**Proposed by**
Passenger ship	$D = \frac{B + 0.3}{1.5}$	
Cargo	$D = \frac{B - 2}{1.4}$	
	$D = \frac{B}{1.65}$	Watson (1998)
Tanker	$D = \frac{L}{13.5}$	
	$D = \frac{L}{12.5}$	Watson (1998)
	$D = \frac{B}{1.9}$	Watson (1998)
	$D = \frac{T}{0.78}$	Watson (1998)
Bulk carrier	$D = \frac{B - 3}{1.5}$	Munro-Smith
	$D = \frac{B}{1.9}$	Watson (1998)
	$D = \frac{T}{0.73}$	Watson (1998)
	$D = \frac{L}{11.5}$	Watson (1998)
Containership	$D = \frac{B}{1.7}$	Watson (1998)
Frigate	$D = \frac{T}{0.46}$	Watson (1998)
	$D = \frac{L}{13.3}$	Watson (1998)

L, B, D in meters.

The depth of a container ship is in general controlled by the number of containers to be carried in the hold. Thus

$$D = 2.43n + h$$

where n is the number of tiers of containers in holds and h is the height of double bottom.

5.2.5. Length to Beam Ratio

L/B ratio affects powering and directional stability. A steady decrease in L/B in recent years can be seen in an effort to reduce ship cost and with increased design effort to produce good inflow to the propeller with the greater beam. Watson&Gilfillan (1977) proposes the following values

$$\frac{L}{B} = 6.5 \qquad L \geq 130 \text{ m}$$
$$\frac{L}{B} = 4.0 + 0.025(L - 30) \qquad 30 \leq L \leq 130 \text{ m}$$
$$\frac{L}{B} = 4.0 \qquad L \leq 30 \text{ m}$$

5.2.6. Length to Depth Ratio

L/D ratio is a primary factor in longitudinal strength. Classification Societies, in general, require special consideration L/D>15.

5.2.7. Beam to Depth Ratio

B/D ratio has a major impact on stability.

5.2.8. Beam to Draught Ratio

If this ratio is too small stability may be a problem; too large residuary resistance goes up.

$$\left(\frac{B}{T}\right)\Bigg|_{\min C_S} = 5.93 - 3.33C_M \qquad \left(\frac{B}{T}\right)_{\max} = 9.625 - 7.5C_B$$

Example 5.4. Estimate the dimensions of a dry cargo ship of 13000 tonnes DWT at a maximum draught of 8.0 m and with a service speed of 15 knots. Assume C_D=0.67 and C_B=0.7.

Solution:

Displacement $\quad \Delta = \dfrac{DWT}{C_D} = \dfrac{13000}{0.67} = 19403\,\text{t}$

Length (Ayre) $\quad L = \Delta^{1/3}\left(\dfrac{10}{3} + \dfrac{5}{3}\dfrac{V}{\sqrt{L}}\right) \quad \Rightarrow \quad L = 145.25 \text{ m}$

Length (Posdunine) $\quad L = C\left(\dfrac{V}{V+2}\right)^2 \Delta^{1/3} \quad \Rightarrow \quad L = 149.6 \text{ m}$ with C=7.15

Length (average) $\quad L = 147.425 \text{ m}$

Breadth $\quad B = \dfrac{L}{9} + 6 = 22.38 \text{ m}$

Draught $\quad T = \dfrac{\nabla}{LBC_B} = \dfrac{19403/1.025}{147.425 \times 22.38 \times 0.7} = 8.2 \text{ m}$

Depth $\quad D = \dfrac{B-2}{1.4} = 14.56 \text{ m}$

$\quad D = \dfrac{B}{1.65} = 13.56 \text{ m}$

Depth (average) $\quad D = 14.06 \text{ m}$

5.2.5. Freeboard (Load Line)

Safe loading, weight and balance have always been very serious issues for seafarers. In England, Samuel Plimsoll became the moving force to establish safe loading as a rule of law in 1875. Through his efforts, safe loading standards were adopted and given the force of law. The first International Convention on Load Lines, adopted in 1930, was based on the principle of reserve buoyancy, although it was recognized then that the freeboard should also ensure adequate stability and avoid excessive stress on the ship's hull as a result of overloading.

5.2.5.1. International Convention on Load Lines (1966)

In the 1966 Load Lines convention, adopted by IMO, provisions are made determining the freeboard of tankers by subdivision and damage stability calculations. Load line conventions were conceived as instruments to assign the maximum safe draught for ships to operate at sea. At the 1966 Load Line Convention, the uppermost criteria were the following

1. Prevent entry of water into the hull
2. Adequate reserve buoyancy
3. Protection of the crew
4. Adequate hull strength and ability
5. Limitation of deck wetness

The 1988 Protocol
Adoption: 11 November 1988 Entry into force: 3 February 2000

The Protocol was primarily adopted in order to harmonize the Convention's survey and certification requirement with those contained in SOLAS and MARPOL 73/78. All three instruments require the issuing of certificates to show that requirements have been met and this has to be done by means of a survey which can involve the ship being out of service for several days.

Revision of Load Lines Convention
The 1966 Load Lines Convention (as revised by the 1988 Protocol entering into force on 3 February 2000) is currently being revised by IMO's Sub-Committee on Stability, Load lines and Fishing Vessel Safety (SLF). In particular, the revision is focusing on wave loads and permissible strengths of hatch covers for bulk carriers and other ship types.

Article 5 *Exceptions :* These Regulations do not apply to

(a) ships of less than 24 metres in length
(b) warships
(c) fishing vessels
(d) pleasure yacht;
(e) ship without means of self-propulsion that is making a voyage

Regulation 3 *Definitions*
Length. The length (L) shall be taken as 96 per cent of the total length on a water line at 85 per cent of the least moulded depth measured from the top of the keel, or as the length from the foreside of the stem to the axis of the rudder stock on that water line, if that is greater.
Perpendiculars. The forward and after perpendiculars shall be taken at the forward and after ends of the length (L). The forward perpendicular shall coincide with the foreside of the stem on the water line on which the length is measured.
Amidships. Amidships is at the middle of the length (L).
Breadth. Unless expressly provided otherwise, the breadth (B) is the maximum breadth of the ship, measured amidships to the moulded line of the frame in a ship with a metal shell and to the outer surface of the hull in a ship with a shell of any other material.
Moulded Depth. The moulded depth is the vertical distance measured from the top of the keel to the top of the freeboard deck beam at side. In wood and composite ships the distance is measured from the lower edge of the keel rabbet.
Depth for Freeboard (D). The depth for freeboard (D) is the moulded depth amidships, plus the thickness of the freeboard deck stringer plate, where fitted, plus $\frac{T(L-S)}{L}$ if the exposed freeboard deck is sheathed, where T is the mean thickness of the exposed sheathing clear of deck openings, and S is the total length of superstructures.

Block Coefficient. The block coefficient (C_b) is given by:

$$C_b = \frac{\nabla}{LBT}$$

∇ is the volume of the moulded displacement of the ship, excluding bossing, in a ship with a metal shell, and is the volume of displacement to the outer surface of the hull in a ship with a shell of any other material, both taken at a moulded draught of T; and where T is 85 per cent of the least moulded depth.

Freeboard. The freeboard assigned is the distance measured vertically downwards amidships from the upper edge of the deck line to the upper edge of the related load line

Freeboard Deck. The freeboard deck is normally the uppermost complete deck exposed to weather and sea, which has permanent means of closing all openings in the weather part thereof, and below which all openings in the sides of the ship are fitted with permanent means of watertight closing.

Superstructure.

(a) A superstructure is a decked structure on the freeboard deck, extending from side to side of the ship or with the side plating not being inboard of the shell plating more than four per cent of the breadth (B). A raised quarter deck is regarded as a superstructure.

(b) The height of a superstructure is the least vertical height measured at side from the top of the superstructure deck beams to the top of the freeboard deck beams.

(c) The length of a superstructure (S) is the mean length of the part of the superstructure which lies within the length (L).

Flush Deck Ship. A flush deck ship is one which has no superstructure on the freeboard deck.

Weathertight. Weathertight means that in any sea conditions water will not penetrate into the ship.

Regulation 4 *Deck Line*

The deck line is a horizontal line 300 mm in length and 23 mm in breadth. It shall be marked amidships on each side of the ship, and its upper edge shall normally pass through the point where the continuation outwards of the upper surface of the freeboard deck intersects the outer surface of the shell (as illustrated in Figure 5.7).

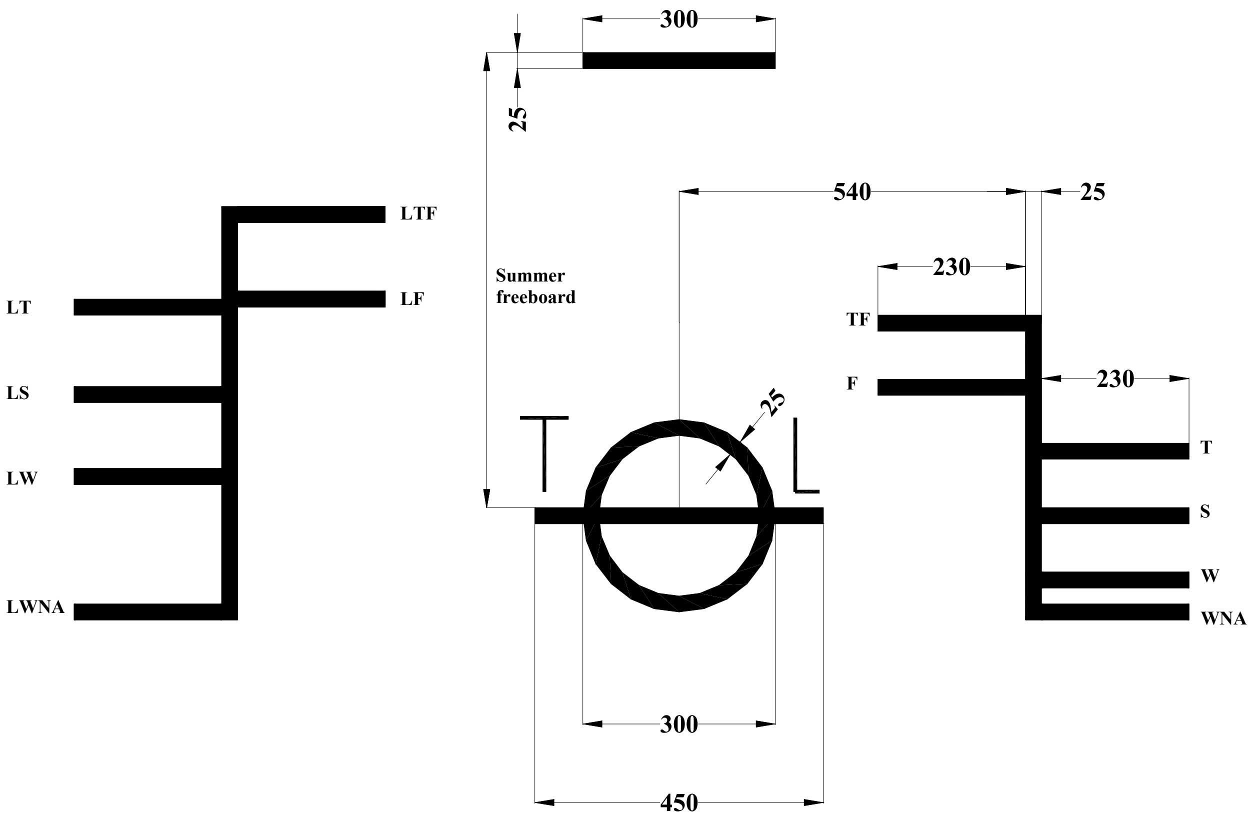


Figure 5.2. Load line mark

Regulation 5 *Load Line Mark*

The Load Line Mark shall consist of a ring 300 mm in outside diameter and 25 mm wide which is intersected by a horizontal line 450 mm in length and 25 mm in breadth, the upper edge of which passes through the centre of the ring. The centre of the ring shall be placed amidships and at a distance equal to the assigned summer freeboard measured vertically below the upper edge of the deck line (as illustrated in Figure 5.7).

Regulation 6 *Lines to be used with the Load Line Mark*

(1) The lines which indicate the load line assigned in accordance with these Regulations shall be horizontal lines 230 mm in length and 25 mm in breadth which extend forward of, unless expressly provided otherwise, and at right angles to, a vertical line 25 mm in breadth marked at a distance 540 mm forward of the centre of the ring (as illustrated in Figure 5.7).

(2) The following load lines shall be used:
   (a) the Summer Load Line indicated by the upper edge of the line which passes through the centre of the ring and also by a line marked S;
   (b) the Winter Load Line indicated by the upper edge of a line marked W;
   (c) the Winter North Atlantic Load Line indicated by the upper edge of a line marked WNA;
   (d) the Tropical Load Line indicated by the upper edge of a line marked T;
   (e) the Fresh Water Load Line in summer indicated by the upper edge of a line marked F. The Fresh Water Load Line in summer is marked abaft the vertical line. The difference between the Fresh Water Load Line in summer and the Summer Load Line is the allowance to be made for loading in fresh water at the other load lines; and
   (f) the Tropical Fresh Water Load Line indicated by the upper edge of a line marked TF, and marked abaft the vertical line.

(3) If timber freeboards are assigned in accordance with these Regulations, the timber load lines shall be marked in addition to ordinary load lines. These lines shall be horizontal lines 230 mm in length and 25 mm in breadth which extend abaft unless expressly provided otherwise, and are at right angles to, a vertical line 25 mm in breadth marked at a distance 540 mm abaft the centre of the ring (as illustrated in Figure 5.7).

(4) The following timber load lines shall be used:
   (a) the Summer Timber Load Line indicated by the upper edge of a line marked LS;
   (b) the Winter Timber Load Line indicated by the upper edge of a line marked LW;
   (c) the Winter North Atlantic Timber Load Line indicated by the upper edge of a line marked LWNA;
   (d) the Tropical Timber Load Line indicated by the upper edge of a line marked LT;
   (e) the Fresh Water Timber Load Line in summer indicated by the upper edge of a line marked LF and marked forward of the vertical line. The difference between the Fresh Water Timber Load Line in summer and the Summer Timber Load Line is the allowance to be made for loading in fresh water at the other timber load lines; and
   (f) the Tropical Fresh Water Timber Load Line indicated by the upper edge of a line marked LTF and marked forward of the vertical line.

Regulation 7 *Mark of Assigning Authority*

The mark of the Authority by whom the load lines are assigned may be indicated alongside the load line ring above the horizontal line which passes through the centre of the ring, or above and below it. This mark shall consist of not more than four initials to identify the Authority's name, each measuring approximately 115 mm in height and 75 mm in width.

Regulation 27 ***Types of Ships***

(1) For the purposes of freeboard computation, ships shall be divided into Type `A' and Type `B'.

Type `A' ships

(2) A Type `A' ship is one which is designed to carry only liquid cargoes in bulk, and in which cargo tanks have only small access openings closed by watertight gasketed covers of steel or equivalent material.

(3) A Type `A' ship shall be assigned a freeboard not less than that based on Table A.

Type `B' ships

(4) All ships which do not come within the provisions regarding Type `A' ships shall be considered as Type `B' ships.

(5) Any Type `B' ships of over 100 m in length may be assigned freeboards less than those required under subsections (6) of this Regulation provided that, in relation to the amount of reduction granted, the Administration is satisfied that:
   (a) the measures provided for the protection of the crew are adequate;
   (b) the freeing arrangements are adequate;
   (c) the covers in positions 1 and 2 comply with the provisions of Regulation 16 and have adequate strength, special care being given to their sealing and securing arrangements;

(d) the ship, when loaded to its summer load water line, will remain afloat in a satisfactory condition of equilibrium after flooding of any single damaged compartment at an assumed permeability of 0.95 excluding the machinery space; and
(e) in such a ship, if over 225 m in length, the machinery space shall be treated as a floodable compartment but with a permeability of 0.85.

The relevant calculations may be based upon the following main assumptions:

- the vertical extent of damage is equal to the depth of the ship;
- the penetration of damage is not more than B/5;
- no main transverse bulkhead is damaged;
- the height of the centre of gravity above the base line is assessed allowing for homogeneous loading of cargo holds, and for 50 per cent of the designed capacity of consumable fluids and stores, etc.

(6) In calculating the freeboards for Type `B' ships which comply with the requirements of subsection (7) of this Regulation, the values from Table B of Regulation 28 shall not be reduced by more than 60 per cent of the difference between the `B' and `A' tabular values for the appropriate ship lengths.
(7) The reduction in tabular freeboard allowed under subsection (8) of this Regulation may be increased up to the total difference between the values in Table A and those in Table B of Regulation 28 on condition that the ship complies with the requirements of Regulations 26(1), (2), (3), (5) and (6), as if it were a Type `A' ship, and further complies with the provisions of paragraphs (7)(a) to (d) inclusive of this Regulation except that the reference in paragraph (d) to the flooding of any single damaged compartment shall be treated as a reference to the flooding of any two adjacent fore and aft compartments, neither of which is the machinery space. Also any such ship of over 225 m in length, when loaded to its summer load water line, shall remain afloat in a satisfactory condition of equilibrium after flooding of the machinery space, taken alone, at an assumed permeability of 0.85.
(8) Type `B' ships, which in position 1 have hatchways fitted with hatch covers which comply with the requirements of Regulation 15, other than subsection (7), shall be assigned freeboards based upon the values given in Table B of Regulation 28 increased by the values given in the following table:

Regulation 29 *Correction to the Freeboard for Ships under100 m in length*
The tabular freeboard for a Type `B' ship of between 24 m and 100 m in length having enclosed superstructures with an effective length of up to 35 per cent of the length of the ship shall be increased by:

$$7.5(100 - \mathrm{L})\left(0.35 - \frac{\mathrm{E}}{\mathrm{L}}\right) \text{ mm}$$

where L = length of ship in metres,
where E = effective length of superstructure in metres defined in Regulations 35.

Regulation 30 *Correction for Block Coefficient*
Where the block coefficient (C_b) exceeds 0.68, the tabular shall be multiplied by the factor

$$\frac{C_b + 0.68}{1.36}$$

Regulation 31 *Correction for Depth*

(1) Where D exceeds $\frac{L}{15}$ the freeboard shall be increased by $\left(D - \frac{L}{15}\right)R$ millimetres, where R is $\frac{L}{0.48}$ at length less than 120 m and 250 at 120 m length and above.

(2) Where D is less than $\frac{L}{15}$, no reduction shall be made except in a ship with an enclosed superstructure covering at least 0.6 L amidships, with a complete trunk, or combination of detached enclosed superstructures and trunks which extend all fore and aft, where the freeboard shall be reduced at the rate prescribed in paragraph (1) of this Regulation.

(3) Where the height of superstructure or trunk is less than the standard height, the reduction shall be in the ratio of the actual to the standard height as defined in Regulation 33.

Regulation 28 : Table A. Freeboard Tables, Type `A' Ships

L [m]	f [mm]	L [m]	f [mm]	L [m]	f [mm]	L [m]	f [mm]	L [m]	f [mm]	L [m]	f [mm]
24	200	**81**	855	**138**	1770	**195**	2562	**252**	3024	**309**	3295
25	208	**82**	869	**139**	1787	**196**	2572	**253**	3030	**310**	3298
26	217	**83**	883	**140**	1803	**197**	2582	**254**	3036	**311**	3302
27	225	**84**	897	**141**	1820	**198**	2592	**255**	3042	**312**	3305
28	233	**85**	911	**142**	1837	**199**	2602	**256**	3048	**313**	3308
29	242	**86**	926	**143**	1853	**200**	2612	**257**	3054	**314**	3312
30	250	**87**	940	**144**	1870	**201**	2622	**258**	3060	**315**	3315
31	258	**88**	955	**145**	1886	**202**	2632	**259**	3066	**316**	3318
32	267	**89**	969	**146**	1903	**203**	2641	**260**	3072	**317**	3322
33	275	**90**	984	**147**	1919	**204**	2650	**261**	3078	**318**	3325
34	283	**91**	999	**148**	1935	**205**	2659	**262**	3084	**319**	3328
35	292	**92**	1014	**149**	1952	**206**	2669	**263**	3089	**320**	3331
36	300	**93**	1029	**150**	1968	**207**	2678	**264**	3095	**321**	3334
37	308	**94**	1044	**151**	1984	**208**	2687	**265**	3101	**322**	3337
38	316	**95**	1059	**152**	2000	**209**	2696	**266**	3106	**323**	3339
39	325	**96**	1074	**153**	2016	**210**	2705	**267**	3112	**324**	3342
40	334	**97**	1089	**154**	2032	**211**	2714	**268**	3117	**325**	3345
41	344	**98**	1105	**155**	2048	**212**	2723	**269**	3123	**326**	3347
42	354	**99**	1120	**156**	2064	**213**	2732	**270**	3128	**327**	3350
43	364	**100**	1135	**157**	2080	**214**	2741	**271**	3133	**328**	3353
44	374	**101**	1151	**158**	2096	**215**	2749	**272**	3138	**329**	3355
45	385	**102**	1166	**159**	2111	**216**	2758	**273**	3143	**330**	3358
46	396	**103**	1181	**160**	2126	**217**	2767	**274**	3148	**331**	3361
47	408	**104**	1196	**161**	2141	**218**	2775	**275**	3153	**332**	3363
48	420	**105**	1212	**162**	2155	**219**	2784	**276**	3158	**333**	3366
49	432	**106**	1228	**163**	2169	**220**	2792	**277**	3163	**334**	3368
50	443	**107**	1244	**164**	2184	**221**	2801	**278**	3167	**335**	3371
51	455	**108**	1260	**165**	2198	**222**	2809	**279**	3172	**336**	3373
52	467	**109**	1276	**166**	2212	**223**	2817	**280**	3176	**337**	3375
53	478	**110**	1293	**167**	2226	**224**	2825	**281**	3181	**338**	3378
54	490	**111**	1309	**168**	2240	**225**	2833	**282**	3185	**339**	3380
55	503	**112**	1326	**169**	2254	**226**	2841	**283**	3189	**340**	3382
56	516	**113**	1342	**170**	2268	**227**	2849	**284**	3194	**341**	3385
57	530	**114**	1359	**171**	2281	**228**	2857	**285**	3198	**342**	3387
58	544	**115**	1376	**172**	2294	**229**	2865	**286**	3202	**343**	3389
59	559	**116**	1392	**173**	2307	**230**	2872	**287**	3207	**344**	3392
60	573	**117**	1409	**174**	2320	**231**	2880	**288**	3211	**345**	3394
61	587	**118**	1426	**175**	2332	**232**	2888	**289**	3215	**346**	3396
62	600	**119**	1442	**176**	2345	**233**	2895	**290**	3220	**347**	3399
63	613	**120**	1459	**177**	2357	**234**	2903	**291**	3224	**348**	3401
64	626	**121**	1476	**178**	2369	**235**	2910	**292**	3228	**349**	3403
65	639	**122**	1494	**179**	2381	**236**	2918	**293**	3233	**350**	3406
66	653	**123**	1511	**180**	2393	**237**	2925	**294**	3237	**351**	3408
67	666	**124**	1528	**181**	2405	**238**	2932	**295**	3241	**352**	3410
68	680	**125**	1546	**182**	2416	**239**	2939	**296**	3246	**353**	3412
69	693	**126**	1563	**183**	2428	**240**	2946	**297**	3250	**354**	3414
70	706	**127**	1580	**184**	2440	**241**	2953	**298**	3254	**355**	3416
71	720	**128**	1598	**185**	2451	**242**	2959	**299**	3258	**356**	3418
72	733	**129**	1615	**186**	2463	**243**	2966	**300**	3262	**357**	3420
73	746	**130**	1632	**187**	2474	**244**	2973	**301**	3266	**358**	3422
74	760	**131**	1650	**188**	2486	**245**	2979	**302**	3270	**359**	3423
75	773	**132**	1667	**189**	2497	**246**	2986	**303**	3274	**360**	3425
76	786	**133**	1684	**190**	2508	**247**	2993	**304**	3278	**361**	3427
77	800	**134**	1702	**191**	2519	**248**	3000	**305**	3281	**362**	3428
78	814	**135**	1719	**192**	2530	**249**	3006	**306**	3285	**363**	3430
79	828	**136**	1736	**193**	2541	**250**	3012	**307**	3288	**364**	3432
80	841	**137**	1753	**194**	2552	**251**	3018	**308**	3292	**365**	3433

Freeboards at intermediate lengths of ship shall be obtained by linear interpolation.

Freeboards for type A ships with length of between 365 metres and 400 metres should be determined by the following formula

$$f = 221 + 16.10L - 0.02L^2$$

where f is the freeboard in mm. Freeboards for type A ships with length of 400 metres and above should be the constant value, 3460 mm.

TABLE B. Freeboard Table for Type `B' Ships

L [m]	f [mm]	L [m]	f [mm]	L [m]	f [mm]	L [m]	f [mm]	L [m]	f [mm]	L [m]	f [mm]
24	200	**81**	905	**138**	2065	**195**	3185	**252**	4045	**309**	4726
25	208	**82**	923	**139**	2087	**196**	3202	**253**	4058	**310**	4736
26	217	**83**	942	**140**	2109	**197**	3219	**254**	4072	**311**	4748
27	225	**84**	960	**141**	2130	**198**	3235	**255**	4085	**312**	4757
28	233	**85**	978	**142**	2151	**199**	3249	**256**	4098	**313**	4768
29	242	**86**	996	**143**	2171	**200**	3264	**257**	4112	**314**	4779
30	250	**87**	1015	**144**	2190	**201**	3280	**258**	4125	**315**	4790
31	258	**88**	1034	**145**	2209	**202**	3296	**259**	4139	**316**	4801
32	267	**89**	1054	**146**	2229	**203**	3313	**260**	4152	**317**	4812
33	275	**90**	1075	**147**	2250	**204**	3330	**261**	4165	**318**	4823
34	283	**91**	1096	**148**	2271	**205**	3347	**262**	4177	**319**	4834
35	292	**92**	1116	**149**	2293	**206**	3363	**263**	4189	**320**	4844
36	300	**93**	1135	**150**	2315	**207**	3380	**264**	4201	**321**	4855
37	308	**94**	1154	**151**	2334	**208**	3397	**265**	4214	**322**	4866
38	316	**95**	1172	**152**	2354	**209**	3413	**266**	4227	**323**	4878
39	325	**96**	1190	**153**	2375	**210**	3430	**267**	4240	**324**	4890
40	334	**97**	1209	**154**	2396	**211**	3445	**268**	4252	**325**	4899
41	344	**98**	1229	**155**	2418	**212**	3460	**269**	4264	**326**	4909
42	354	**99**	1250	**156**	2440	**213**	3475	**270**	4276	**327**	4920
43	364	**100**	1271	**157**	2460	**214**	3490	**271**	4289	**328**	4931
44	374	**101**	1293	**158**	2480	**215**	3505	**272**	4302	**329**	4943
45	385	**102**	1315	**159**	2500	**216**	3520	**273**	4315	**330**	4955
46	396	**103**	1337	**160**	2520	**217**	3537	**274**	4327	**331**	4965
47	408	**104**	1359	**161**	2540	**218**	3554	**275**	4339	**332**	4975
48	420	**105**	1380	**162**	2560	**219**	3570	**276**	4350	**333**	4985
49	432	**106**	1401	**163**	2580	**220**	3586	**277**	4362	**334**	4995
50	443	**107**	1421	**164**	2600	**221**	3601	**278**	4373	**335**	5005
51	455	**108**	1440	**165**	2620	**222**	3615	**279**	4385	**336**	5015
52	467	**109**	1459	**166**	2640	**223**	3630	**280**	4397	**337**	5025
53	478	**110**	1479	**167**	2660	**224**	3645	**281**	4408	**338**	5035
54	490	**111**	1500	**168**	2680	**225**	3660	**282**	4420	**339**	5045
55	503	**112**	1521	**169**	2698	**226**	3675	**283**	4432	**340**	5055
56	516	**113**	1543	**170**	2716	**227**	3690	**284**	4443	**341**	5065
57	530	**114**	1565	**171**	2735	**228**	3705	**285**	4455	**342**	5075
58	544	**115**	1587	**172**	2754	**229**	3720	**286**	4467	**343**	5086
59	559	**116**	1609	**173**	2774	**230**	3735	**287**	4478	**344**	5097
60	573	**117**	1630	**174**	2795	**231**	3750	**288**	4490	**345**	5108
61	587	**118**	1651	**175**	2815	**232**	3765	**289**	4502	**346**	5119
62	601	**119**	1671	**176**	2835	**233**	3780	**290**	4513	**347**	5130
63	615	**120**	1690	**177**	2855	**234**	3795	**291**	4525	**348**	5140
64	629	**121**	1709	**178**	2875	**235**	3808	**292**	4537	**349**	5150
65	644	**122**	1729	**179**	2895	**236**	3821	**293**	4548	**350**	5160
66	659	**123**	1750	**180**	2915	**237**	3835	**294**	4560	**351**	5170
67	674	**124**	1771	**181**	2933	**238**	3849	**295**	4572	**352**	5180
68	689	**125**	1793	**182**	2952	**239**	3864	**296**	4583	**353**	5190
69	705	**126**	1815	**183**	2970	**240**	3880	**297**	4595	**354**	5200
70	721	**127**	1837	**184**	2988	**241**	3893	**298**	4607	**355**	5210
71	738	**128**	1859	**185**	3007	**242**	3906	**299**	4618	**356**	5220
72	754	**129**	1880	**186**	3025	**243**	3920	**300**	4630	**357**	5230
73	769	**130**	1901	**187**	3044	**244**	3934	**301**	4642	**358**	5240
74	784	**131**	1921	**188**	3062	**245**	3949	**302**	4654	**359**	5250
75	800	**132**	1940	**189**	3080	**246**	3965	**303**	4665	**360**	5260
76	816	**133**	1959	**190**	3098	**247**	3978	**304**	4676	**361**	5268
77	833	**134**	1979	**191**	3116	**248**	3992	**305**	4686	**362**	5276
78	850	**135**	2000	**192**	3134	**249**	4005	**306**	4695	**363**	5285
79	868	**136**	2021	**193**	3151	**250**	4018	**307**	4704	**364**	5294
80	887	**137**	2043	**194**	3167	**251**	4032	**308**	4714	**365**	5303

Freeboards at intermediate lengths of ship shall be obtained by linear interpolation.

Freeboards for type A ships with length of between 365 metres and 400 metres should be determined by the following formula

$$f = -587 + 23L - 0.0188L^2$$

where f is the freeboard in mm. Freeboards for type A ships with length of 400 metres and above should be the constant value, 5605 mm.

Regulation 33 *Standard Height of Superstructure*
The standard height of a superstructure shall be as given in the following table:

L (metres)	Standard Height (in metres)	
	Raised Quarter Deck	All other Superstructures
≤ 30	0.90	1.80
75	1.20	1.80
≥ 125	1.80	2.30

The standard heights at intermediate lengths of the ship shall be obtained by linear interpolation.

Regulation 34 *Length of Superstructure*
(1) Except as provided in subsection (2) of this Regulation, the length of a superstructure (S) shall be the mean length of the parts of the superstructure which lie within the length (L).

Regulation 35 *Effective Length of Superstructure*
(1) Except as provided for in subsection (2) of this Regulation, the effective length (E) of an enclosed superstructure of standard height shall be its length.
(2) In all cases where an enclosed superstructure of standard height is set in from the sides of the ship as permitted in subsection 3(10) the effective length is the length modified by the ratio of b/Bs, where
"b" is the breadth of the superstructure at the middle of its length, and
"Bs" is the breadth of the ship at the middle of the length of the superstructure, and
where a superstructure is set in for a part of its length, this modification shall be applied only to the set in part.
(3) Where the height of an enclosed superstructure is less than the standard height, the effective length shall be its length reduced in the ratio of the actual height to the standard height. Where the height exceeds the standard, no increase shall be made to the effective length of the superstructure.
(4) The effective length of a raised quarter deck, if fitted with an intact front bulkhead, shall be its length up to a maximum of 0.6 L. Where the bulkhead is not intact, the raised quarter deck shall be treated as a poop of less than standard height.
(5) Superstructures which are not enclosed shall have no effective length.

Regulation 36 *Trunks*
(1) A trunk or similar structure which does not extend to the sides of the ship shall be regarded as efficient on the following conditions:
   (a) the trunk is at least as strong as a superstructure;
   (b) the hatchways are in the trunk deck, and the hatchway coamings and covers comply with the requirements of Regulations 13 to 16 inclusive and the width of the trunk deck stringer provides a satisfactory gangway and sufficient lateral stiffness. However, small access openings with watertight covers may be permitted in the freeboard deck;
   (c) a permanent working platform fore and aft fitted with guard-rails is provided by the trunk deck, or by detached trunks connected to superstructures by efficient permanent gangways;
   (d) ventilators are protected by the trunk, by watertight covers or by other equivalent means;
   (e) open rails are fitted on the weather parts of the freeboard deck in way of the trunk for at least half their length;
   (f) the machinery casings are protected by the trunk, by a superstructure of at least standard height, or by a deckhouse of the same height and of equivalent strength;
   (g) the breadth of the trunk is at least 60 per cent of the breadth of the ship; and
   (h) where there is no superstructure, the length of the trunk is at least 0.6 L.
(2) The full length of an efficient trunk reduced in the ratio of its mean breadth to B shall be its effective length.
(3) The standard height of a trunk is the standard height of a superstructure other than a raised quarter deck.
(4) Where the height of a trunk is less than the standard height, its effective length shall be reduced in the ratio of the actual to the standard height. Where the height of the hatchway coamings on the trunk deck is less than that required under Regulation 15(1), a reduction from the actual height of trunk shall be made which corresponds to the difference between the actual and the required height of coaming.

Regulation 37 *Deduction for Superstructures and Trunks*

(1) Where the effective length of superstructures and trunks is 1.0 L, the deduction from the freeboard shall be 350 mm at 24 m length of ship, 860 mm at 85 m length, and 1,070 mm at 122 m length and above; deductions at intermediate lengths shall be obtained by linear interpolation.

L [m]	f_e [mm]
24	350
85	860
≥ 122	1070

(2) Where the total effective length of superstructures and trunks is less than 1.0 L the deduction shall be a percentage obtained from one of the following tables:

Percentage of Deduction for Type `A' ships

Total Effective Length of Superstructures and Trunks	0L	0.1L	0.2L	0.3L	0.4L	0.5L	0.6L	0.7L	0.8L	0.9L	1.0L
Percentage of deduction for all types of superstructures	0	7	14	21	31	41	52	63	75.5	87.7	100

Percentages at intermediate lengths of superstructures and trunks shall be obtained by linear interpolation.

Percentage of Deduction for Type `B' ships

Total Effective Length of Superstructures and Trunks	0L	0.1L	0.2L	0.3L	0.4L	0.5L	0.6L	0.7L	0.8L	0.9L	1.0L
Ships with forecastle and without detached bridge	0	5	10	15	23.5	32	46	63	75.3	87.7	100
Ships with forecastle and with detached bridge	0	6.3	12.7	19	27.5	36	46	63	75.3	87.7	100

Percentages at intermediate lengths of superstructures and trunks shall be obtained by linear interpolation.

(3) For ships of Type `B':

(a) where the effective length of a bridge is less than 0.2 L, the percentages shall be obtained by linear interpolation between lines I and II;
(b) where the effective length of a forecastle is more than 0.4 L, the percentages shall be obtained from line II; and
(c) where the effective length of a forecastle is less than 0.07 L, the above percentages shall be reduced by:

$$5 \times \frac{0.07L - f}{0.07L}$$

where f is the effective length of the forecastle.

Regulation 38 ***Sheer***

(1) The sheer shall be measured from the deck at side to a line of reference drawn parallel to the keel through the sheer line amidships.
(2) In ships designed with a rake of keel, the sheer shall be measured in relation to a reference line drawn parallel to the design load water line.
(3) In flush deck ships and in ships with detached superstructures the sheer shall be measured at the freeboard deck.

(4) In ships with topsides of unusual form in which there is a step or break in the topsides, the sheer shall be considered in relation to the equivalent depth amidships.

(5) In ships with a superstructure of standard height which extends over the whole length of the freeboard deck, the sheer shall be measured at the superstructure deck. Where the height exceeds the standard the least difference (Z) between the actual and standard heights shall be added to each end ordinate. Similarly, the intermediate ordinates at distances of 1/6 L and 1/3 L from each perpendicular shall be increased by 0.444 Z and 0.111 Z respectively.

(6) Where the deck of an enclosed superstructure has at least the same sheer as the exposed freeboard deck, the sheer of the enclosed portion of the freeboard deck shall not be taken into account.

(7) Where an enclosed poop or forecastle is of standard height with greater sheer than that of the freeboard deck, or is of more than standard height, an addition to the sheer of the freeboard deck shall be made as provided in subsection (12) of this Regulation.

Standard Sheer Profile

(8) The ordinates of the standard sheer profile are given in the following table:

Standard Sheer Profile (Where L is in metres)

	Station	Ordinate (in millimetres)	Factor
After Half	After Perpendicular	$25\left(\frac{L}{3}+10\right)$	1
	1/6 L from A.P.	$11.1\left(\frac{L}{3}+10\right)$	3
	1/3 L from A.P.	$2.8\left(\frac{L}{3}+10\right)$	3
	Amidships	0	1
Forward Half	Amidships	0	1
	1/3 L from F.P.	$5.6\left(\frac{L}{3}+10\right)$	3
	1/6 L form F.P.	$22.2\left(\frac{L}{3}+10\right)$	3
	Forward Perpendicular	$50\left(\frac{L}{3}+10\right)$	1

Measurement of Variation from Standard Sheer Profile

(9) Where the sheer profile differs from the standard, the four ordinates of each profile in the forward or after half shall be multiplied by the appropriate factors given in the table of ordinates. The difference between the sums of the respective products and those of the standard divided by eight measures the deficiency or excess of sheer in the forward or after half. The arithmetical mean of the excess or deficiency in the forward and after halves measures the excess or deficiency of sheer.

(10) Where the after half of the sheer profile is greater than the standard and the forward half is less than the standard, no credit shall be allowed for the part in excess and deficiency only shall be measured.

(11) Where the forward half of the sheer profile exceeds the standard, and the after portion of the sheer profile is not less than 75 per cent of the standard, credit shall be allowed for the part in excess; where the after part is less than 50 per cent of the standard, no credit shall be given for the excess sheer forward. Where the after sheer is between 50 per cent and 75 per cent of the standard, intermediate allowances may be granted for excess sheer forward.

(12) Where sheer credit is given for a poop or forecastle the following formula shall be used:

$$s = \frac{y}{3}\frac{L'}{L}$$

where s = sheer credit, to be deducted from the deficiency or added to the excess of sheer,
y = difference between actual and standard height of superstructure at the end of sheer,
L' = mean enclosed length of poop or forecastle up to a maximum length of 0.5 L,
L = length of ship

The above formula provides a curve in the form of a parabola tangent to the actual sheer curve at the freeboard deck and intersecting the end ordinate at a point below the superstructure deck a distance equal to the standard height of a superstructure. The superstructure deck shall not be less than standard height above this curve at any point. This curve shall be used in determining the sheer profile for forward and after halves of the ship.

Correction for Variations from Standard Sheer Profile

(13)The correction for sheer shall be the deficiency or excess of sheer (see subsections (9) to (11) inclusive of this Regulation), multiplied by

$$0.75 - \frac{S}{2L}$$

where S is the total length of enclosed superstructures.

Addition for Deficiency in Sheer

(14)Where the sheer is less than the standard, the correction for deficiency in sheer (see subsection (13) of this Regulation) shall be added to the freeboard.

Deduction for Excess Sheer

(15)In ships where an enclosed superstructure covers 0.1 L before and 0.1 L abaft amidships, the correction for excess of sheer as calculated under the provisions of subsection (13) of this Regulation shall be deducted from the freeboard; in ships where no enclosed superstructure covers amidships, no deduction shall be made from the freeboard; where an enclosed superstructure covers less than 0.1 L before and 0.1 L abaft amidships, the deduction shall be obtained by linear interpolation. The maximum deduction for excess sheer shall be at the rate of 125 mm per 100 m of length.

Regulation 39. M*inimum Bow Height*

(1) The bow height defined as the vertical distance at the forward perpendicular between the water line corresponding to the assigned summer freeboard and the designed trim and the top of the exposed deck at side shall be not less than:

for ships below 250 m in length,

$$56L\left(1 - \frac{L}{500}\right)\frac{1.36}{C_b + 0.68}\ \text{mm}$$

for ships of 250 m and above in length,

$$7000\frac{1.36}{C_b + 0.68}\ \text{mm}$$

where L is the length of the ship in metres, Cb is the block coefficient which is to be taken as not less than 0.68.

(2) Where the bow height required in subsection (1) of this Regulation is obtained by sheer, the sheer shall extend for at least 15 per cent of the length of the ship measured from the forward perpendicular. Where it is obtained by fitting a superstructure, such superstructure shall extend from the stem to a point at least 0.07 L abaft the forward perpendicular, and it shall comply with the following requirements:

(a) for ships not over 100 m in length it shall be enclosed as defined in Regulation 3(10); and
(b) for ships over 100 m in length it shall be fitted with satisfactory closing appliances.

(3) Ships which, to suit exceptional operational requirements, cannot meet the requirements of subsections (1) and (2) of this Regulation may be given special consideration by the Administration.

Regulation 40 *Minimum Freeboards*

Summer Freeboard
The minimum freeboard in summer shall be the freeboard derived from the tables as modified by the corrections

Tropical Freeboard
The minimum freeboard in the Tropical Zone shall be the freeboard obtained by a deduction from the summer freeboard of 1/48th of the summer draught measured from the top of the keel to the centre of the ring of the load line mark.

$$f_T = f_S - \frac{T}{48}$$

Winter Freeboard
The minimum freeboard in winter shall be the freeboard obtained by an addition to the summer freeboard of 1/48th of summer draught, measured from the top of the keel to the centre of the ring of the load line mark.

$$f_W = f_S + \frac{T}{48}$$

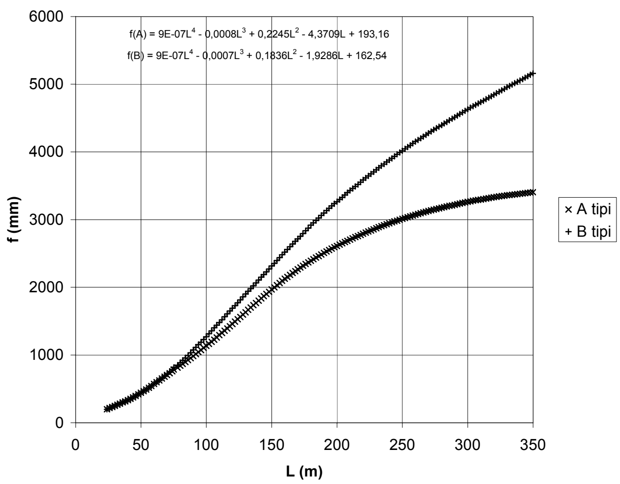
Winter North Atlantic Freeboard
The minimum freeboard for ships of not more than 100 m in length that enter any part of the North Atlantic defined in section 7 of Schedule II during the winter seasonal period shall be the winter freeboard plus 50 mm. For other ships, the Winter North Atlantic Freeboard shall be the winter freeboard.

$$f_{WNA} = f_W + 50$$

Fresh Water Freeboard
The minimum freeboard in fresh water of unit density shall be obtained by deducting from the minimum freeboard in salt water:

$$f_F = f_S - \frac{\Delta}{40T_1} \qquad f_{TF} = f_F - \frac{T}{48}$$

where Δ = displacement in salt water in tonnes at the summer load water line,
T = tonnes per centimetre immersion in salt water at the summer load water line.



Certificate No.: **060596-1**

TÜRK LOYDU

INTERNATIONAL LOAD LINE CERTIFICATE (1966) OF COMPLIANCE

Issued under the provisions of the International Convention on Load Lines, 1966,
under the authority of the Government of **THE REPUBLIC OF TURKEY**
by TÜRK LOYDU

Name of Ship	Distinctive Number or Letters	Port of Registry	Length (L) as defined in Article 2(8)
YARBAY KUDRED GÜNGÖR	-	GÖLCÜK-KOCAELİ	133.01

Freeboard assigned as * A new ship / ~~An existing ship~~

Type of ship * Type A / ~~Type B~~ / ~~Type B with reduced freeboard~~ / ~~Type B with increased freeboard~~

Freeboard from deck line				**Load Line**
Tropical	-	mm (Y)	-	mm above (S)
Summer	*1965.5	mm (S)	Upper edge of line through centre of ring	
Winter	-	mm (W)	-	mm below (S)
Winter North Atlantic	-	mm (WNA)	-	mm below (S)
Timber Tropical		mm (LT)		mm above (LS)
Timber Summer		mm (LS)		mm above (S)
Timber Winter		mm (LW)		mm below (LS)
Timber Winter North Atlantic		mm (LWNA)		mm (below (LS)

* **According to LLC 66, Reg. 6(6) FREEBOARD assigned as per scatling draft from The Classification Rules.**

Note: Freeboards and load lines which are not applicable need not be entered on the certificate.

Allowance for fresh water for all freeboards other than timber 179* mm. For timber freeboards - mm.
The upper edge of the deck line from which these freeboards are measured is 450 mm.

lower from the main deck at side.

Date of Initial or Periodical Survey

May. 1996

This is to certify that this ship has been surveyed and that the freeboards have been assigned and load lines shown above have been marked in accordance with the International Convention on Load Lines, 1966.

This certificate is valid until - subject to periodical inspections in accordance with Article 14(1)(c) of the Convention.

ISTANBUL
Issued at

06.05.1996
Date of issue

Fuat ÇAKMAK
Signature

* Delete whatever is inapplicable

Form No :TL 12A/94

Freeboard Calculation according to International Convention on Load Line 1

1 - Principle Dimentions

L.O.A.	=	143.100	m
L.B.P.	=	134.000	m
B.	=	22.800	m
D.	=	10.000	m
T.	=		m

2 - Determination of the length

* d1 = 8.500 m

Length on waterline at 8.500 m draught

L1	=	136.310	m
L'	=	130.858	m

* Length on waterline at 8.500 m draught measured from the forward edge of the steam to the rudder head 's

L'' = 133.010 m

L'' > L'

L = 133.010 m

3 - Block Coefficient

Volume of Displ. at 8.500 m draught

Volume	=	21524.000	m3
Cb	=	0.835	

4 - Tabular Freeboard

Length	Type A	Type B
133.000	1684.000	
134.000	1702.000	
133.010	1684.180	

5 - Correction for Block Coefficient

Cb = 0.835 > 0.680

K 1	=	1.114

6 - Correction for depth

D = 10.000 + 0.016 = 10.016 m

L / 15 = 8.867

D > (L / 15)

K2 = 287.042 mm

7 - Correction for Superstructure

Effective Length of Superstructure 44.860 m

E / L = 0.337

Deduction from the Freeboard = 1070.000

0.300 L	21.000 %
0.400 L	31.000 %
0.337 L	24.727 %

K 3 = 264.577 mm

8 - Sheer Correction

Station	Standard ordinate	Factor	Pruduct	Actuel ordinate	Factor	Pruduct
A.P.	1358.417	1.000	1358.417	231.000	1.000	231.000
1/6 L fr A.P.	603.137	3.000	1809.411	6.000	3.000	18.000
1/3 L fr A.P.	152.143	3.000	456.428	0.000	3.000	0.000
Amidship	0.000	1.000	0.000	0.000	1.000	0.000
			3624.256			249.000
Amidship	0.000	1.000	0.000	0.000	1.000	0.000
1/3 L fr F.P.	304.285	3.000	912.856	0.000	3.000	0.000
1/6 L fr F.P.	1206.274	3.000	3618.822	27.000	3.000	81.000
F.P.	2716.833	1.000	2716.833	520.000	1.000	520.000
			7248.511			601.000

Deficiency of the Sheer SUM/8= 106.250

in the after half 453.032
in the forward half 906.064

Sheer Credit for Forecastle			L f =	11.610	m	
y	=	2560.000	-	2300.000	=	260.000
s	=	7.565	mm			
Deficiency of the sheer in the forward half				906.064		
Sheer Credit for Poopdeck			L p =	33.250	m	
y	=	2680.000	-	2300.000	=	380.000
s	=	31.664	mm			
Deficiency of the sheer in the aft half				453.032		
The Aritmatical mean of the deficiency				587.194		
Actual length of the superstructure			E =	44.860		
Ccr	=	0.581				
K 4	=	341.375	mm			

9 - Summary

		+	-
Correction for depth	K 2	287.042	
Correction for superstr.	K 3		264.577
Correction for Sheer	K4	341.375	
		628.416	264.577

Correction Sum 363.840 mm

10 - Summer Freeboard

Tabular freeboard for type	A	1684.180
Tabular freeboard for type	B	0.000
		1684.180
Summer		2239.97
Correction for deckline		-450.000
SUMMER FREEBOARD		1790.0
Height to the freeboard deck		10.016 m
Draft to the summer freeboard		7775.53 mm
TROPICAL FREEBOARD	(S.F-)	-161.99
WINTER FREEBOARD	(S.F+)	161.99

FRESH WATER FREE.	(S.F-)	-183.76
Displacement at		7775.53
	D =	20169.5 ton
	TP1 =	27.44 ton/cm
	dF =	183.76
TROPICAL F.WATER FR.	(F.W.F-)	-183.76

11- Minimum Bow Height

H min = 4907.754

12- Effective Bow Height

H eff = 5194

H eff > H min

Example 5.5. Calculate the minimum freeboard requirements for the following ship in accordance with ICLL 66 regulations

Main particulars

Ship type	: Dry cargo (B)
L_{BP}	: 120.00 m
B	: 19.50 m
D	: 10.00 m
L_{WL} at 0.85 D	: 126.00 m
Thickness of deck plating (t)	: 25 mm
Block coefficent at 0.85D	: 0.722
T_1	: 9

Superstructure

	Length	Height
Poop	23.16	2.60
Raised Quarter Deck	21.40	1.50
Forecastle	13.00	2.80

The ship's sheer profile is as follows

AP	L/6	L/3	L/2	2L/3	5L/6	FP
750	340	85	0	300	1200	2500

Solution

Freeboard Length

$$\left.\begin{aligned} L_{BP} &= 120.00 \\ 0.96L_{WL} &= 0.96 \times 126 = 120.96 \end{aligned}\right\} \quad L = 120.96\text{m}$$

Freeboard depth

$D_f = D + t = 10.00+0.025 = 10.025$ m

Tabular freeboard value

From the Table B

Ship length (m)	Freeboard (mm)
120	1690
120.96	f_T
122	1729

The tabular value of freeboard can be calculated by linear interpolation

$$f_T = 1690 + (1729 - 1690)\frac{120.96 - 120}{122 - 120} = 1708.72\text{mm}$$

Correction for length

The tabular freeboard for a Type `B' ship of between 24 m and 100 m in length having enclosed superstructures with an effective length of up to 35 per cent of the length of the ship shall be increased by:

$$7.5(100 - L)\left(0.35 - \frac{E}{L}\right) \text{ mm}$$

where L = length of ship in metres,

where E = effective length of superstructure in metres defined in Regulations 35.

Since the ship is greater than 100 m there is no need for correction

$$f_1 = f_T = 1708.72\,\text{mm}$$

Correction for Block Coefficient

Where the block coefficient (C_b) exceeds 0.68, the freeboard shall be multiplied by the factor

$$\frac{C_b + 0.68}{1.36}$$

The ship's block coefficient is 0.722>0.68 hence the corrected freeboard is

$$f_2 = f_1 \times \frac{C_B + 0.68}{1.36} = 1708.72 \times \frac{0.722 + 0.68}{1.36} = 1761.5\ \text{mm}$$

Correction for Depth

(4) Where D exceeds $\frac{L}{15}$ the freeboard shall be increased by $\left(D - \frac{L}{15}\right)R$ millimetres, where R is $\frac{L}{0.48}$ at length less than 120 m and 250 at 120 m length and above.

(5) Where D is less than $\frac{L}{15}$, no reduction shall be made.

Since D=10.025 m and $\frac{L}{15} = \frac{120.96}{15} = 8.064$ a depth correction is required

$$f_3 = f_2 + (D - \frac{L}{15})R = 1761.5 + (10.025 - 8.064)250 = 2251.8\ \text{mm}$$

Correction for Superstructures

The standard height of a superstructure shall be as given in the following table:

L (metres)	Standard Height (in metres)	
	Raised Quarter Deck	All other Superstructures
≤ 30	0.90	1.80
75	1.20	1.80
≥ 125	1.80	2.30

The standard heights at intermediate lengths of the ship shall be obtained by linear interpolation.

Since the length of the ship is 120.96 m the standard height for the superstructures are as follows.

Raised quarter deck

$$1.20 + (1.80 - 1.20)\frac{120.96 - 75}{125 - 75} = 1.75\text{m}$$

Other superstructures

$$1.80 + (2.30 - 1.80)\frac{120.96 - 75}{125 - 75} = 2.26\text{m}$$

The effective length is the length modified by the ratio of b/Bs and h/Hs, where

b is the breadth of the superstructure at the middle of its length, and
B is the breadth of the ship at the middle of the length of the superstructure, and
h is the height of superstructure

H is the standard height

Poop

Enclosed length(S) : 23.16 m

Effective length (E) : $\ell \frac{b}{B}\frac{h}{H} = 23.16$ m (h/H is taken 1)

Raised Quarterdeck

Enclosed length (S) : 21.40 m

Effective length (E) : $\ell \frac{b}{B}\frac{h}{H} = 21.40\frac{1.5}{1.75} = 18.34$ m

Forecastle :

Enclosed length (S) : 13.00 m

Effective length (E) : $\ell \frac{b}{B}\frac{h}{H} = 13.00$ m (h/H is taken 1)

	Enclosed length (m)	Effective length (m)
Poop	23.16	23.16
Raised quarter deck	21.40	18.34
Forecastle	13.00	13.00
Total	57.56	54.50

Deduction for Superstructures and Trunks

(4) Where the effective length of superstructures and trunks is 1.0 L, the deduction from the freeboard shall be 350 mm at 24 m length of ship, 860 mm at 85 m length, and 1,070 mm at 122 m length and above; deductions at intermediate lengths shall be obtained by linear interpolation.

L [m]	f_e [mm]
24	350
85	860
≥ 122	1070

The length of ship is 120.96 m, thus

$$f_e = 860 + (1070 - 860)\frac{120.96 - 85}{122 - 85} = 1064.1\text{mm}$$

the ratio of effective length to ship length is 54.5/120.96=0.45. Thus from the following table the percentage of deduction is 0.2775.

Total Effective Length of Superstructures and Trunks	0L	0.1L	0.2L	0.3L	0.4L	0.5L	0.6L	0.7L	0.8L	0.9L	1.0L
Ships with forecastle and without detached bridge	0	5	10	15	23.5	32	46	63	75.3	87.7	100
Ships with forecastle and with detached bridge	0	6.3	12.7	19	27.5	36	46	63	75.3	87.7	100

(d) where the effective length of a bridge is less than 0.2 L, the percentages shall be obtained by linear interpolation between lines I and II;

(e) where the effective length of a forecastle is more than 0.4 L, the percentages shall be obtained from line II; and

(f) where the effective length of a forecastle is less than 0.07 L, the above percentages shall be reduced by:

$$5 \times \frac{0.07L - f}{0.07L}$$

where f is the effective length of the forecastle.

The freeboard following the superstructure correction is

$f_4 = f_3 - 0.2775 f_e = 2251.8 - 0.2775 \times 1064.1 = 1956.5$ mm

Correction for Sheer

Where the sheer profile differs from the standard, the four ordinates of each profile in the forward or after half shall be multiplied by the appropriate factors given in the table of ordinates. The difference between the sums of the respective products and those of the standard divided by eight measures the deficiency or excess of sheer in the forward or after half.

Station	Standard	Factor	Product	Current	Factor	Product
AP	$25\left(\frac{L}{3}+10\right)$	1	1258	750	1	750
1/ 6 L	$11.1\left(\frac{L}{3}+10\right)$	3	1675.656	340	3	1020
1/3 L	$2.8\left(\frac{L}{3}+10\right)$	3	422.688	85	3	255
1/2 L	0	1	0	0	1	0
TOTAL		**Σ_1=**	**3356.344**		**Σ_3=**	**2025**
1/2 L	0	1	0	0	1	0
2/3 L	$5.6\left(\frac{L}{3}+10\right)$	3	845.376	300	3	900
5/6 L	$22.2\left(\frac{L}{3}+10\right)$	3	3351.312	1200	3	3600
FP	$50\left(\frac{L}{3}+10\right)$	1	2516	2500	1	2500
TOTAL		**Σ_2=**	**6712.688**		**Σ_4=**	**7000**

$$\delta S_A = \frac{\Sigma_1 - \Sigma_3}{8} = \frac{3356.344 - 2025}{8} = 166.418$$

$$\delta S_F = \frac{\Sigma_2 - \Sigma_4}{8} = \frac{6712.688 - 7000}{8} = -35.914$$

Where an enclosed poop or forecastle is of standard height with greater sheer than that of the freeboard deck, or is of more than standard height, an addition to the sheer of the freeboard deck shall be made in accordance with the following formula

$$s = \frac{y}{3}\frac{L'}{L}$$

where s = sheer credit, to be deducted from the deficiency or added to the excess of sheer,
y = difference between actual and standard height of superstructure at the end of sheer,
L' = mean enclosed length of poop or forecastle up to a maximum length of 0.5 L,
L = length of ship as defined in Regulation 3(1).

s values for the poop and forecastle are calculated in the following table

	Actual height	Standard height	Difference	s
Poop	2600	2260	340	$\frac{340}{3}\frac{23.16}{120.96} = 21.7$

Forecastle	2800	2260	540	$\frac{540}{3}\frac{13.00}{120.96}=19.3$

Than the modifed forward and aft sheers are

$$\delta S_A = 166.418 - 21.7 = 144.718 \text{ mm}$$
$$\delta S_F = -35.914 - 19.3 = -55.214 \text{ mm}$$

The excess/deficiancy of sheer is

$$\delta S = \frac{\delta S_A + \delta S_F}{2} = \frac{144.718 - 55.214}{2} = 44.752 \, \text{mm}$$

Where the forward half of the sheer profile exceeds the standard and the after sheer is between 50 per cent and 75 per cent of the standard, intermediate allowances may be granted for excess sheer forward. In this example the excess ratio of the after portion of sheer is

$$\frac{2025}{3356.5} = 0.60$$

Hence the deficiency is

$$\left[\delta S \times \frac{0.60 - 0.50}{0.75 - 0.50}\right] = 44.752 \times 0.4 = 30.3864 \, \text{mm}$$

The correction for sheer shall be the deficiency or excess of multiplied by

$$0.75 - \frac{S}{2L}$$

where S is the total length of enclosed superstructures. The increase in freeboard due to the excess of sheer is

$$\left(0.75 - \frac{57.56}{2 \times 120.96}\right) \times 30.3864 = 15.56 \text{ mm}$$

The freeboard following the sheer correction is

$$f_5 = f_4 + 15.56 = 1956.5 + 15.56 = 1972.06 \text{ mm}$$

Then the maximum draught in summer is $T = D - f = 10.025 - 1972.06 = 8.098 \text{ m}$

Minimum Bow Height

The bow height defined as the vertical distance at the forward perpendicular between the water line corresponding to the assigned summer freeboard and the designed trim and the top of the exposed deck at side shall be not less than:

for ships below 250 m in length,

$$56L\left(1 - \frac{L}{500}\right)\frac{1.36}{C_b + 0.68} \text{ mm}$$

for ships of 250 m and above in length,

$$7000\frac{1.36}{C_b + 0.68} \text{ mm}$$

where L is the length of the ship in metres, Cb is the block coefficient which is to be taken as not less than 0.68. For this example the minimum bow height is

$$56\times120.96\times\left(1-\frac{120.96}{500}\right)\frac{1.36}{0.722+0.68}=4981\text{mm}.$$

Minimum Freeboards

Summer Freeboard

$$f_S = 1972.06 \text{ mm}$$

Tropical Freeboard

$$f_T = f_S - \frac{T}{48} = 1972.06 - \frac{8098}{48} = 1803 \text{ mm}$$

Winter Freeboard

$$f_W = f_S + \frac{T}{48} = 1972.06 + \frac{8098}{48} = 2141 \text{ mm}$$

Winter North Atlantic Freeboard

$$f_{WNA} = f_W + 50 = 2191 \text{ mm}$$

Fresh Water Freeboard

$$f_F = f_S - \frac{\Delta}{40T_1} = 1972.06 - \frac{120\times19.5\times6\times0.722\times1.025}{40\times9} = 1942.97 \text{ mm}$$

Example 5.6. (Baxter) A type B ship has a freeboard length of 145 m measured on a waterline at 85% of the moulded depth of 12 m and a beam of 21 m. There is no bridge amidships and the forecastle and poop have mean covered lengths of 30 m and 15 m and heights of 2.6 m, respectively

The sheer of the freeboard deck in milimeters is as follows

AP	L/6	L/3	L/2	2L/3	5L/6	FP
2730	320	0	0	0	1630	4060

The displacement at a moulded draught of 85% of the moulded depth is 22700 m^3 and the displacement in seawater at the summer LWL is 19420 tonnes wşth a corresponding tonnes immersion per cm of 25. Determine the freeboards.

Solution

Freeboard Length L = 145 m

Freeboard depth D_f = D + t = 12.00+0.02 = 12.02 m

Tabular freeboard value : From the Table B

Ship length (m)	Freeboard (mm)
144	2190
145	f_T
146	2229

The tabular value of freeboard can be calculated by linear interpolation

$$f_T = 2190 + (2229 - 2190)\frac{145-144}{146-144} = 2209.5 \text{ mm}$$

Correction for length: Since the ship is greater than 100 m there is no need for correction

$$f_1 = f_T = 2209.5 \text{ mm}$$

Correction for Block Coefficient: Where the block coefficient (C_b) exceeds 0.68, the freeboard shall be multiplied by the factor

$$\frac{C_B + 0.68}{1.36}$$

The ship's block coefficient is

$$C_B = \frac{\nabla}{LBT} = \frac{22700}{145 \times 21 \times 12 \times 0.85} = 0.731$$

0.731>0.68 hence the corrected freeboard is

$$f_2 = f_1 \times \frac{C_B + 0.68}{1.36} = 12209.5 \times \frac{0.731 + 0.68}{1.36} = 2292.3 \text{ mm}$$

Correction for Depth

Where D exceeds $\frac{L}{15}$ the freeboard shall be increased by $\left(D - \frac{L}{15}\right)R$ millimetres, where R is $\frac{L}{0.48}$ at length less than 120 m and 250 at 120 m length and above.

Since D=12.02 m and $\frac{L}{15} = \frac{145}{15} = 9.667$ a depth correction is required

$$f_3 = f_2 + (D - \frac{L}{15})R = 2292.3 + (12.02 - 9.667) \times 250 = 2880.6 \text{ mm}$$

Correction for Superstructures

The standard height of a superstructure shall be as given in the following table:

L (metres)	Standard Height (in metres)	
	Raised Quarter Deck	All other Superstructures
≤ 30	0.90	1.80
75	1.20	1.80
≥ 125	1.80	2.30

The standard heights at intermediate lengths of the ship shall be obtained by linear interpolation.

Since the length of the ship is 145 m the standard height for the superstructures ais 2.30 m.

The effective length is the length modified by the ratio of b/Bs and h/Hs, where

b is the breadth of the superstructure at the middle of its length, and
B is the breadth of the ship at the middle of the length of the superstructure, and
h is the height of superstructure
H is the standard height

Poop

Enclosed length(S) : 15 m

Effective length (E) : $\ell \frac{b}{B}\frac{h}{H} = 15$ m (h/H is taken 1)

Forecastle :

Enclosed length (S) : 30 m

Effective length (E) : $\ell \frac{b}{B}\frac{h}{H} = 30$ m (h/H is taken 1)

	Enclosed length (m)	Effective length (m)
Poop	15	15
Forecastle	30	30
Total	45	45

Deduction for Superstructures and Trunks

(5) Where the effective length of superstructures and trunks is 1.0 L, the deduction from the freeboard shall be 350 mm at 24 m length of ship, 860 mm at 85 m length, and 1,070 mm at 122 m length and above; deductions at intermediate lengths shall be obtained by linear interpolation.

L [m]	f_e [mm]
24	350
85	860
≥ 122	1070

The length of ship is 145 m, thus f_e=1070 mm. The ratio of effective length to ship length is 45/145=0.31. Thus from the following table the percentage of deduction is 0.1585.

Total Effective Length of Superstructures and Trunks	0L	0.1L	0.2L	0.3L	0.4L	0.5L	0.6L	0.7L	0.8L	0.9L	1.0L
Ships with forecastle and without detached bridge	0	5	10	15	23.5	32	46	63	75.3	87.7	100
Ships with forecastle and with detached bridge	0	6.3	12.7	19	27.5	36	46	63	75.3	87.7	100

(g) where the effective length of a bridge is less than 0.2 L, the percentages shall be obtained by linear interpolation between lines **I** and **II**;
(h) where the effective length of a forecastle is more than 0.4 L, the percentages shall be obtained from line **II**; and
(i) where the effective length of a forecastle is less than 0.07 L, the above percentages shall be reduced by:

$$5 \times \frac{0.07L - f}{0.07L}$$

where f is the effective length of the forecastle.

The freeboard following the superstructure correction is

$$f_4 = f_3 - 0.1585 f_e = 2880.6 - 0.1585 \times 1070 = 2711 \text{ mm}$$

Correction for Sheer

Where the sheer profile differs from the standard, the four ordinates of each profile in the forward or after half shall be multiplied by the appropriate factors given in the table of ordinates. The difference between the sums of the respective products and those of the standard divided by eight measures the deficiency or excess of sheer in the forward or after half.

Station	Standard	Factor	Product	Current	Factor	Product
AP	$25\left(\frac{L}{3}+10\right)$	1	1458	2730	1	2730
1/ 6 L	$11.1\left(\frac{L}{3}+10\right)$	3	1942.5	320	3	960
1/3 L	$2.8\left(\frac{L}{3}+10\right)$	3	490	0	3	0
1/2 L	0	1	0	0	1	0
TOTAL		Σ_1**=**	**3890.833**		Σ_3**=**	**3690**
1/2 L	0	1	0	0	1	0
2/3 L	$5.6\left(\frac{L}{3}+10\right)$	3	845.376	0	3	0
5/6 L	$22.2\left(\frac{L}{3}+10\right)$	3	3351.312	1630	3	4890
FP	$50\left(\frac{L}{3}+10\right)$	1	2516	4060	1	4060
TOTAL		Σ_2**=**	**7781.667**		Σ_4**=**	**8950**

$$\delta S_A = \frac{\Sigma_1 - \Sigma_3}{8} = \frac{3890.833 - 3690}{8} = 25.104 \text{ mm}$$

$$\delta S_F = \frac{\Sigma_2 - \Sigma_4}{8} = \frac{7781.667 - 8950}{8} = -146.042 \text{ mm}$$

Where an enclosed poop or forecastle is of standard height with greater sheer than that of the freeboard deck, or is of more than standard height, an addition to the sheer of the freeboard deck shall be made in accordance with the following formula

$$s = \frac{y}{3}\frac{L'}{L}$$

where s = sheer credit, to be deducted from the deficiency or added to the excess of sheer,
y = difference between actual and standard height of superstructure at the end of sheer,
L' = mean enclosed length of poop or forecastle up to a maximum length of 0.5 L,
L = length of ship

s values for the poop and forecastle are calculated in the following table

	Actual height	Standard height	Difference	s
Poop	2600	2300	300	$\frac{300}{3}\frac{15}{145}=10.345$
Forecastle	2600	2300	300	$\frac{300}{3}\frac{30}{145}=20.690$

Than the modifed forward and aft sheers are

$$\delta S_A = 25.104 - 10.345 = 14.759 \text{ mm}$$
$$\delta S_F = -146.042 - 20.690 = -166.732 \text{ mm}$$

The excess/deficiancy of sheer is

$$\delta S = \frac{\delta S_A + \delta S_F}{2} = \frac{14.759 - 166.732}{2} = -90.75\,\text{mm}$$

Where the forward half of the sheer profile exceeds the standard and the after portion of the sheer profile is no less than 75 per cent of the standard, credit shall be allowed for the part in excess.

$$\frac{3690}{3890.833} = 0.95$$

The correction for sheer shall be the deficiency or excess of multiplied by

$$0.75 - \frac{S}{2L}$$

where S is the total length of enclosed superstructures. The increase in freeboard due to the excess of sheer is

$$\left(0.75 - \frac{45}{2\times145}\right)\times(-90.75) = -54\,\text{mm}$$

The freeboard following the sheer correction is

$$f_5 = 2711 - 54 = 2657 \text{ mm}$$

Then the maximum summer freeboard is $T = D - f = 12.02 - 2.657 = 9.363 \text{ m}$

Minimum Bow Height

For ships below 250 m in length the bow height shall be not less than:

$$56L\left(1 - \frac{L}{500}\right)\frac{1.36}{C_b + 0.68} \text{ mm}$$

where L is the length of the ship in metres, Cb is the block coefficient which is to be taken as not less than 0.68. For this example the minimum bow height is

$$56\times145\times\left(1 - \frac{145}{500}\right)\frac{1.36}{0.731 + 0.68} = 5557 \text{ mm}.$$

Minimum Freeboards

Summer Freeboard $f_S = 2657 \text{ mm}$

Tropical Freeboard $f_T = f_S - \frac{T}{48} = 2657 - \frac{9363}{48} = 2462 \text{ mm}$

Winter Freeboard $f_W = f_S + \frac{T}{48} = 2657 + \frac{9363}{48} = 2852 \text{ mm}$

Winter North Atlantic Freeboard $f_{WNA} = f_W + 50 = 2902 \text{ mm}$

Fresh Water Freeboard $f_F = f_S - \frac{\Delta}{40T_1} = 2657 - \frac{19420}{40\times25} = 2638 \text{ mm}$

CHAPTER 11

Michael G. Parsons

PARAMETRIC DESIGN

11.1 NOMENCLATURE

A_M submerged hull section area amidships (m^2)
AP after perpendicular, often at the center of the rudder post
A_W area of design waterplane (m^2)
A_X maximum submerged hull section area (m^2)
B molded beam of the submerged hull (m)
BM_T transverse metacenteric radius (m)
BM_L longitudinal metacenteric radius (m)
C coefficient in Posdunine's formula, equation 5; straight line course Stability Criterion
C distance aft of FP where the hull begins its rise from the baseline to the stern (m)
C_B block coefficient = ∇/LBT
C_{BD} block coefficient to molded depth D
C_B' block coefficient at 80% D
C_{DWT} total deadweight coefficient = DWT_T/Δ
C_I transverse waterplane inertia coefficient
C_{IL} longitudinal waterplane inertia coefficient
C_M midship coefficient = A_M/BT
C_m coefficient in non prime mover machinery weight equation, equation 42
C_o outfit weight coefficient = W_o/LB
C_P longitudinal prismatic coefficient = ∇/A_XL
C_S wetted surface coefficient = $S/\sqrt{(\nabla L)}$
C_∇ volumetric coefficient = ∇/L^3
C_{VP} vertical prismatic coefficient = ∇/A_WT
C_{WP} waterplane coefficient = A_W/LB
C_X maximum transverse section coefficient = A_X/BT
D molded depth (m)
D_{er} depth to overhead of engine room (m)
DWT_C cargo deadweight (t)
DWT_T total deadweight (t)
E modified Lloyd's Equipment Numeral, equation 33
Fn Froude number = $V/\sqrt{(gL)}$, nondimensional
FP forward perpendicular, typically at the stem at the design waterline
FS free surface margin as % KG
F_∇ volumetric Froude number = $V/\sqrt{(g\nabla^{1/3})}$
g acceleration of gravity (m/s^2); 9.81 m/s^2
GM_T transverse metacentric height (m)
GM_L longitudinal metacentric height (m)
h_{db} innerbottom height, depth of doublebottom (m)
h_i superstructure/deckhouse element i height (m)
K constant in Alexander's equation, equation 14; constant in structural weight equation
circle K traditional British coefficient = $2F_\nabla\sqrt{\pi}$
KB vertical center of buoyancy above baseline (m)
KG vertical center of gravity above baseline (m)
ℓ_i length of superstructure/deckhouse element i(m)
ℓ_i component i fractional power loss in reduction gear
L molded ship length, generally LWL or LBP
L_f molded ship length (ft)
LBP length between perpendiculars (m)
LCB longitudinal center of buoyancy (m aft FP or %L, +fwd amidships)
LCF longitudinal center of flotation (m aft FP or %L, +fwd amidships)
LCG longitudinal center of gravity (m aft FP or %L, +fwd amidships)
LOA length overall (m)
LWL length on the design waterline (m)
MCR Maximum Continuous Rating of main engine(s) (kW)
circle M traditional British coefficient = $L/\nabla^{1/3}$
M_D power design or acquisition margin
M_S power service margin
N_e main engine revolutions per minute (rpm)
P_B brake power (kW)
P_D delivered power (kW)
P_E effective power (kW)
P_S shaft power (kW)
r bilge radius (m)
R Coefficient of Correlation
$\hat{R}$ Bales' Seakeeping Rank Estimator
RFR Required Freight Rate ($/unit of cargo)
R_T total resistance (kN)
s shell and appendage allowance
S wetted surface of submerged hull (m^2)
SE Standard Error of the Estimate
SFR Specific Fuel Rate of main engine(s) (t/kWhr)
t thrust deduction or units in tonnes
T design molded draft (m)
T_{reqd} required thrust per propeller (kN)

V ship speed (m/s)= 0.5144 V_k
V_k ship speed (knots)
w average longitudinal wake fraction
$W_{C\&E}$ weight of crew and their effects (t)
W_{FL} weight of fuel oil (t)
W_{FW} weight of fresh water (t)
W_{LO} weight of lube oil (t)
W_{LS} Light Ship weight (t)
W_M propulsion machinery weight (t)
W_{ME} weight of main engine(s) (t)
W_o outfit and hull engineering weight (t)
W_{PR} weight of provisions and stores (t)
W_{rem} weight of remainder of machinery weight (t)
W_S structural weight (t)
γ water weight density; 1.025 t/m^3 SW at 15˚C; 1.000 t/m^3 FW at 15˚C
$\delta\%$ distance between hull structure LCG and LCB (%L, + aft)
Δ displacement at the design waterline (t)
η_b line bearing efficiency
η_c electric transmission/power conversion efficiency
η_g reduction gear efficiency
η_{gen} electric generator efficiency
η_h hull efficiency = $(1 - t)/(1 - w)$
η_m electric motor efficiency
η_o propeller open water efficiency
η_p propeller behind condition efficiency
η_r relative rotative efficiency
η_s stern tube bearing efficiency
η_t overall transmission efficiency; just η_g with gearing only
σ fraction of volume occupied by structure and distributive systems
∇ molded volume to the design waterline (m^3)
∇_T hull volume occupied by fuel, ballast, water, lube oil, etc. tankage (m^3)
∇_{LS} hull volume occupied by machinery and other light ship items (m^3)
∇_U useful hull volume for cargo or payload (m^3)

11.2 PARAMETRIC SHIP DESCRIPTION

In the early stages of conceptual and preliminary design, it is necessary to develop a consistent definition of a candidate design in terms of just its dimensions and other descriptive parameters such as L, B, T, C_B, LCB, etc. This description can then be optimized with respect to some measure(s) of merit or subjected to various parametric tradeoff studies to establish the basic definition of the design to be developed in more detail. Because more detailed design development involves significant time and effort, even when an integrated Simulation Based Design (SBD) environment is available, it is important to be able to reliably define and size the vessel at this parameter stage. This chapter will focus on the consistent parametric description of a vessel in early design and introduce methods for parametric model development and design optimization.

11.2.1 Analysis of Similar Vessels

The design of a new vessel typically begins with a careful analysis of the existing fleet to obtain general information on the type of vessel of interest. If a similar successful design exists, the design might proceed using this vessel as the *basis ship* and, thus, involve scaling its characteristics to account for changes intended in the new design. If a design is to be a new vessel within an existing class of vessels; for example, feeder container ships of 300 to 1000 TEU, the world fleet of recent similar vessels can be analyzed to establish useful initial estimates for ship dimensions and characteristics. If the vessel is a paradigm shift from previous designs, such as the stealth vessel *Sea Shadow* (see Chapter 46, Figure 46.17), dependence must be placed primarily on physics and first principles. Regardless, a design usually begins with a careful survey of existing designs to establish what can be learned and generalized from these designs.

For common classes of vessels, parametric models may already exist within the marine design literature. Examples include Watson and Gilfillan (1) for commercial ships; Eames and Drummond (2) for small military vessels; Nethercote and Schmitke (3) for SWATH vessels; Fung (4) for naval auxiliaries; Chou et al for Tension Leg Platforms (5); informal MARAD studies for fishing vessels (6), offshore supply vessels (7), and tug boats (8); etc. Integrated synthesis models may also exist for classes of vessels such as in the U.S. Navy's ASSET design program (9). Overall design process and vessel class studies also exist within the marine design literature, for example Evans (10), Benford (11 & 12), Miller (13), Lamb (14), Andrews (15), and Daidola and Griffin (16). Any design models from the literature are, however, always subject to obsolescence as transportation practices, regulatory requirements, and other factors evolve over time. Schneekluth and Bertram (17) and Watson (18) are excellent recent general texts on the preliminary ship design process.

This Section presents thoughts on the overall approach to be taken for the initial sizing of a vessel and methods for parametric description of a vessel. Section 11.3 presents example approaches for the parametric weight and centers modeling. Section 11.4

presents example methods for the parametric estimation of the hydrodynamic performance of a candidate design. Section 11.5 presents methods useful in the analysis of data from similar vessels determined by the designer to be current and relevant to the design of interest. Rather than risk the use of models based upon obsolescent data, the preferred approach is for each designer to develop his or her own models from a database of vessels that are known to be current and relevant. Section 11.6 presents a brief introduction to optimization methods that can be applied to parametric vessel design models.

11.2.2 Overall Strategy–Point-Based versus Set-Based Design

11.2.2.1 Point-Based Design

The traditional conceptualization of the initial ship design process has utilized the “design spiral” since first articulated by J. Harvey Evans in 1959 (10). This model emphasizes that the many design issues of resistance, weight, volume, stability, trim, etc. interact and these must be considered in sequence, in increasing detail in each pass around the spiral, until a single design which satisfies all constraints and balances all considerations is reached. This approach to conceptual design can be classed as a *point-based design* since it is seeks to reach a single point in the design space. The result is a base design that can be developed further or used as the start point for various tradeoff studies. A disadvantage of this approach is that, while it produces a feasible design, it may not produce a global optimum in terms of the ship design measure of merit, such as the Required Freight Rate (RFR).

Other designers have advocated a discrete search approach by developing in parallel a number of early designs that span the design space for the principal variables, at least length (11, 14, 19). A design spiral may apply to each of these discrete designs. The RFR and other ship design criteria are often fairly flat near their optimum in the design space. Thus, the designer has the latitude to select the design that balances the factors that are modeled as well as the many other factors that are only implied at this early stage. Lamb (20) advocated a parameter bounding approach in which a number of designs spanning a cube in the (L, B, D) parameter space are analyzed for DWT_T and volumetric capacity.

11.2.2.2 Set-Based Design

The design and production of automobiles by Toyota is generally considered world-class and it is, thus, the subject of considerable study. The study of the Toyota production system led to the conceptualization of Lean Manufacturing (21). The Japanese Technology Management Program sponsored by the Air Force Office of Scientific Research at the University of Michigan has more recently studied the Toyota approach to automobile design (22). This process produces world-class designs in a significantly shorter time than required by other automobile manufacturers. The main features of this Toyota design process include:

- broad sets are defined for design parameters to allow concurrent design to begin,
- these sets are kept open much longer than typical to reveal tradeoff information, and
- the sets are gradually narrowed until a more global optimum is revealed and refined.

This design approach has been characterized by Ward as *set-based design* (22). It is in contrast to point-based design or the common systems engineering approach where critical interfaces are defined by precise specifications early in the design so that subsystem development can proceed concurrently. Often these interfaces must be defined, and thus constrained, long before the needed tradeoff information is available. This inevitably results in a suboptimal overall design. A simple example is the competition between an audio system and a heating system for volume under the dashboard of a car. Rather than specify in advance the envelope into which each vendor’s design must fit, they can each design a range of options within broad sets so that the design team can see the differences in performance and cost that might result in tradeoffs in volume and shape between these two competing items.

The set-based design approach has a parallel in the *Method of Controlled Convergence* conceptual design approach advocated by Stuart Pugh (23) and the parameter bounding approach advocated by Lamb. These set-based approaches emphasizes a *Policy of Least Commitment*; that is, keeping all options open as long a possible so that the best possible tradeoff information can be available at the time specific design decisions have to be made. Parsons et al (24) have introduced a hybrid human-computer agent approach that facilitates set-based conceptual ship design by an Integrated Product Team.

11.2.3 Overall Sizing Strategy

The strategy used in preliminary sizing will vary depending upon the nature of the vessel or project of interest. Every design must achieve its unique balance of weight carrying capability and available volume for payload. All vessels will satisfy Archimedes Principle; that is, weight must equal displacement,

$$\Delta = \gamma \, LBT \, C_B \, (1 + s) \qquad [1]$$

where the hull dimensions length L, beam B, and draft T are the molded dimensions of the submerged hull to the inside of the shell plating, γ is the weight density of water, C_B is the block coefficient, and s is the shell appendage allowance which adapts the molded volume to the actual volume by accounting for the volume of the shell plating and appendages (typically about 0.005 for large vessels). Thus, with dimensions in meters and weight density in t/m^3, equation 1 yields the displacement in tonnes (t).

The hull size must also provide the useful hull volume ∇_U needed within the hull for cargo or payload,

$$\nabla_U = LBD\, C_{BD}(1 - \sigma) - \nabla_{LS} - \nabla_T \qquad [2]$$

where D is the molded depth, C_{BD} is the block coefficient to this full depth, and σ is an allowance for structure and distributive systems within the hull. When the upper deck has sheer and chamber and these contribute to the useful hull volume, an effective depth can be defined (18). Watson (18) also recommends estimating C_{BD} from the more readily available hull characteristics using,

$$C_{BD} = C_B + (1 - C_B)\,((0.8D - T)/3T) \qquad [3]$$

Equation 2 is symbolic in that each specific design needs to adapt the equation for its specific volume accounting; here ∇_{LS} is the volume within the hull taken up by machinery and other Light Ship items and ∇_T is the volume within the hull devoted to fuel, ballast, water, and other tankage.

If the vessel is *weight limited*, primarily dry bulk carriers today, the primary sizing is controlled by equation 1. The design sizing must be iterated until the displacement becomes equal to the total of the estimates of the weight the vessel must support. A typical design strategy would select L as the independent variable of primary importance, then select a compatible beam and draft, and select an appropriate block coefficient based upon the vessel length and speed (Froude number) to establish a candidate displacement. Guidance for the initial dimensions can be taken from regression analyses of a dataset of similar vessels as described in Section 11.5 below. Target transverse dimensions might be set by stowage requirements for unitized cargo; e.g., a conventional cellular container ship using hatch covers might have beam and depth of about 22.2 m and 12.6 m, respectively, to accommodate a 7x5 container block within the holds. Parametric weight models can then be used to estimate the components of the total weight of the vessel and the process can be iterated until a balance is achieved. Depth is implicit in equation 1 and is, thus, set primarily by freeboard or discrete cargo considerations.

An initial target for the displacement can be estimated using the required total deadweight and a deadweight coefficient $C_{DWT} = DWT/\Delta$ obtained from similar vessels. This can be used to help establish the needed molded dimensions and guide the initial selection of block coefficient. Generally, the coefficient C_{DWT} increases with both ship size and block coefficient. Typical ranges for C_{DWT} defined relative to both cargo deadweight and total deadweight are shown in Table 11.I for classes of commercial vessels.

TABLE 11.I - TYPICAL DEADWEIGHT COEFFICIENT RANGES

Vessel type	$C_{cargo\ DWT}$	$C_{total\ DWT}$
large tankers	0.85 - 0.87	0.86 - 0.89
product tankers	0.77 - 0.83	0.78 - 0.85
container ships	0.56 - 0.63	0.70 - 0.78
Ro-Ro ships	0.50 - 0.59	
large bulk carriers	0.79 - 0.84	0.81 - 0.88
small bulk carriers	0.71 - 0.77	
refrigerated cargo ships	0.50 - 0.59	0.60 - 0.69
fishing trawlers	0.37 - 0.45	

If the vessel is *volume limited*, as are most other vessels today, the basic sizing will be controlled by the need to provide a required useful hull volume ∇_U. Watson (18) notes that the transition from *weight limited* to *volume limited* comes when the cargo (plus required segregated ballast) stowage factor is about 1.30 m^3/t or inversely when the cargo (plus required segregated ballast) density is about 0.77 t/m^3. The size of some vessels is set more by the required total hull or deck length than the required volume. On military vessels, the summation of deck requirements for sensors, weapon systems, catapults, elevators, aircraft parking, etc. may set the total vessel length and beam. The vessel sizing must then be iterated to achieve a balance between the required and available hull volume (or length), equation 2. Parametric volume as well as parametric weight models are then needed. The balance of weight and displacement in equation 1 then yields a design draft that is typically less than that permitted by freeboard requirements. The overall approach of moving from an assumed length to other dimensions and block coefficient remains the same, except that in this case hull depth becomes a critical parameter through its control of hull volume. Draft is implicit in equation 2 and is, thus, set by equation 1.

From a design strategy viewpoint, a third class of vessels could be those with functions or requirements that tend to directly set the overall dimensions. These might be called *constraint-limited* vessels. Benford called some of these vessels “rules or paragraph vessels” where a paragraph of the regulatory requirements, such as the tonnage rules or a sailing yacht racing class rule, dictates the strategy for the primary dimension selection. Watson and Gilfillan (1) use the term "linear dimension" vessel when the operating environment constraints or functional requirements tend to set the basic dimensions. Watson includes containerships in this category since the container stack cross-section essentially sets the beam and depth of the hull. Classic examples would be Panamax bulk carriers, St. Lawrence Seaway-size bulk carriers, or the largest class of Great Lakes bulk carriers. These latter vessels essentially all have (L, B, T) = (304.8 m, 32.0 m, 8.53 m), the maximum dimensions allowed at the Poe Lock at Sault Ste. Marie, MI.

11.2.4 Relative Cost of Ship Parameters

In making initial sizing decisions, it is necessary to consider the effect of the primary ship parameters on resistance, maneuvering, and seakeeping performance; the project constraints; and size-related manufacturing issues. It is also necessary to consider, in general, the relative cost of ship parameters. This general effect was well illustrated for large ships by a study performed in the 1970's by Fisher (25) on the relative cost of length, beam, depth, block coefficient and speed of a 300 m, 148,000 DWT, 16.0 knot diesel ore carrier and a 320 m, 253,000 DWT, 14.4 knot steam VLCC crude oil tanker. Fisher's Table 11.II shows the incremental change in vessel capital cost that would result from a 1% change in length, beam, depth, block coefficient, or speed. Note that one could choose to change the length, beam, or block coefficient to achieve a 1% change in the displacement of the vessel. The amounts of these incremental changes that are changes in the steel, outfit, and machinery costs are also shown. One can see in Table 11.II that a 1% change in length results in about a 1% change in capital cost.

Further in Table 11.II, a 1% increase in beam increases the cost 0.78% for the ore carrier and 0.58% for the VLCC. A 1% increase in depth increases the cost 0.24% for the ore carrier and 0.40% for the VLCC. The 1% block coefficient change is only about one fifth as expensive as a 1 % length change. The relative cost of a 1% speed change is a 1% ship cost change for the ore carrier and only a 0.5% ship cost change for the relatively slower tanker. Thus, it is five times more expensive in terms of capital cost to increase displacement by changing length than by changing block coefficient.

TABLE 11.II - EFFECTS OF INCREMENTAL CHANGES IN PARAMETERS ON CAPITAL COST (25)

Incremental changes in total capital cost as percent of original capital cost
due to a 1% increase in the parameter

category	percent of total		L		B		D		C_B		V_k	
	ore carrier	VLCC tanker	ore carrier	VLCC tanker	ore carrier	VLCC tanker	ore carrier	VLCC tanker	ore carrier	VLCC tanker	ore carrier	VLCC tanker
steel	28%	41%	0.47	0.81	0.30	0.43	0.24	0.38	0.11	0.17		
outfit	26%	22%	0.27	0.06	0.27	0.04		0.02		0.01		
machinery	30%	20%	0.29	0.14	0.21	0.11			0.07	0.04	1.01	0.50
misc/ovhd	16%	17%										
total	100%	100%	1.03	1.01	0.78	0.58	0.24	0.40	0.18	0.22	1.01	0.50

TABLE 11.III - EFFECTS OF INCREMENTAL CHANGES IN PARAMETERS ON REQUIRED FREIGHT RATE (25)

Incremental changes in Required Freight Rates as percent of original Reqired Freight Rate
due to a 1% increase in the parameter, using CR(15%, 10 years) = 0.199

category	percent of total		L		B		D		C_B		V_k	
	ore carrier	VLCC tanker	ore carrier	VLCC tanker	ore carrier	VLCC tanker	ore carrier	VLCC tanker	ore carrier	VLCC tanker	ore carrier	VLCC tanker
capital recov.	62%	54%	0.84	0.63	0.59	0.32	0.17	0.21	0.12	0.11	0.98	0.36
fixed annual costs *	21%	22%	0.20	0.20	0.14	0.11	0.06	0.08	0.03	0.04	0.26	0.11
voyage costs	17%	24%	0.18	0.26	0.15	0.17	0.09	0.01	0.10	0.05	0.54	1.30
total	100%	100%	1.22	1.09	0.88	0.60	0.32	0.30	0.25	0.20	1.78	1.77

* including crew, stores, and supplies

Ship dimension, block coefficient, and speed changes will obviously affect hull resistance, fuel consumption, and operating costs as well as vessel capital cost so a complete assessment needs to consider how the Required Freight Rate (RFR) would be affected by these changes. Table 11.III shows the incremental change in vessel RFR that would result from a 1% change in length, beam, depth, block coefficient, or speed. A 1% change in ship length would result in a 1.2% increase in RFR for the ore carrier and a 1.1% change in the RFR for the VLCC. A 1% increase in beam increases the RFR 0.9% for the ore carrier and 0.6% for the VLCC. A 1% change in depth and block coefficient have, respectively, about 0.27 and about 0.20 as much impact on RFR as a 1% change in length. Thus, if one of these designs needed 1% more displacement, the most economic way to achieve this change would be to increase block coefficient 1%, with a 1% beam change second. The most economic way to decrease displacement by 1% would be to reduce the length 1%. When the impact on fuel cost and other operating costs are considered, a 1% change in ship speed will have greater impact resulting in about a 1.8% change in RFR for either type of vessel.

11.2.5 Initial Dimensions and Their Ratios

A recommended approach to obtain an initial estimate of vessel length, beam, depth, and design draft is to use a dataset of similar vessels, if feasible, to obtain guidance for the initial values. This can be simply by inspection or regression equations can be developed from this data using primary functional requirements, such as cargo deadweight and speed, as independent variables. Development of these equations will be discussed further in Section 11.5. In other situations, a summation of lengths for various volume or weather deck needs can provide a starting point for vessel length. Since the waterline length at the design draft T is a direct factor in the displacement and resistance of the vessel, LWL is usually the most useful length definition to use in early sizing iterations.

The typical primary influence of the various hull dimensions on the function/performance of a ship design is summarized in Table 11.IV. The parameters are listed in a typical order of importance indicating an effective order for establishing the parameters. Of course, length, beam, and draft all contribute to achieving the needed displacement for the hull. The primary independent sizing variable is typically taken as length. With length estimated, a beam that is consistent with discrete cargo needs and/or consistent with the length can be selected. With a candidate length and beam selected, a depth that is consistent with functional needs can be selected. The initial draft can then be selected. In all cases, of course, dimensional constraints need to be considered.

Watson (18) notes that with a target displacement and an acceptable choice of vessel length-beam ratio, beam-draft ratio, and block coefficient based upon vessel type and Froude number, equation 1 becomes,

$$L = \{(\Delta\, (L/B)^2\, B/T)/(\gamma\, C_B\, (1 + s))\}^{1/3} \qquad [4]$$

This approach can provide a way to obtain an initial estimate of the vessel length.

Table 11.IV - PRIMARY INFLUENCE OF HULL DIMENSIONS

Parameter	Primary Influence of Dimensions
length	resistance, capital cost, maneuverability, longitudinal strength, hull volume, seakeeping
beam	transverse stability, resistance, maneuverability, capital cost, hull volume
depth	hull volume, longitudinal strength, transverse stability, capital cost, freeboard
draft	displacement, freeboard, resistance, transverse stability

A number of approximate equations also exist in the literature for estimating vessel length from other ship characteristics. For illustration, a classic example is Posdunine's formula,

$$L\ (m) = C\, (V_k/(V_k + 2))^2\, \Delta^{1/3} \qquad [5]$$

where displacement is in tonnes and the speed is in knots (as indicated by the subscript k) and the coefficient C can be generalized from similar vessels. Typical coefficient C ranges are 7.1 – 7.4 for single screw vessels of 11 to 18.5 knots, 7.4 – 8.0 for twin screw vessels of 15 to 20 knots, and 8.0 – 9.7 for twin screw vessels of 20 to 30 knots

A general consideration of hull resistance versus length shows that frictional resistance increases with length as the wetted surface increases faster than the frictional resistance coefficient declines with Reynolds number. The wave resistance, however, decreases with length. The net effect is that resistance as a function of ship length typically exhibits a broad, flat minimum. Since the hull cost increases with length, an economic choice is usually a length at the lower end of this minimum region where the resistance begins to increase rapidly with further length reduction. Below this length higher propulsion requirements and higher operating costs will then offset any further reduction in hull capital cost.

11.2.5.1 Length–Beam Ratio L/B

Various non-dimensional ratios of hull dimensions can be used to guide the selection of hull dimensions or alternatively used as a check on the dimensions selected based upon similar ships, functional requirements, etc. Each designer develops his or her own preferences, but generally the length-beam ratio L/B, and the beam-depth ratio B/D, prove to be the most useful.

The length-beam ratio can be used to check independent choices of L and B or with an initial L, a choice of a desired L/B ratio can be used to obtain an estimated beam B. The L/B ratio has significant influence on hull resistance and maneuverability – both the ability to turn and directional stability. With the primary influence of length on capital cost, there has been a trend toward shorter wider hulls supported by design refinement to ensure adequate inflow to the propeller. Figure 11.1 from Watson (18) shows the relationship of L and B for various types of commercial vessels. Note that in this presentation, rays from the origin are lines of constant L/B ratio. From this Watson and Gilfillan (1) recommended,

$$L/B = 4.0, \qquad \text{for } L \le 30 \text{ m}$$
$$L/B = 4.0 + 0.025\,(L - 30), \qquad \text{for } 30 \le L \le 130 \text{ m}$$
$$L/B = 6.5, \qquad \text{for } 130 \text{ m} \le L \qquad [6]$$

They also noted a class of larger draft-limited vessels that need to go to higher beam leading to a lower L/B ratio of about 5.1. Watson (18) noted that recent large tankers had L/B ≈ 5.5 while recent reefers, containerships, and bulk carriers had L/B ≈ 6.25. This guidance is useful, but only an indication of general design trends today. Similar information could be developed for each specific class of vessels of interest. Specific design requirements can lead to a wide range of L/B choices. Great Lakes 1000’ ore carriers have L/B = 9.5 as set by lock dimensions.

Icebreakers tend to be short and wide to have good maneuverability in ice and to break a wide path for other vessels leading to L/B values of about 4.0. Similarly, the draft-limited Ultra Large Crude Carriers (ULCC’s) have had L/B ratios in the range of 4.5 to 5.5. The recent *Ramform* acoustic survey vessels have an L/B of about 2.0 (see Chapter 30, Figure 30.15). At the high end, World War II Japanese cruisers, such as the *Furutaka* class, had an L/B of 11.7 and not surprisingly experienced stability problems due to their narrow hulls.

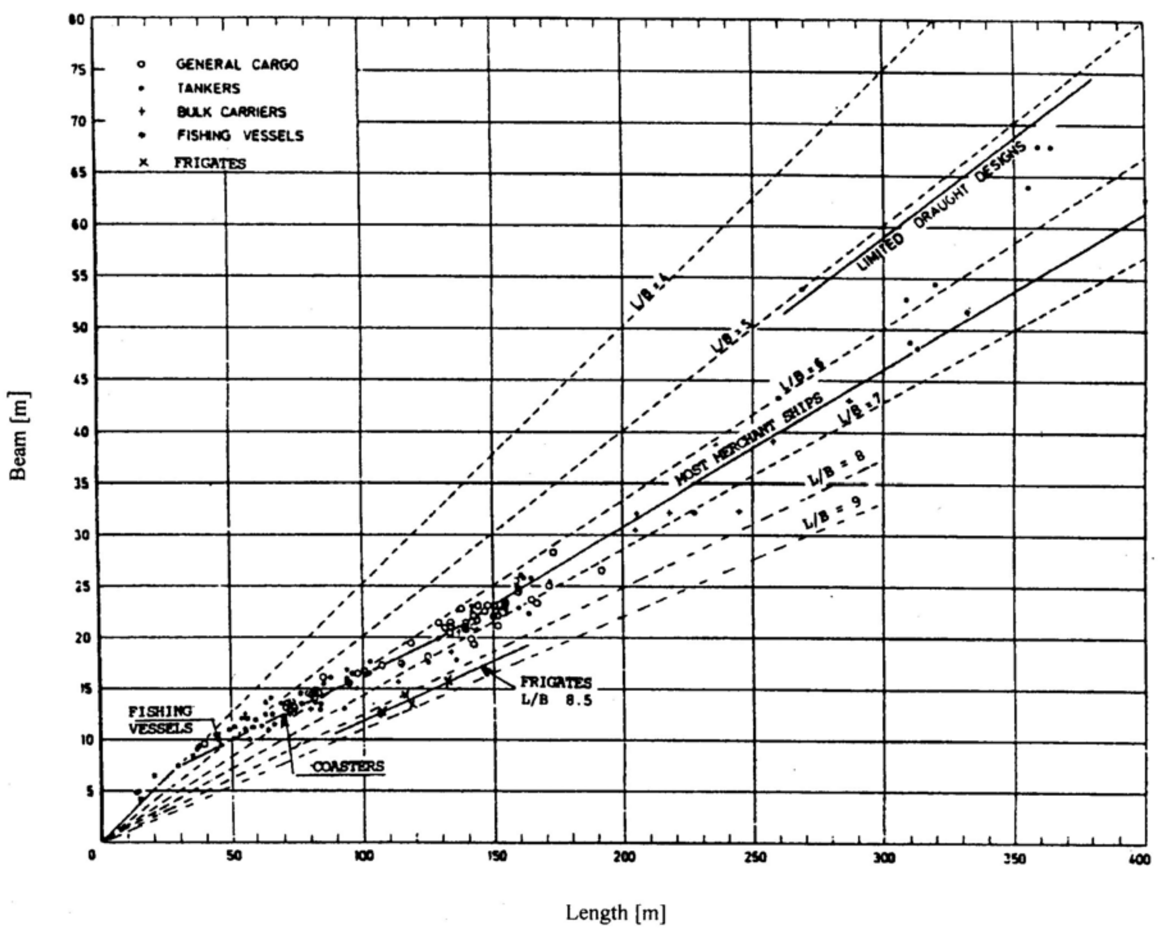


Figure 11.1 - Beam versus Length (18)

11.2.5.2 Beam–Depth Ratio B/D

The next most important non-dimensional ratio is the beam-depth ratio B/D. This provides effective early guidance on initial intact transverse stability. In early design, the transverse metacentric height is usually assessed using,

$$GM_T = KB + BM_T - 1.03\ KG \geq \text{req'd}\ GM_T \quad [7]$$

where the 3% (or similar) increase in KG is included to account for anticipated free surface effects. Using parametric models that will be presented below, it is possible to estimate the partial derivatives of GM_T with respect to the primary ship dimensions. Using parametric equations for form coefficients and characteristics for a typical Seaway size bulk carrier for illustration this yields,

$\partial GM_T/\partial B = +0.48$
$\partial GM_T/\partial D = -0.70$
$\partial GM_T/\partial T = -0.17$
$\partial GM_T/\partial L = +0.00$
$\partial GM_T/\partial C_B = +1.34$

The value of the transverse metacenteric radius BM_T is primarily affected by beam (actually B^2/C_BT) while the vertical center of gravity KG is primarily affected by depth so the B/D ratio gives early guidance relative to potential stability problems. Watson (18) presents data for commercial vessels included in Figure 11.2. From this data, Watson and Gilfillan (1) concluded that weight limited vessels had B/D ≈ 1.90 while stability constrained volume limited vessels had B/D ≈ 1.65. Watson (18) noted that recent large tankers had B/D ≈ 1.91; recent bulk carriers had B/D ≈ 1.88, while recent reefers and containerships had B/D ≈ 1.70. Extreme values are Great Lakes iron ore carriers with B/D = 2.1 and ULCC's with values as high as 2.5.

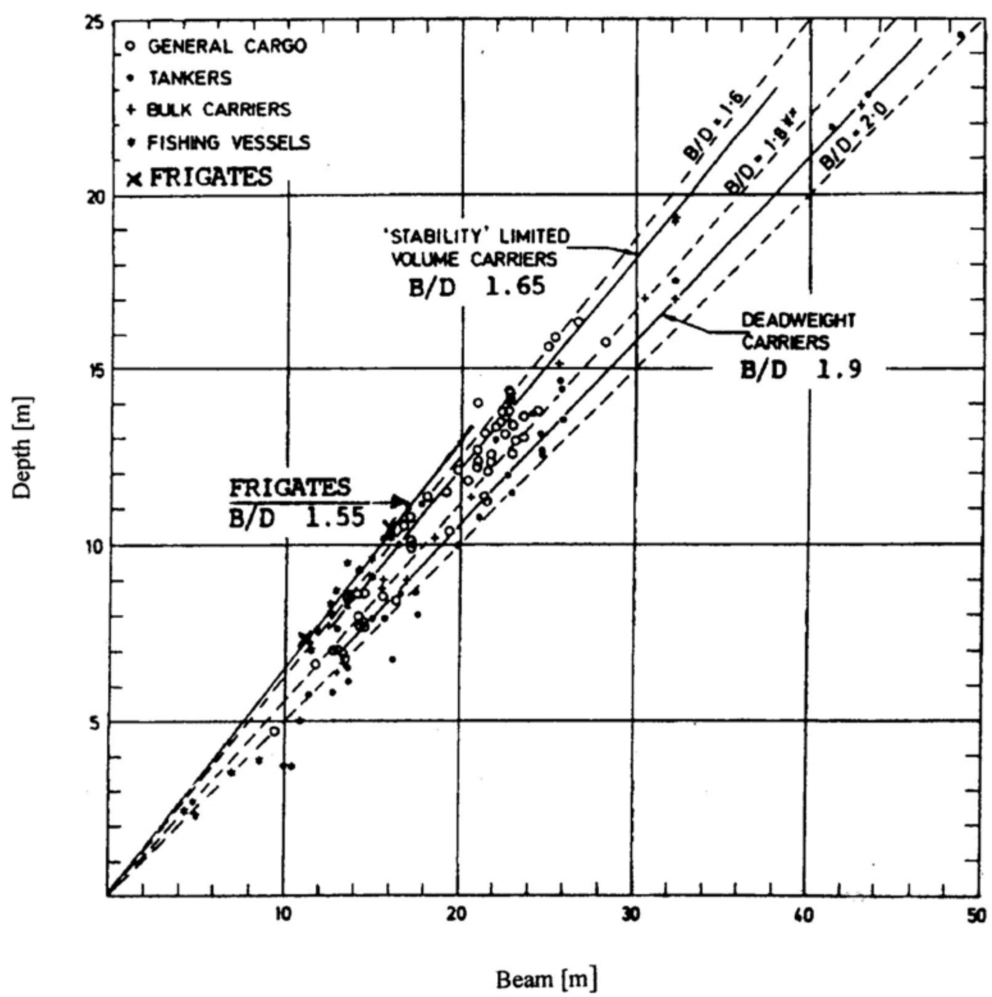


Figure 11.2 - Depth versus Beam (18)

Early designs should proceed with caution if the B/D is allowed to drop below 1.55 since transverse stability problems can be expected when detailed analyses are completed.

11.2.5.3 Beam–Draft Ratio B/T

The third most important nondimensional ratio is the beam-draft ratio B/T. The beam-draft ratio is primarily important through its influence on residuary resistance, transverse stability, and wetted surface. In general, values range between $2.25 \leq B/T \leq 3.75$, but values as high as 5.0 appear in heavily draft-limited designs. The beam-draft ratio correlates strongly with residuary resistance, which increases for large B/T. Thus, B/T is often used as an independent variable in residuary resistance estimating models. As B/T becomes low, transverse stability may become a problem as seen from the above example partial derivatives. Saunders (26) presented data for the non-dimensional wetted surface coefficient $C_S = S/\sqrt{(\nabla L)}$ for the Taylor Standard Series hulls that is instructive in understanding the influence of B/T on wetted surface and, thus particularly, frictional resistance. Saunders' contour plot of C_S versus C_M and B/T is shown in Figure 11.3. One can see that the minimum wetted surface for these hulls is achieved at about $C_M = 0.90$ and $B/T = 3.0$. The dashed line shows the locus of B/T values which yield the minimum wetted surface hulls for varying C_M and is given by,

$$B/T|_{\min C_S} = 5.93 - 3.33\, C_M \qquad [8]$$

In their SNAME-sponsored work on draft-limited conventional single screw vessels, Roseman et al (27) recommended that the beam-draft ratio be limited to the following maximum,

$$(B/T)_{max} = 9.625 - 7.5\, C_B \qquad [9]$$

in order to ensure acceptable flow to the propeller on large draft-limited vessels.

11.2.5.4 Length–Depth Ratio L/D

The length-depth ratio L/D is primarily important in its influence on longitudinal strength. In the length range from about 100 to 300 m, the primary loading vertical wave bending moment is the principal determinant of hull structure. In this range, the vertical wave bending moment increases with ship length. Local dynamic pressures dominate below about 300 feet. Ocean wavelengths are limited, so beyond 1000 feet the vertical wave bending moment again becomes less significant. The ability of the hull to resist primary bending depends upon the midship section moment of inertia, which varies as B and D^3. Thus, the ratio L/D relates to the ability of the hull to be designed to resist longitudinal bending with reasonable scantlings. Classification society requirements require special consideration when the L/D ratio lies outside the range assumed in the development of their rules.

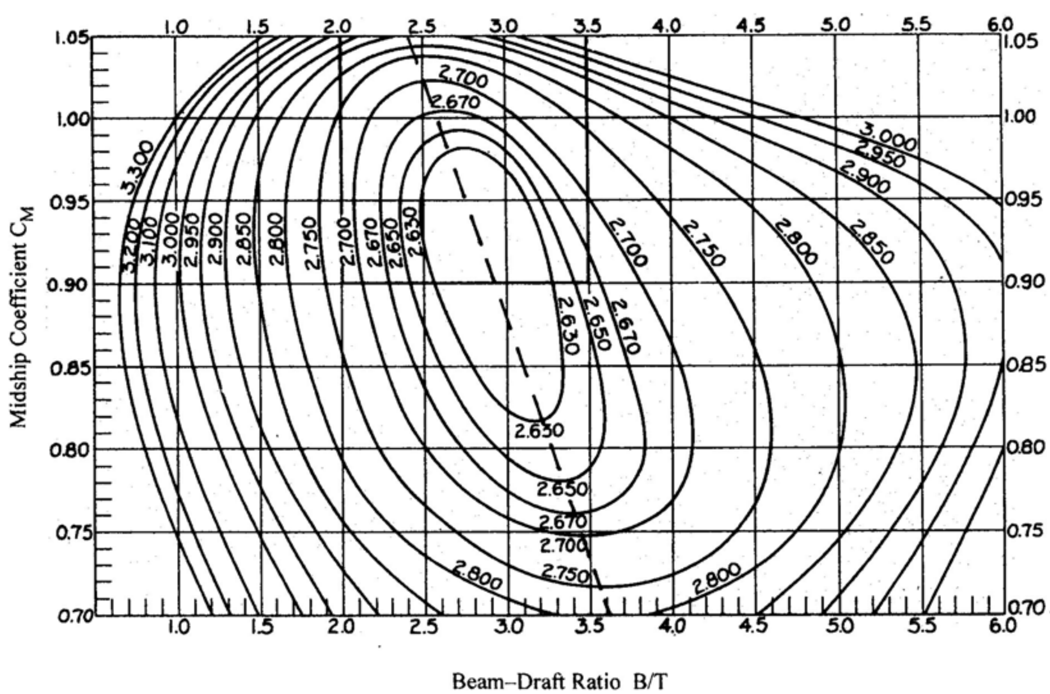


Figure 11.3 - Wetted Surface Coefficient for Taylor Standard Series Hulls (26)

11.2.6 Initial Hull Form Coefficients

The choice of primary hull form coefficient is a matter of design style and tradition. Generally, commercial ships tend to be developed using the block coefficient C_B as the primary form coefficient, while faster military vessels tend to be developed using the longitudinal prismatic C_P as the form coefficient of greatest importance. Recall that through their definitions, the form coefficients are related by dual identities, one for the longitudinal direction and one for the vertical direction, they are

$$C_B \equiv C_P\, C_X \qquad [10]$$

$$C_B \equiv C_{VP}\, C_{WP} \qquad [11]$$

Thus with an estimate or choice of any two coefficients in either equation, the third is established by its definition. A designer cannot make three independent estimates or choices of the coefficients in either identity.

11.2.6.1 Block Coefficient C_B

The block coefficient C_B measures the fullness of the submerged hull, the ratio of the hull volume to its surrounding parallelepiped LBT. Generally, it is economically efficient to design hulls to be slightly fuller than that which will result in minimum resistance per tonne of displacement. The most generally accepted guidance for the choice of block coefficient for vessels in the commercial range of hulls is from Watson and Gilfillan (1) as shown in Figure 11.4. This useful plot has the dimensional speed length ratio $V_k/\sqrt{L_f}$ (with speed in knots and length in feet) and the Froude number Fn as the independent variables. Ranges of typical classes of commercial vessels are shown for reference. The recommended C_B is presented as a mean line and an acceptable range of ± 0.025. Watson's recommended C_B line from his earlier 1962 paper is also shown. This particular shape results because at the left, slow end hulls can have full bows, but still need fairing at the stern to ensure acceptable flow into the propeller leading to a practical maximum recommended C_B of about 0.87. As a practical exception, data for the 1000 foot Great Lakes ore carrier *James R. Barker* (hull 909) is shown for reference. At the right, faster end the resistance becomes independent of C_B and, thus, there appears to be no advantage to reducing C_B below about 0.53.

In his sequel, Watson (28) noted that the recommended values in the $0.18 \leq Fn \leq 0.21$ range might be high. This results because the bulk carriers considered in this range routinely claim their speed as their maximum speed (at full power using the service margin) rather than their service or trial speed as part of tramp vessel marketing practices. Independent analysis tends to support this observation. Many designers and synthesis models now use the Watson and Gilfillan mean line to select the initial C_B given Fn. This is based upon a generalization of existing vessels, and primarily reflects smooth water powering.

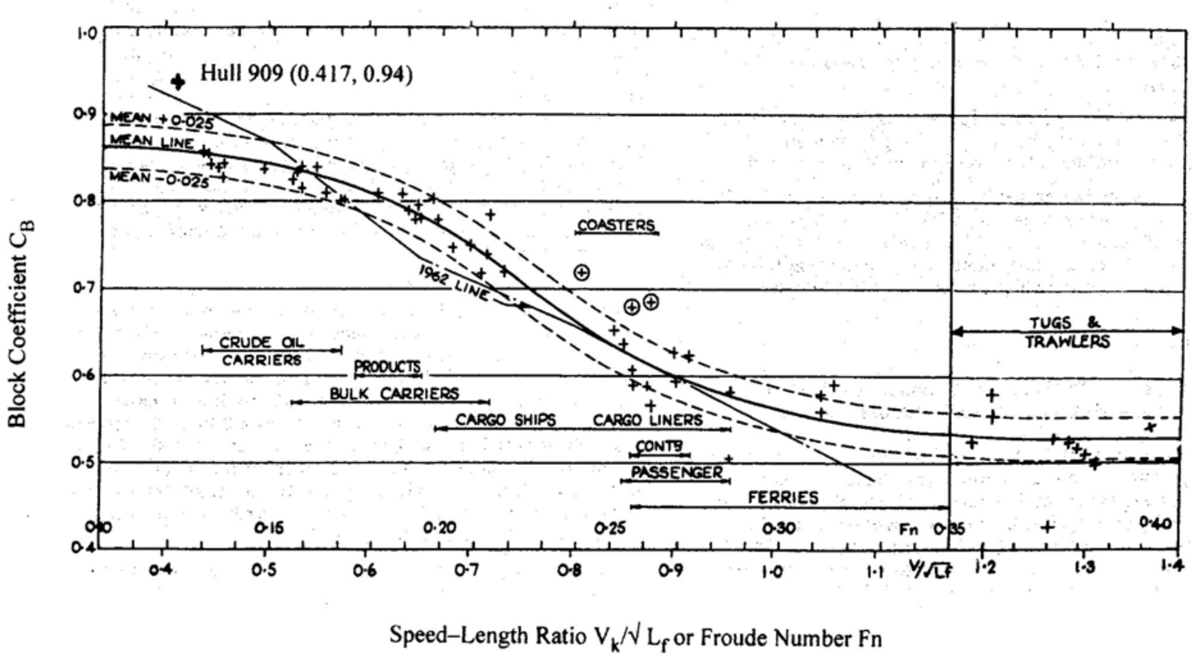


Figure 11.4 - Watson and Gilfillan Recommended Block Coefficient (1,18)

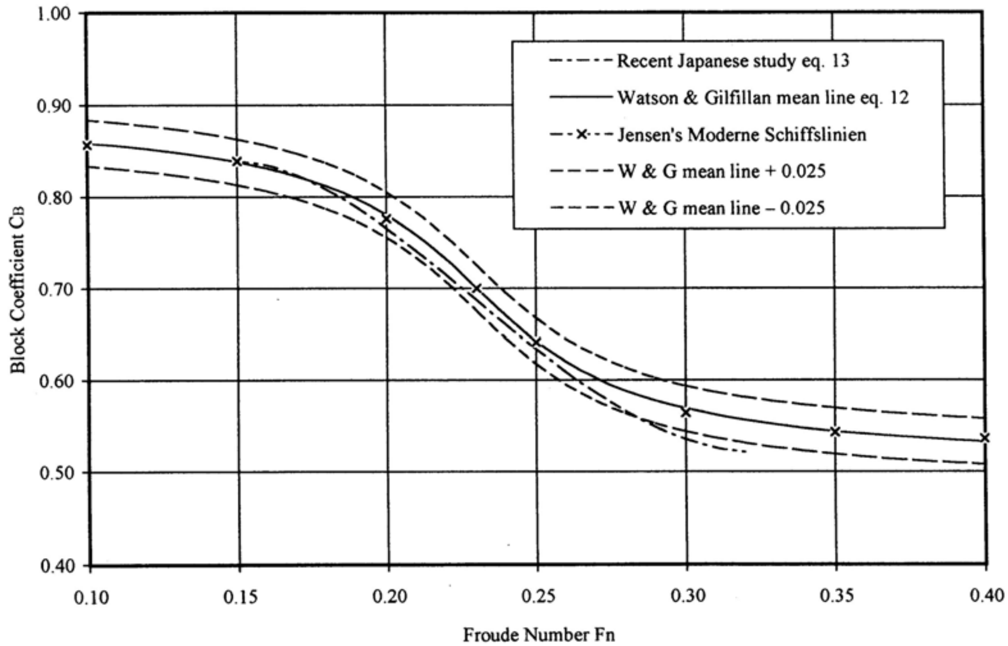


Figure 11.5 - Comparison of Recent Block Coefficient Recommendations

Any particular design has latitude certainly within at least the ± 0.025 band in selecting the needed C_B, but the presentation provides primary guidance for early selection. To facilitate design, Towsin in comments on Watson's sequel (28) presented the following equation for the Watson and Gilfillan mean line,

$$C_B = 0.70 + 0.125 \tan^{-1}((23 - 100\ Fn)/4) \quad [12]$$

(In evaluating this on a calculator, note that the radian mode is needed when evaluating the arctan.)

Watson (18) notes that a study of recent commercial designs continues to validate the Watson and Gilfillan mean line recommendation, or conversely most designers are now using this recommendation in their designs. Schneekluth and Bertram (17) note that a recent Japanese statistical study yielded for vessels in the range $0.15 \leq Fn \leq 0.32$,

$$C_B = -4.22 + 27.8\sqrt{Fn} - 39.1\ Fn + 46.6\ Fn^3 \quad [13]$$

Jensen (29) recommends current best practice in German designs, which appears to coincide with the Watson and Gilfillan mean line. Figure 11.5 shows the Watson and Gilfillan mean line equation 12 and its bounds, the Japanese study equation 13, and the Jensen recommendations for comparison. Recent Japanese practice can be seen to be somewhat lower than the Watson and Gilfillan mean line above $Fn \approx 0.175$.

The choice of C_B can be thought of as selecting a fullness that will not result in excessive power requirements for the Fn of the design. As noted above, designs are generally selected to be somewhat fuller than the value, which would result in the minimum resistance per tonne. This can be illustrated using Series 60 resistance data presented by Telfer in his comments on Watson and Gilfillan (1). The nondimensional resistance per tonne of displacement for Series 60 hulls is shown in Figure 11.6 as a function of speed length ratio $V_k/\sqrt{L_f}$ with C_B the parameter on curves.

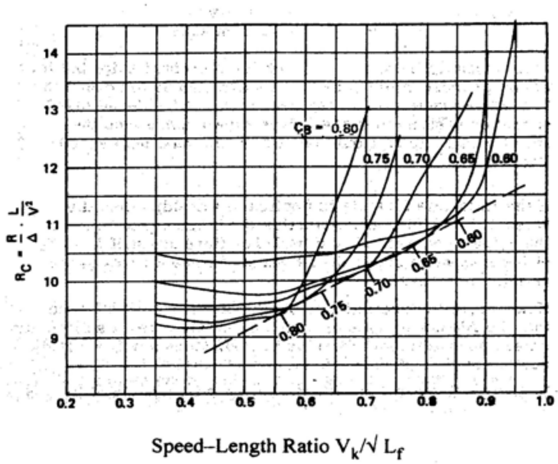


Figure 11.6 - Resistance per Tonne for Series 60 (28)

Fitting an approximate equation to this locus yields the block coefficient for minimum resistance per tonne,

$$C_B = 1.18 - 0.69\ V_k/\sqrt{L_f} \qquad [14]$$

This equation can be plotted on Figure 11.4 where it can be seen that it roughly corresponds to the Watson and Gilfillan mean line – 0.025 for the speed length ratio range $0.5 \leq V_k/\sqrt{L_f} \leq 0.9$.

One of the many classic formulae for block coefficient can be useful in the intermediate $0.50 \leq V_k/\sqrt{L_f} \leq 1.0$ region. Alexander's formula has been used in various forms since about 1900,

$$C_B = K - 0.5\ V_k/\sqrt{L_f} \qquad [15]$$

where $K = 1.33 - 0.54\ V_k/\sqrt{L_f} + 0.24(V_k/\sqrt{L_f})^2$, is recommended for merchant vessels. Other examples are available in the literature for specific types of vessels.

11.2.6.2 Maximum Section Coefficient C_X and Midship Section Coefficient C_M

The midship and maximum section coefficient $C_M \approx C_X$ can be estimated using generalizations developed from existing hull forms or from systematic hull series. For most commercial hulls, the maximum section includes amidships. For faster hulls, the maximum section may be significantly aft of amidships. Recommended values for C_M are,

$$C_M = 0.977 + 0.085\ (C_B - 0.60) \qquad [16]$$

$$C_M = 1.006 - 0.0056\ C_B^{\ -3.56} \qquad [17]$$

$$C_M = (1 + (1 - C_B)^{3.5})^{-1} \qquad [18]$$

Benford developed equation 16 from Series 60 data. Equations 17 and 18 are from Schneekluth and Bertram (17) and attributed to Kerlen and the HSVA Linienatlas, respectively. Jensen (29) recommends equation 18 as current best practice in Germany. These recommendations are presented in Figure 11.7 with a plot of additional discrete recommendations attributed by Schneekluth and Bertram to van Lammeren. If a vessel is to have a full midship section with no deadrise, flat of side, and a bilge radius, the maximum section coefficient can be easily related to the beam, draft, and the bilge radius r as follows:

$$C_M = 1 - 0.4292\ r^2/BT \qquad [19]$$

If a vessel is to have a flat plate keel of width K and a rise of floor that reaches F at B/2, this becomes,

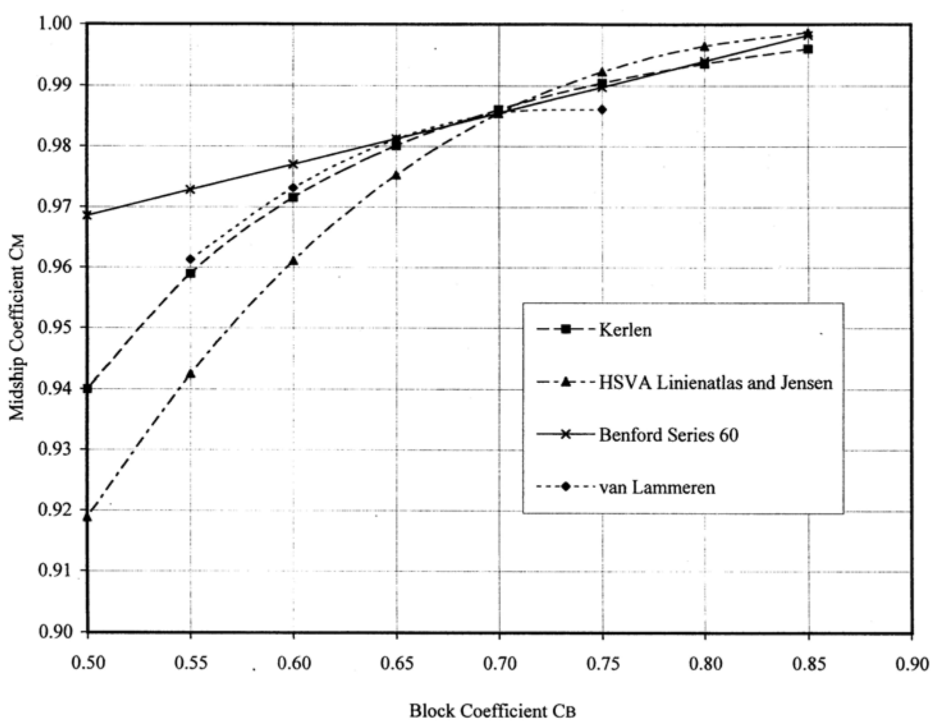


Figure 11.7 - Recommended Midship Coefficients

$$C_M = 1 - \{F((B/2 - K/2) - r^2/(B/2 - K/2)) + 0.4292\, r^2\}/BT \qquad [20]$$

Producibility considerations will often make the bilge radius equal to or slightly below the innerbottom height h_{db} to facilitate the hull construction. In small to medium sized vessels, the bilge quarter circle arc length is often selected to be the shipyard's single standard plate width. Using B/T = 3.0 and an extreme r = T, equation 19 yields a useful reference lower bound of C_M = 0.857. Using B/T = 2.0 and r = T giving a half circle hull section, this yields C_M = 0.785.

11.2.6.3 Longitudinal Prismatic Coefficient C_P

The design of faster military and related vessels typically uses the longitudinal prismatic coefficient C_P, rather than C_B, as the primary hull form coefficient. The longitudinal prismatic describes the distribution of volume along the hull form. A low value of C_P indicates significant taper of the hull in the entrance and run. A high value of C_P indicates more full hull possibly with parallel midbody over a significant portion of the hull. If the design uses C_B as the principal hull form coefficient and then estimates C_X, C_P can be obtained from the identity equation 10. If C_P is the principal hull form coefficient, the remaining C_B or C_X could then be obtained using equation 10.

The classic principal guidance for selecting the longitudinal prismatic coefficient C_P was presented by Saunders (26), Figure 11.8. This plot presents recommended design lanes for C_P and the displacement-length ratio in a manner similar to Figure 11.4. Again, the independent variable is the dimensional speed length ratio (Taylor Quotient) $V_k/\sqrt{L_f}$ or the Froude number Fn. This plot is also useful in that it shows the regions of residuary resistance humps and hollows, the regions of relatively high and low wave resistance due to the position of the crest of the bow wave system relative to the stern. Saunders' design lane is directly comparable to the Watson and Gilfillan mean line ± 0.025 for C_B.

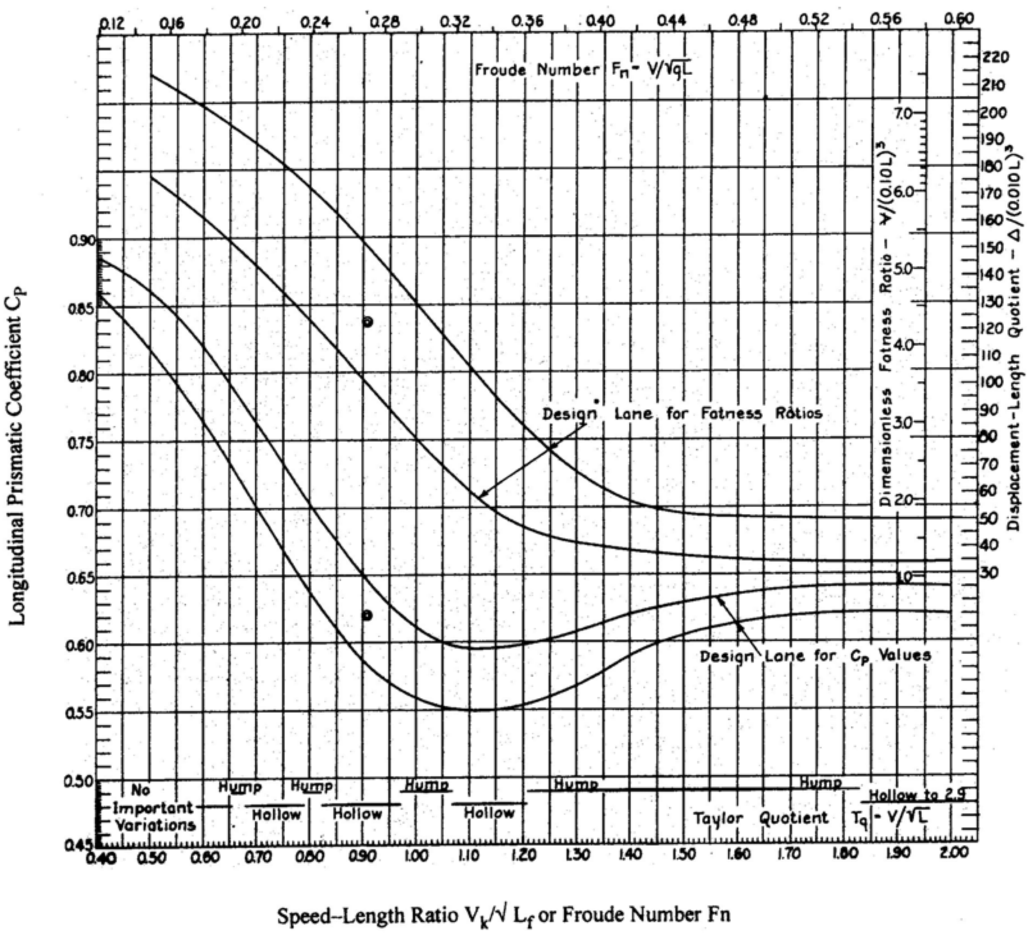


Figure 11.8 - Saunders' Design Lanes for Longitudinal Prismatic and Volumetric Coefficient (26)

Saunders' recommendation remains the principal C_P reference for the design and evaluation of U.S. Naval vessels.

A quite different recommendation for the selection of C_P appeared in comments by D. K. Brown on Andrews (15). The tentative design lane proposed by Brown based upon minimization of Froude's circle C (total resistance per tonne divided by circle K squared) is shown in Figure 11.9. This shows a recommended design lane for C_P versus the Froude's circle K and volumetric Froude number F_∇ derived from tests at Haslar. Note that Brown recommends significantly lower values for C_P than recommended by Saunders.

11.2.6.4 Displacement–Length Ratio and Volumetric Coefficient C_∇

The block coefficient describes the fullness of the submerged hull and the longitudinal prismatic describes the distribution of its volume along the length of the hull for normal hull forms with taper in the entrance and run. But, neither of these reveals a third important characteristic of a hull form. Consider a unit cube and a solid with unit cross-section and length 10. Each would have $C_B = 1$ and $C_P = 1$, but they would obviously have significantly different properties for propulsion and maneuvering. The relationship between volume and vessel length, or its fatness, also needs to be characterized. There are a number of hull form coefficients that are used to describe this characteristic. The traditional English dimensional parameter is the displacement-length ratio $= \Delta/(0.01L_f)^3$, with displacement in long tons and length in feet. Others use a dimensionless fatness ratio $\nabla/(0.10L)^3$ or the volumetric coefficient $C_\nabla = \nabla/L^3$. Traditional British practice uses an inversely related circle M coefficient defined as $L/\nabla^{1/3}$. Saunders recommends design lanes for the first two of these ratios in Figure 11.8. Some naval architects use this parameter as the primary hull form coefficient, in preference to C_B or C_P, particularly in designing tugboats and fishing vessels.

11.2.6.5 Waterplane Coefficient C_{WP}

The waterplane coefficient C_{WP} is usually the next hull form coefficient to estimate. The shape of the design waterplane correlates well with the distribution of volume along the length of the hull, so C_{WP} can usually be estimated effectively in early design from the chosen C_P, provided the designer's intent relative to hull form, number of screws, and stern design is reflected. An initial estimate of C_{WP} is used to estimate the transverse and longitudinal inertia properties of the waterplane needed to calculate BM_T and BM_L, respectively. With a C_{WP} estimate, the identity equation 11 can be used to calculate a consistent C_{VP} that can be used to estimate the vertical center of buoyancy KB of the hull.

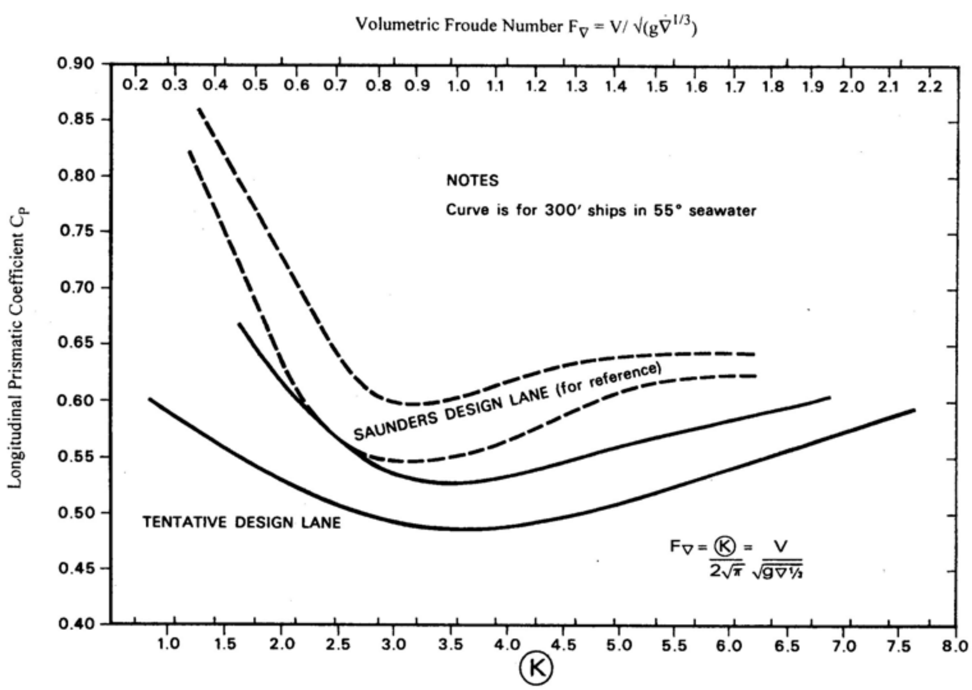


Figure 11.9 - Brown's Recommended Design Lane for Longitudinal Prismatic (15)

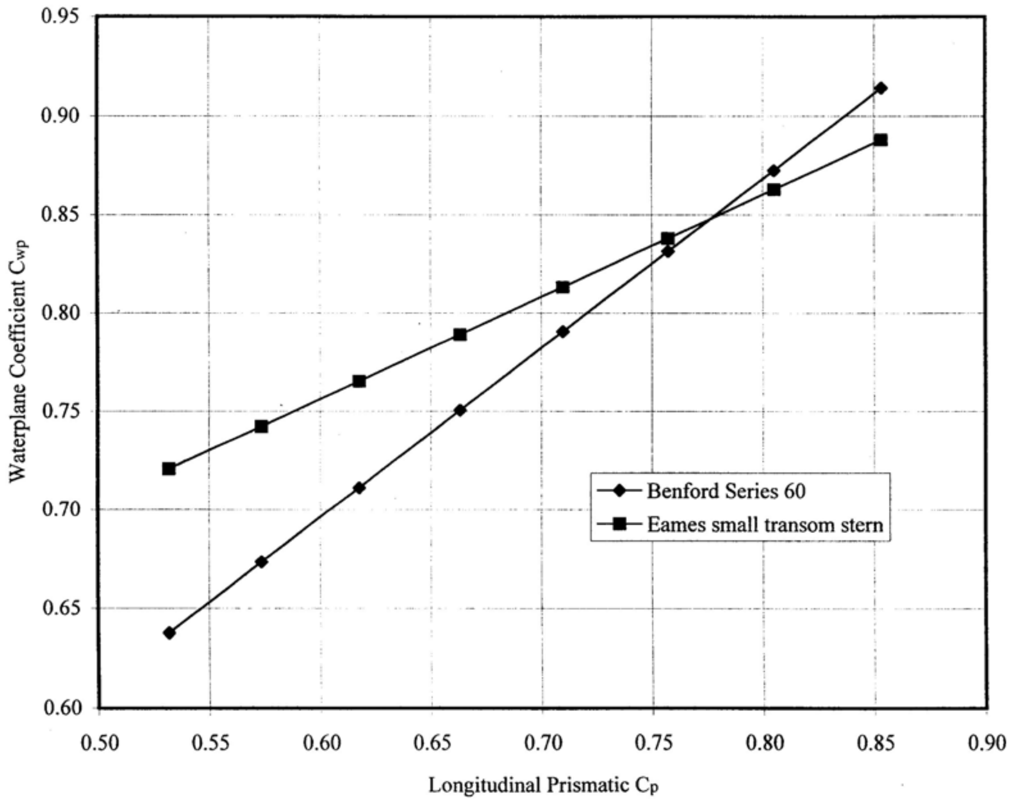


Figure 11.10 - Estimates for Waterplane Coefficient C_{WP}

There is a catalog of models in the literature that allow estimation of C_{WP} from C_P, C_B, or C_B and C_M. These models are summarized in Table 11.V. The first two models are plotted in Figure 11.10 and show that the use of a transom stern increases C_{WP} by about 0.05 to 0.08 at the low C_P values typical of the faster transom stern hulls. It is important to be clear on the definition of stern types in selecting which of these equations to use. Three types of sterns are sketched in Figure 11.11. The cruiser stern gets its name from early cruisers, such as the 1898 British cruiser *Leviathan* used as the parent for the Taylor Standard Series. Cruisers of this time period had a canoe-like stern in which the waterplane came to a point at its aft end. Cruisers of today typically have "hydrodynamic" transom sterns, for improved high-speed resistance, in which the waterplane ends with a finite transom beam at the design waterline at zero speed. Leading to further potential confusion, most commercial ships today have flat transoms above the waterline to simplify construction and save on hull cost, but these sterns still classify as cruiser sterns <u>below</u> the waterline, not hydrodynamic transom sterns.

The 4th through 6th equations in Table 11.V are plotted in Figure 11.12. The effect of the transom stern can be seen to increase C_{WP} about 0.05 in this comparison. The wider waterplane aft typical with twin-screw vessels affects the estimates a lesser amount for cruiser stern vessels. The 9th through 11th equations in Table 11.V are plotted in Figure 11.13. The choice of a V-shaped rather than a U-shaped hull significantly widens the waterplane resulting in up to a 0.05 increase in C_{WP}. V-shaped hulls typically have superior vertical plane (heave and pitch) seakeeping characteristics, but poorer smooth water powering characteristics leading to an important design tradeoff in some designs.

11.2.6.6 Vertical Prismatic Coefficient C_{VP}

The vertical prismatic coefficient is used in early design to estimate the vertical center of buoyancy KB needed to assess the initial stability. The vertical prismatic coefficient describes the vertical distribution of the hull volume below the design waterline.

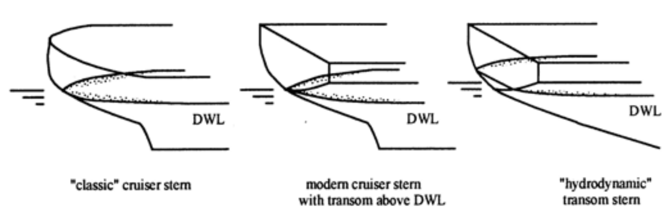


Figure 11.11 - Types of Sterns

Since conventional hull forms typically have their greatest waterplane area near the water surface, a C_{VP} approaching 0.5 implies a triangular-shaped or V-shaped hull.

A C_{VP} approaching 1.0 implies a full, extreme U-shaped hull. Small Waterplane Twin Hull (SWATH) vessels would, obviously, require a unique interpretation of C_{VP}.

The vertical prismatic coefficient C_{VP} inversely correlates with hull wave damping in heave and pitch, thus, low values of C_{VP} and corresponding high values of C_{WP} produce superior vertical plane seakeeping hulls. If a designer were to select C_{VP} to affect seakeeping performance, identity equation 11 can then be used to obtain the consistent value for C_{WP}. This characteristic can be illustrated by work of Bales (30) in which he used regression analysis to obtain a rank estimator $\hat{R}$ for vertical plane seakeeping performance of combatant monohulls. This estimator yields a ranking number between 1 (poor seakeeping) and 10 (superior seakeeping) and has the following form:

$$\hat{R} = 8.42 + 45.1\, C_{WPf} + 10.1\, C_{WPa} - 378\, T/L + 1.27\, C/L - 23.5\, C_{VPf} - 15.9\, C_{VPa} \qquad [21]$$

TABLE 11.V - DESIGN EQUATIONS FOR ESTIMATING WATERPLANECOEFFICIENT

Equation	Applicability/Source
$C_{WP} = 0.180 + 0.860\, C_P$	Series 60
$C_{WP} = 0.444 + 0.520\, C_P$	Eames, small transom stern warships (2)
$C_{WP} = C_B /(0.471 + 0.551\, C_B)$	tankers and bulk carriers (17)
$C_{WP} = 0.175 + 0.875\, C_P$	single screw, cruiser stern
$C_{WP} = 0.262 + 0.760\, C_P$	twin screw, cruiser stern
$C_{WP} = 0.262 + 0.810\, C_P$	twin screw, transom stern
$C_{WP} = C_P^{\,2/3}$	Schneekluth 1 (17)
$C_{WP} = (1 + 2\, C_B/C_M^{\,1/2})/3$	Schneekluth 2 (17)
$C_{WP} = 0.95\, C_P + 0.17\,(1 - C_P)^{1/3}$	U-form hulls
$C_{WP} = (1 + 2\, C_B)/3$	Average hulls, Riddlesworth (2)
$C_{WP} = C_B^{\,1/2} - 0.025$	V-form hulls

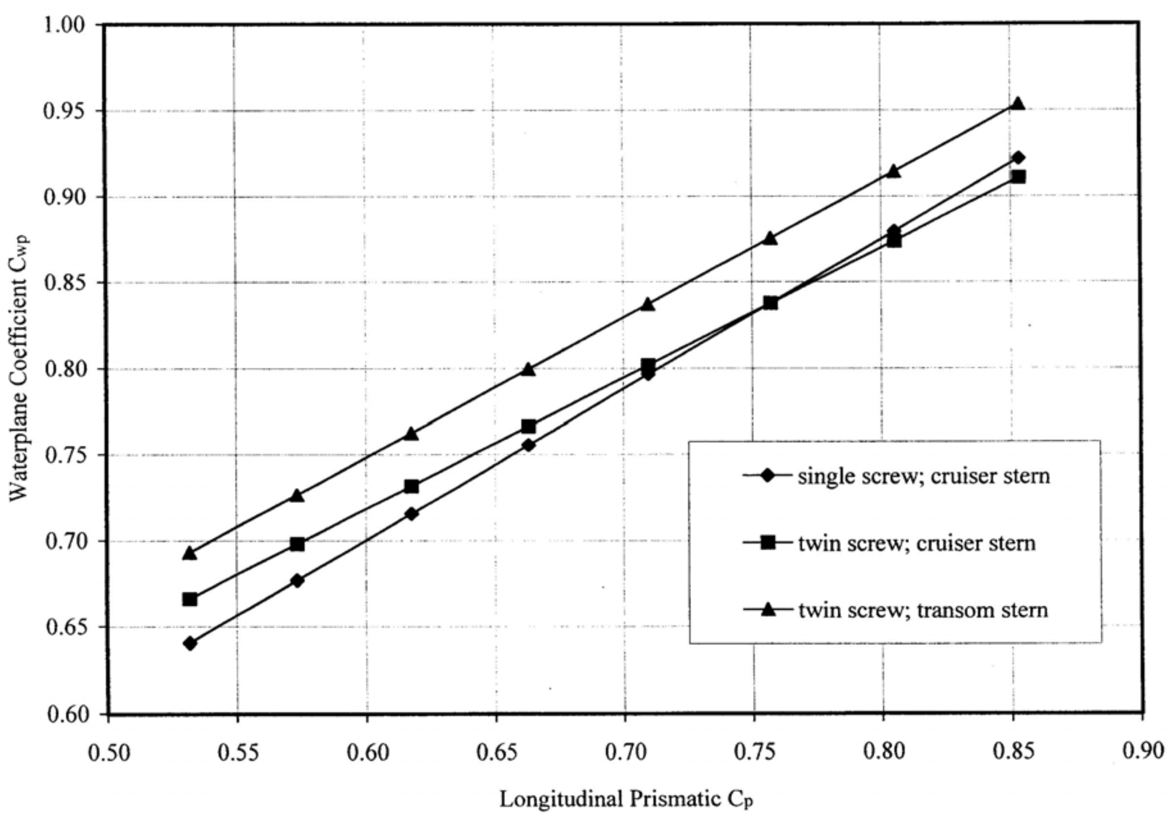


Figure 11.12 - Estimates of Waterplane Coefficient C_{WP} – Effect of Stern Type

Here the waterplane coefficient and the vertical prismatic coefficient are expressed separately for the forward (f) and the aft (a) portions of the hull. Since the objective for superior seakeeping is high $\hat{R}$, high C_{WP} and low C_{VP}, corresponding to V-shaped hulls, can be seen to provide improved vertical plane seakeeping. Note also that added waterplane forward is about 4.5 times as effective as aft and lower vertical prismatic forward is about 1.5 times as effective as aft in increasing $\hat{R}$. Thus, V-shaped hull sections forward provide the best way to achieve greater wave damping in heave and pitch and improve vertical plane seakeeping. Low draft-length ratio T/L and keeping the hull on the baseline well aft to increase the cut-up-ratio C/L also improve vertical plane seakeeping. Parameter C is the distance aft of the forward perpendicular where the hull begins its rise from the baseline to the stern. This logic guided the shaping of the DDG51 hull that has superior vertical-plane seakeeping performance compared to the earlier DD963 hull form that had essentially been optimized based only upon smooth water resistance.

11.2.7 Early Estimates of Hydrostatic Properties

The hydrostatic properties KB and BM_T are needed early in the parametric design process to assess the adequacy of the transverse GM_T relative to design requirements using equation 7.

11.2.7.1 Vertical Center of Buoyancy KB

An extreme U-shaped hull would have C_{VP} near 1.0 and a KB near 0.5T; an extreme V-shaped hull would be triangular with C_{VP} near 0.5 and a KB near 2/3 T. Thus, there is a strong inverse correlation between KB and C_{VP} and C_{VP} can be used to make effective estimates of the vertical center of buoyancy until actual hull offsets are available for hydrostatic analysis.

Two useful theoretical results have been derived for the KB as a function of C_{VP} for idealized hulls with uniform hull sections described by straight sections and a hard chine and by an exponential half breadth distribution with draft, respectively. These results are useful for early estimates for actual hull forms. The first approach yields Moorish's (also Normand's) formula,

$$KB/T = (2.5 - C_{VP})/3 \qquad [22]$$

which is recommended only for hulls with $C_M \leq 0.9$. The second approach yields a formula attributed to both Posdunine and Lackenby,

$$KB/T = (1 + C_{VP})^{-1} \qquad [23]$$

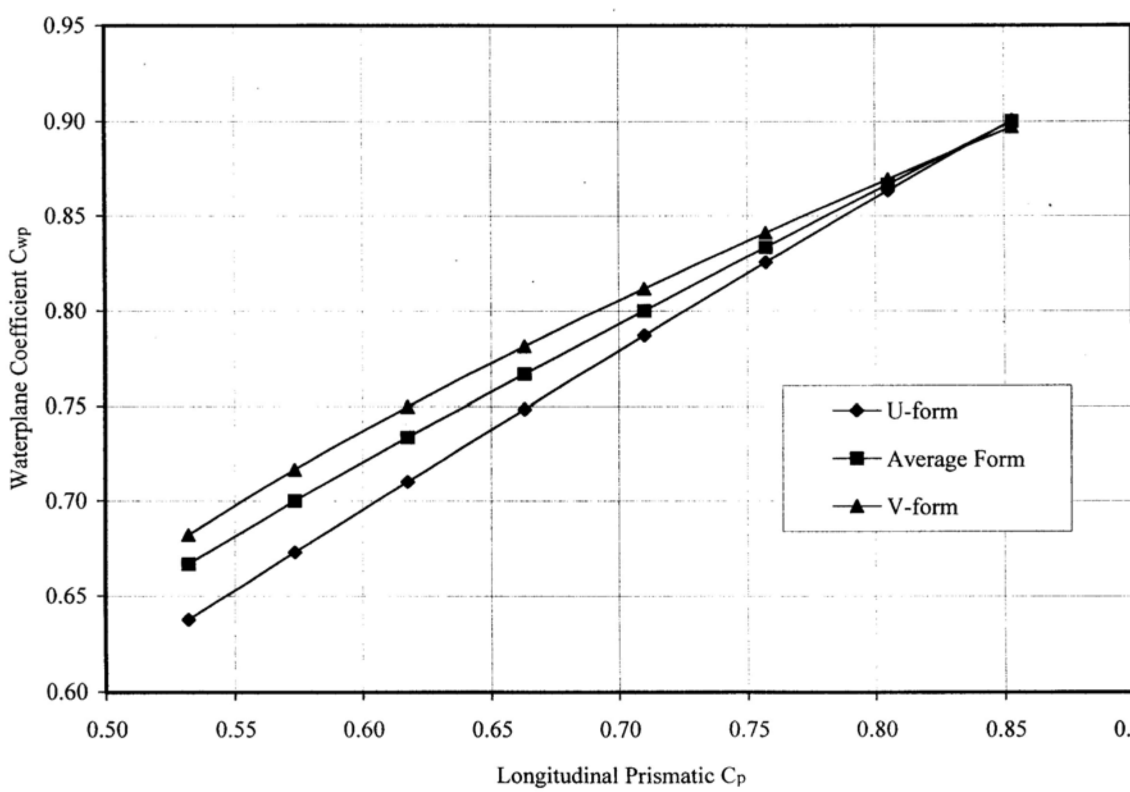


Figure 11.13 - Estimates of Waterplane Coefficient C_{WP} – Effect of Hull Form

This second approximation is recommended for hulls with $0.9 < C_M$. Posdunine's equation is, thus, recommended for typical larger commercial vessels.

Schneekluth and Bertram (17) also present three regression equations attributed to Normand, Schneekluth, and Wobig, respectively,

$$KB/T = (0.90 - 0.36\ C_M) \quad [24]$$

$$KB/T = (0.90 - 0.30\ C_M - 0.10\ C_B) \quad [25]$$

$$KB/T = 0.78 - 0.285\ C_{VP} \quad [26]$$

11.2.7.2. Location of the Metacenters

The dimensions and shape of the waterplane determine the moments of inertia of the waterplane relative to a ship's transverse axis I_T and longitudinal axis I_L. These can be used to obtain the vertical location of the respective metacenters relative to the center of buoyancy using the theoretical results,

$$BM_T = I_T/\nabla \quad [27]$$

$$BM_L = I_L/\nabla \quad [28]$$

In early design, the moments of inertia of the waterplane can be effectively estimated using nondimensional inertia coefficients that can be estimated using the waterplane coefficient. Recalling that the moment of inertia of a rectangular section is $bh^3/12$, it is consistent to define nondimensional waterplane inertia coefficients as follows:

$$C_I = I_T/LB^3 \quad [29]$$

$$C_{IL} = I_L/BL^3 \quad [30]$$

There is a catalog of models in the literature that allow estimation of C_I and C_{IL} from C_{WP}. These models are summarized in Table 11.VI. The next to last C_I equation represents a 4% increase on McCloghrie's formula that can be shown to be exact for diamond, triangular, and rectangular waterplanes. The seven models for C_I are plotted in Figure 11.14 for comparison. Note that some authors choose to normalize the inertia by the equivalent rectangle value including the constant 12 and the resulting nondimensional coefficients are an order of magnitude higher (a factor of 12). It is, therefore, useful when using other estimates to check for this possibility by comparing the numerical results with one of the estimates in Table 11.VI to ensure that the correct non-dimensionalization is being used.

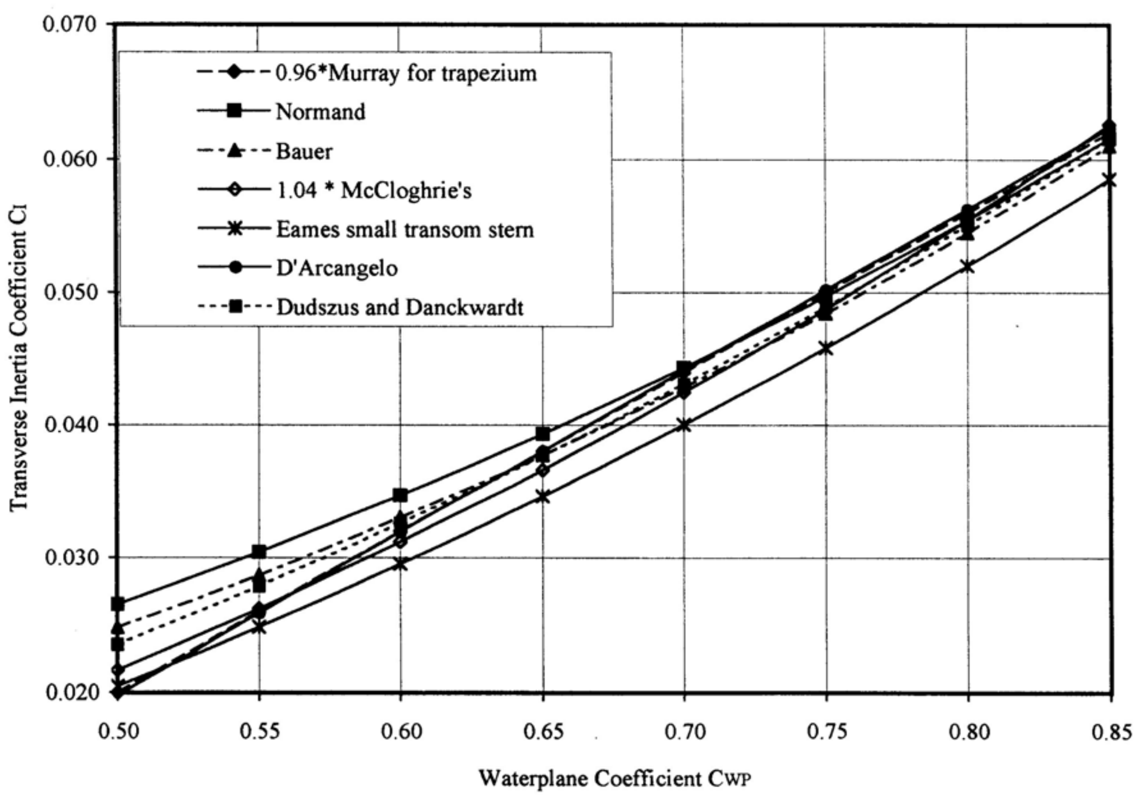


Figure 11.14 - Estimates of Transverse Inertial Coefficient C_I

Table 11.VI - EQUATIONS FOR ESTIMATING WATERPLANE INERTIA COEFFICIENTS

Equations	Applicability/Source
$C_I = 0.1216\ C_{WP} - 0.0410$	D'Arcangelo transverse
$C_{IL} = 0.350\ C_{WP}^2 - 0.405\ C_{WP} + 0.146$	D'Arcangelo long'l
$C_I = 0.0727\ C_{WP}^2 + 0.0106\ C_{WP} - 0.003$	Eames, small transom stern (2)
$C_I = 0.04\ (3\ C_{WP} - 1)$	Murray, for trapezium reduced 4% (17)
$C_I = (0.096 + 0.89\ C_{WP}^2)/12$	Normand (17)
$C_I = (0.0372\ (2\ C_{WP} + 1)^3)/12$	Bauer (17)
$C_I = 1.04\ C_{WP}^2/12$	McCloghrie +4% (17)
$C_I = (0.13\ C_{WP} + 0.87\ C_{WP}^2)/12$	Dudszus and Danckwardt (17)

11.2.8 Target Value for Longitudinal Center of Buoyancy LCB

The longitudinal center of buoyancy LCB affects the resistance and trim of the vessel. Initial estimates are needed as input to some resistance estimating algorithms. Likewise, initial checks of vessel trim require a sound LCB estimate. The LCB can change as the design evolves to accommodate cargo, achieve trim, etc., but an initial starting point is needed. In general, LCB will move aft with ship design speed and Froude number. At low Froude number, the bow can be fairly blunt with cylindrical or elliptical bows utilized on slow vessels. On these vessels it is necessary to fair the stern to achieve effective flow into the propeller, so the run is more tapered (horizontally or vertically in a buttock flow stern) than the bow resulting in an LCB which is forward of amidships. As the vessel becomes faster for its length, the bow must be faired to achieve acceptable wave resistance, resulting in a movement of the LCB aft through amidships. At even higher speeds the bow must be faired even more resulting in an LCB aft of amidships. This physical argument is based primarily upon smooth water powering, but captures the primary influence.

The design literature provides useful guidance for the initial LCB position. Benford analyzed Series 60 resistance data to produce a design lane for the acceptable range of LCB as a function of the longitudinal prismatic. Figure 11.15 shows Benford's "acceptable" and "marginal" ranges for LCB as a percent of ship length forward and aft of amidships, based upon Series 60 smooth water powering results. This follows the correlation of C_P with Froude number Fn. This exhibits the characteristic form: forward for low Froude numbers, amidships for moderate Froude number ($C_P \approx 0.65$, Fn ≈ 0.25), and then aft for higher Froude numbers. Note that this "acceptable" range is about 3% ship length wide indicating that the designer has reasonable freedom to adjust LCB as needed by the design as it proceeds without a significant impact on resistance.

Harvald includes a recommendation for the "best possible" LCB as a percent of ship length, plus forward of amidships, in his treatise on ship resistance and propulsion (31),

$$\text{LCB} = 9.70 - 45.0\ \text{Fn} \pm 0.8 \qquad [31]$$

This band at 1.6% L wide is somewhat more restrictive than Benford's "acceptable" range. Schneekluth and Bertram (17) note two similar recent Japanese results for recommended LCB position as a per cent of ship length, plus forward of amidships,

$$\text{LCB} = 8.80 - 38.9\ \text{Fn} \qquad [32]$$

$$\text{LCB} = -13.5 + 19.4\ C_P \qquad [33]$$

Equation 33 is from an analysis of tankers and bulk carriers and is shown in Figure 11.15 for comparison. It may be linear in longitudinal prismatic simply because a linear regression of LCB data was used in this study.

Watson (18) provides recommendations for the range of LCB "in which it is possible to develop lines with resistance within 1% of optimum." This presentation in similar to Benford's but uses C_B, which also correlates with Froude number Fn, as the independent variable. Watson's recommendation is shown in Figure 11.16. Since a bulbous bow will move the LCB forward, Watson shows ranges for both a bulbous bow and a "normal" bow. This recommendation also exhibits the expected general character. The design lane is about 1.5% L wide when the LCB is near amidships and reduces to below 1.0% for lower and higher speed vessels. Jensen's (29) recommendation for LCB position based upon recent best practice in Germany is also shown in Figure 11.16.

Schneekluth and Bertram (17) note that these LCB recommendations are based primarily on resistance minimization, while propulsion (delivered power) minimization results in a LCB somewhat further aft. Note also that these recommendations are with respect to length between perpendiculars and its midpoint amidships. Using these recommendations with LWL that is typically longer than LBP and using its midpoint, as amidships, which is convenient in earliest design, will result in a further aft position relative to length between perpendiculars approaching the power minimization.

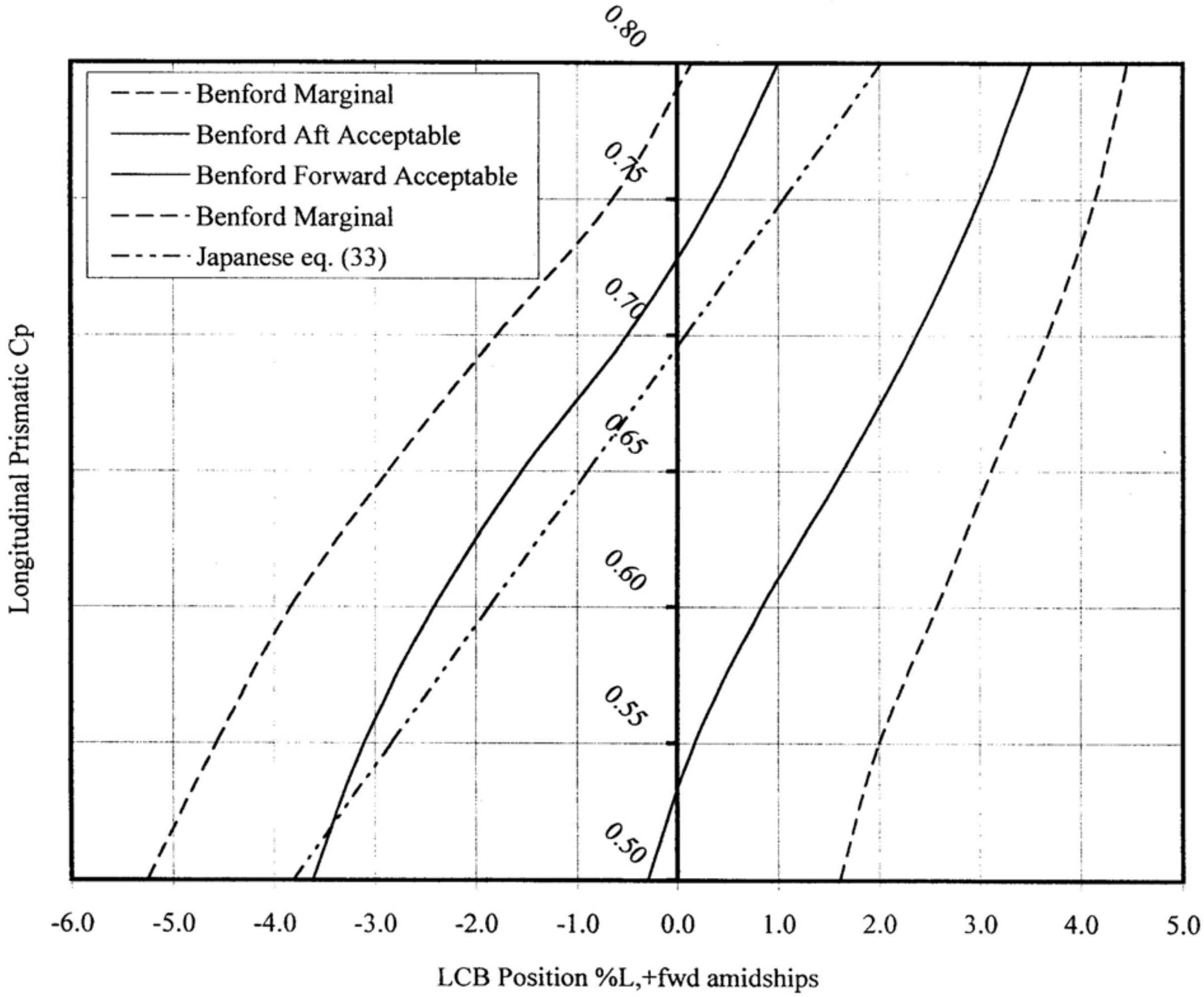


Figure 11.15 - Benford's Recommended Design Lane for Longitudinal Center of Buoyancy LCB

11.3 PARAMETRIC WEIGHT AND CENTERS ESTIMATION

To carryout the iteration on the ship dimensions and parameters needed to achieve a balance between weight and displacement and/or between required and available hull volume, deck area, and/or deck length, parametric models are needed for the various weight and volume requirements. Some of this information is available from vendor's information as engines and other equipment are selected or from characteristics of discrete cargo and specified payload equipment. In this Section, parametric models will be illustrated for the weight components and their centers for commercial vessels following primarily the modeling of Watson and Gilfillan (1) and Watson (18). It is not a feasible goal here to be comprehensive. The goal is to illustrate the approach used to model weights and centers and to illustrate the balancing of weight and displacement at the parametric stage of a larger commercial vessel design.

See Watson (18) and Schneekluth and Bertram (17) for additional parametric weight and volume models.

11.3.1 Weight Classification

The data gathering, reporting, and analysis of ship weights are facilitated by standard weight classification. The Maritime Administration has defined the typical commercial ship design practice; Navy practice uses the Extended Ship Work Breakdown Structure (ESWBS) defined in (32). The total displacement in commercial ships is usually divided into the Light Ship weight and the Total Deadweight, which consists of the cargo and other variable loads.

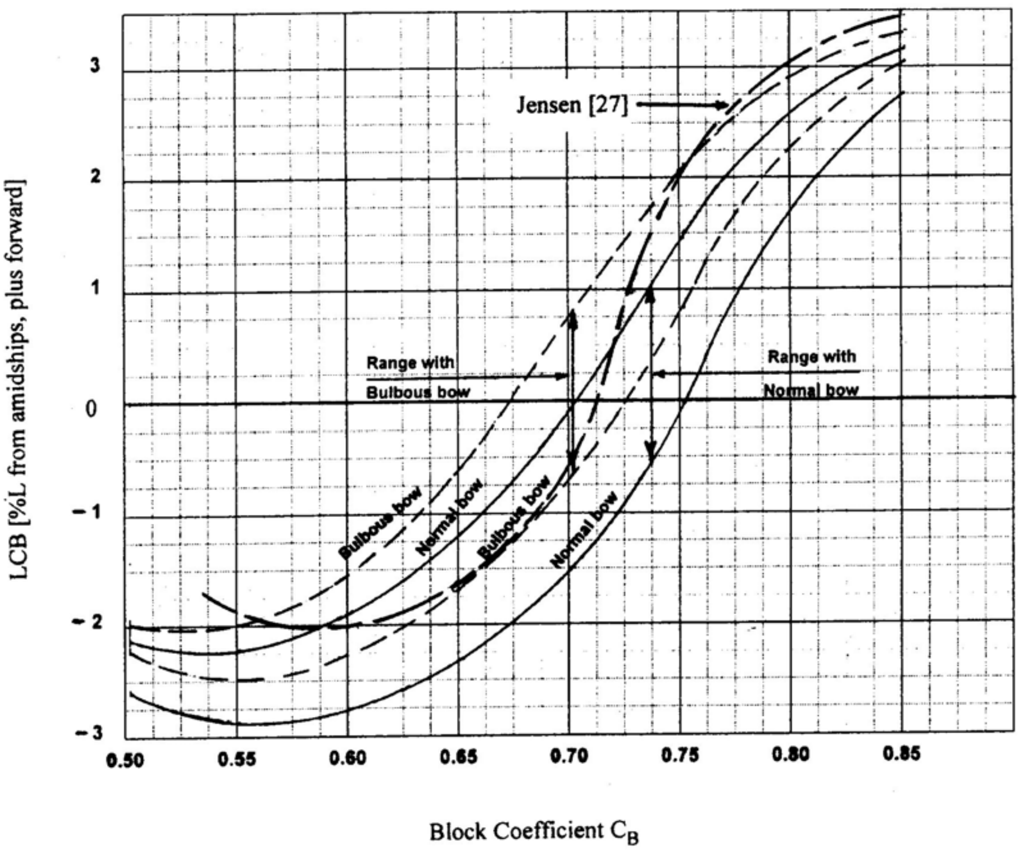


Figure 11.16 - Watson's (18) and Jensen's (28) Recommended Longitudinal Center of Buoyancy LCB

The naval ship breakdown includes seven "one-digit" weight groups consisting of:

Group 1	Hull Structure
Group 2	Propulsion Plant
Group 3	Electric Plant
Group 4	Command and Surveillance
Group 5	Auxiliary Systems
Group 6	Outfit and Furnishings
Group 7	Armament.

Navy design practice, as set forth in the Ship Space Classification System (SSCS), also includes five "one-digit" area/volume groups consisting of:

Group 1	Military Mission
Group 2	Human Support
Group 3	Ship Support
Group 4	Ship Machinery
Group 5	Unassigned.

In small boat designs, a weight classification system similar to the navy groups is often followed. The total displacement is then as follows depending upon the weight classification system used,

$$\Delta = W_{LS} + DWT_T$$

$$= \sum_{i=1}^{m} W_i + \sum_{j=1}^{n} loads_j + W_{margin} + W_{growth} \quad [32]$$

Focusing on the large commercial vessel classification system as the primary example here, the Light Ship weight reflects the vessel ready to go to sea without cargo and loads and this is further partitioned into,

$$W_{LS} = W_S + W_M + W_o + W_{margin} \quad [33]$$

where W_S is the structural weight, W_M is the propulsion machinery weight, W_o is the outfit and hull engineering weight, and W_{margin} is a Light Ship design (or Acquisition) weight margin that is included as protection against the underprediction of the required displacement. In military vessels, future growth in weight and KG is expected as weapon systems and sensors (and other mission systems) evolve so an explicit future growth or Service Life Allowance (SLA) weight margin is also included as W_{growth}.

The total deadweight is further partitioned into,

$$DWT_T = DWT_C + W_{FO} + W_{LO} + W_{FW} + W_{C\&E} + W_{PR} \quad [34]$$

where DWT_C is the cargo deadweight, W_{FO} is the fuel oil weight, W_{LO} is the lube oil weight, W_{FW} is the fresh water weight, $W_{C\&E}$ is the weight of the crew and their effects, and W_{PR} is the weight of the provisions.

11.3.2 Weight Estimation

The estimation of weight at the early parametric stage of design typically involves the use of parametric models that are typically developed from weight information for similar vessels. A fundamental part of this modeling task is the selection of relevant independent variables that are correlated with the weight or center to be estimated. The literature can reveal effective variables or first principles can be used to establish candidate variables. For example, the structural weight of a vessel could vary as the volume of the vessel as represented by the Cubic Number. Thus, many weight models use CN = LBD/100 as the independent variable. However, because ships are actually composed of stiffened plate surfaces, some type of area variable would be expected to provide a better correlation. Thus, other weight models use the area variable L(B + D) as their independent variable. Section 11.5 below will further illustrate model development using multiple linear regression analysis. The independent variables used to scale weights from similar naval vessels were presented for each "three digit" weight group by Straubinger et al (33).

11.3.2.1 Structural Weight

The structural weight includes (1) the weight of the basic hull to its depth amidships; (2) the weight of the superstructures, those full width extensions of the hull above the basic depth amidships such as a raised forecastle or poop; and (3) the weight of the deckhouses, those less than full width erections on the hull and superstructure. Because the superstructures and deckhouses have an important effect on the overall structural VCG and LCG, it is important to capture the designer's intent relative to the existence and location of superstructures and deckhouses as early as possible in the design process.

Watson and Gilfillan proposed an effective modeling approach using a specific modification of the Lloyd's Equipment Numeral E as the independent variable (1),

$$\begin{aligned} E &= E_{hull} + E_{SS} + E_{dh} \\ &= L(B + T) + 0.85L(D - T) + 0.85 \sum_i \ell_i h_i \\ &\quad + 0.75 \sum_j \ell_j h_j \end{aligned} \qquad [35]$$

This independent variable is an area type independent variable. The first term represents the area of the bottom, the equally heavy main deck, and the two sides below the waterline. (The required factor of two is absorbed into the constant in the eventual equation.) The second term represents the two sides above the waterline, which are somewhat (0.85) lighter since they do not experience hydrostatic loading. There first two terms are the hull contribution E_{hull}. The third term is the sum of the profile areas (length x height) of all of the superstructure elements and captures the superstructure contribution to the structural weight. The fourth term is the sum of the profile area of all of the deckhouse elements, which are relatively lighter (0.75/0.85) because they are further from wave loads and are less than full width.

Watson and Gilfillan (1) found that if they scaled the structural weight data for a wide variety of large steel commercial vessels to that for a standard block coefficient at 80% of depth $C_B' = 0.70$, the data reduced to an acceptably tight band allowing its regression relative to E as follows:

$$W_S = W_S(E) = K\, E^{1.36} (1 + 0.5(C_B' - 0.70)) \qquad [36]$$

The term in the brackets is the correction when the block coefficient at 80% of depth C_B' is other than 0.70. Since most designers do not know C_B' in the early parameter stage of design, it can be estimated in terms of the more commonly available parameters by,

$$C_B' = C_B + (1 - C_B)((0.8D - T)/3T) \qquad [37]$$

Watson and Gilfillan found that the 1.36 power in equation 36 was the same for all ship types, but that the constant K varied with ship type as shown in Table 11.VII.

TABLE 11.VII - STRUCTURAL WEIGHT COEFFICIENT K (1, 18)

Ship type	K mean	K range	Range of E
Tankers	0.032	±0.003	1500 < E < 40000
chemical tankers	0.036	±0.001	1900 < E < 2500
bulk carriers	0.031	±0.002	3000 < E < 15000
container ships	0.036	±0.003	6000 < E < 13000
cargo	0.033	±0.004	2000 < E < 7000
refrigerator ships	0.034	±0.002	4000 < E < 6000
coasters	0.030	±0.002	1000 < E < 2000
offshore supply	0.045	±0.005	800 < E < 1300
tugs	0.044	±0.002	350 < E < 450
fishing trawlers	0.041	±0.001	250 < E < 1300
research vessels	0.045	±0.002	1350 < E < 1500
RO-RO ferries	0.031	±0.006	2000 < E < 5000
passenger ships	0.038	±0.001	5000 < E < 15000
frigates/corvettes	0.023		

This estimation is for 100% mild steel construction. Watson (18) notes that this scheme provides estimates that are “a little high today.”

This structural weight-modeling scheme allows early estimation and separate location of the superstructure and deckhouse weights, since they are included as explicit contributions to E. The weight estimate for a single deckhouse can be estimated using the following approach:

$$W_{dh} = W_S(E_{hull} + E_{SS} + E_{dh}) - W_S(E_{hull} + E_{SS}) \qquad [38]$$

Note that the deckhouse weight cannot be estimated accurately using $W_{dh}(E_{dh})$ because of the nonlinear nature of this model. If there are two deckhouses, a similar approach can be used by removing one deckhouse at a time from E. A comparable approach would directly estimate the unit area weights of all surfaces of the deckhouse; for example, deckhouse front 0.10 t/m^2; deckhouse sides, top and back 0.08 t/m^2; decks inside deckhouse 0.05 t/m^2; engine casing 0.07 t/m^2, and build up the total weight from first principles.

Parallel to equation 38, the weight estimate for a single superstructure can be estimated using,

$$W_{SS} = W_S(E_{hull} + E_{SS}) - W_S(E_{hull}) \qquad [39]$$

These early weight estimates for deckhouse and superstructure allow them to be included with their intended positions (LCG and VCG) as early as possible in the design process.

11.3.2.2 Machinery Weight

First, note that the machinery weight in the commercial classification includes only the propulsion machinery - primarily the prime mover, reduction gear, shafting, and propeller. Watson and Gilfillan proposed a useful separation of this weight between the main engine(s) and the remainder of the machinery weight (1),

$$W_M = W_{ME} + W_{rem} \qquad [40]$$

This approach is useful because in commercial design, it is usually possible to select the main engine early in the design process permitting the use of specific vendor’s weight and dimension information for the prime mover from very early in the design. If an engine has not been selected, they provided the following conservative regression equation for an estimate about 5% above the mean of the 1977 diesel engine data,

$$W_{ME} = \sum_i 12.0\,(MCR_i/N_{ei})^{0.84} \qquad [41]$$

where i is the index on multiple engines each with a Maximum Continuous Rating MCR_i (kW) and engine rpm N_{ei}. The weight of the remainder of the machinery varies as the total plant MCR as follows:

$$W_{rem} = C_m\,(MCR)^{0.70} \qquad [42]$$

where C_m = 0.69 bulk carriers, cargo vessels, and container ships; 0.72 for tankers; 0.83 for passenger vessels and ferries; and 0.19 for frigates and corvettes when the MCR is in kW.

With modern diesel electric plants using a central power station concept, Watson (18) suggests that the total machinery weight equation 40 can be replaced by,

$$W_M = 0.72\,(MCR)^{0.78} \qquad [43]$$

where now MCR is the total capacity of all generators in kW. These electric drive machinery weight estimates take special care since the outfit weight included below traditionally includes the ship service electrical system weights.

11.3.2.3 Outfit Weight

The outfit includes the remainder of the Light Ship Weight. In earlier years, these weights were classified into two groups as *outfit*, which included electrical plant, other distributive auxiliary systems such as HVAC, joiner work, furniture, electronics, paint, etc., and *hull engineering*, which included the bits, chocks, hatch covers, cranes, windlasses, winches, etc. Design experience revealed that these two groups varied in a similar manner and the two groups have been combined today into the single group called Outfit. Watson and Gilfillan estimate these weights using the simple model (1),

$$W_o = C_o\,LB \qquad [44]$$

where the outfit weight coefficient C_o is a function of ship type and for some ship types also ship length as shown in Figure 11.17.

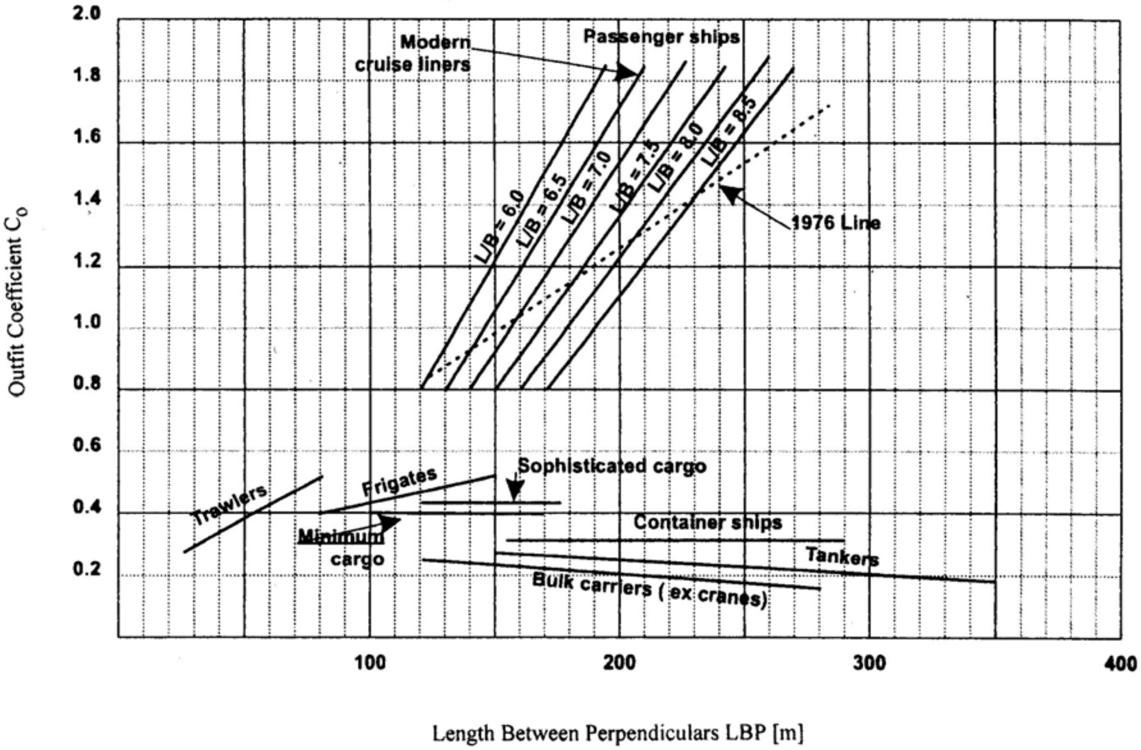


Figure 11.17 - Outfit Weight Coefficient C_0 (18)

11.3.2.4 Deadweight Items

The cargo deadweight is usually an owner's requirement or it can be estimated from an analysis of the capacity of the hull. The remaining deadweight items can be estimated from first principles and early decisions about the design of the vessel. The selection of machinery type and prime mover permits the estimation of the Specific Fuel Rate (SFR) (t/kWhr) for the propulsion plant so that the fuel weight can be estimated using,

$$W_{FO} = SFR \bullet MCR \bullet range/speed \bullet margin \quad [45]$$

Early general data for fuel rates can be found in the SNAME Technical and Research Bulletins #3-11 for steam plants (34), #3-27 for diesel plants (35) and #3-28 for gas turbine plants (36). For diesel engines, the SFR can be taken as the vendor's published test bed data with 10% added for shipboard operations producing a value of about 0.000190 t/kWhr for a large diesel today. Second generation gas turbines might have a SFR of about 0.000215 t/kWhr. In equation 45, the margin is for the fuel tankage that can be an overall percentage such as 5% or it might be 10% for just the final leg of a multi-leg voyage. Overall this estimate is conservative, because the vessel may not require full MCR except in the worst service conditions and there are margins both in the SFR and on the overall capacity. This conservatism can cover generator fuel that can be estimated separately in a similar manner as the design evolves.

The lube oil weight can be taken from practice on similar vessels. This usually depends upon the type of main machinery. Overall recommendations (37) include,

$$W_{LO} = 20\text{ t}, \quad \text{medium speed diesel(s)}$$
$$= 15\text{ t}, \quad \text{low speed diesel} \quad [46]$$

As an alternative, an approach like equation 45 can be used with the vendor's specific lube oil consumption data with tankage provided for the total consumption in about 20 voyages.

The weight of fresh water depends upon the designer's intent relative to onboard distillation and storage. Modern commercial vessels often just carry water for the entire voyage and eliminate the need to operate and maintain water-making equipment with a small crew. Naval vessels and cruise vessels obviously have much higher capacity demands making onboard distillation more of a necessity. On the basis of using 45 gallons per person • day, the total water tankage weight would need to be,

$$W_{FW} = 0.17\text{ t/(person} \bullet \text{day)} \quad [47]$$

with perhaps 10 days storage provided with onboard distillation and 45 days provided without onboard distillation. The weight of the crew and their effects can be estimated as,

$$w_{C\&E} = 0.17 \text{ t/person} \quad [48]$$

for a commercial vessel's crew and extranumeraries, while a naval vessel might use 0.18 t/person for officers and 0.104 t/person for enlisted (33). The provisions and stores weight can be estimated as,

$$W_{PR} = 0.01 \text{ t/(person • day)} \quad [49]$$

for the provisions, stores, and their packaging. Naval vessel standards provide about 40 gallons water per person or accommodation • day and provisions and stores at about 0.0036 t/(person • day) (33).

11.3.3 Centers Estimation

The estimation of centers of the various weight groups early in the design process can use parametric models from the literature and reference to a preliminary inboard profile, which reflects the early design intent for the overall arrangements. The structural weight can be separated into the basic hull and the superstructure and deckhouse weights using equations 38 and 39. The VCG of the basic hull can be estimated using an equation proposed by Kupras (38),

$$\begin{aligned} VCG_{hull} &= 0.01D\,(46.6 + 0.135(0.81 - C_B)(L/D)^2) \\ &\quad + 0.008D(L/B - 6.5), \qquad L \le 120 \text{ m} \\ &= 0.01D\,(46.6 + 0.135(0.81 - C_B)(L/D)^2), \\ &\qquad 120 \text{ m} < L \quad [50] \end{aligned}$$

The longitudinal position of the basic hull weight will typically be slightly aft of the LCB position. Watson (18) gives the suggestion,

$$LCG_{hull} = -0.15 + LCB \quad [51]$$

where both LCG and LCB are in percent ship length, plus forward of amidships.

The vertical center of the machinery weight will depend upon the innerbottom height h_{bd} and the height of the overhead of the engine room D'. With these known, Kupras (38) notes that the VCG of the machinery weight can be estimated as,

$$VCG_M = h_{db} + 0.35(D' - h_{db}) \quad [52]$$

which places the machinery VCG at 35% of the height within the engine room space. This type of simple logic can be adapted for the specific design intent in a particular situation. In order to estimate the height of the innerbottom, minimum values from classification and Coast Guard requirements can be consulted giving for example,

$$h_{db} \ge 32B + 190\sqrt{T} \text{ (mm) (ABS), or}$$

$$h_{db} \ge 45.7 + 0.417L \text{ (cm) (46CFR171.105)}$$

The innerbottom height might be made greater than indicated by these minimum requirements in order to provide greater doublebottom tank capacity, meet double hull requirements, or to allow easier structural inspection and tank maintenance.

The longitudinal center of the machinery weight depends upon the overall layout of the vessel. For machinery aft vessels, the LCG can be taken near the after end of the main engines. With relatively lighter prime movers and longer shafting, the relative position of this center will move further aft. Lamb (14) proposed a scheme that separated the weights and centers of the engines, shafting, and propeller at the earliest stage of design in order to develop an aggregate center for W_M.

The vertical center of the outfit weight is typically above the main deck and can be estimated using an equation proposed by Kupras (38),

$$\begin{aligned} VCG_o &= D + 1.25, && L \le 125 \text{ m} \\ &= D + 1.25 + 0.01(L-125), && 125 < L \le 250 \text{ m} \\ &= D + 2.50, && 250 \text{ m} < L \quad [53] \end{aligned}$$

The longitudinal center of the outfit weight depends upon the location of the machinery and the deckhouse since significant portions of the outfit are in those locations. The remainder of the outfit weight is distributed along the entire hull. Lamb (14) proposed a useful approach to estimate the outfit LCG that captures elements of the design intent very early in the design process. Lamb proposed that the longitudinal center of the machinery LCG_M be used for a percentage of W_o, the longitudinal center of the deckhouse LCG_{dh} be used for a percentage of W_o, and then the remainder of W_o be placed at amidships. Adapting the original percentages proposed by Lamb to a combined outfit and hull engineering weight category, this yields approximately,

$$LCG_o = (25\%\ W_o \text{ at } LCG_M,\ 37.5\% \text{ at } LCG_{dh}, \text{ and } 37.5\% \text{ at amidships}) \quad [54]$$

The specific fractions can be adapted based upon data for similar ships. This approach captures the influence of the machinery and deckhouse locations on the associated outfit weight at the earliest stages of the design.

The centers of the deadweight items can be estimated based upon the preliminary inboard profile arrangement and the intent of the designer.

11.3.4 Weight Margins

Selecting margins, whether on power, weight, KG, chilled water, space, or many other quantities, is a matter of important design philosophy and policy. If a margin is too small, the design may fail to meet design requirements. If a margin is too large, the vessel will be overdesigned resulting in waste and potentially the designer's failure to be awarded the project or contract. There is a multiplier effect on weight and most other ship design characteristics: for example, adding one tonne of weight will make the entire vessel more than one tonne heavier since the hull structure, machinery, etc. must be enlarged to accommodate that added weight. Most current contracts include penalty clauses that enter effect if the vessel does not make design speed or some other important attribute.

A typical commercial vessel Light Ship design (or acquisition) weight margin might be 3-5%; Watson and Gilfillan (1) recommend using 3% when using their weight estimation models. This is usually placed at the center of the rest of the Light Ship weight. This margin is included to protect the design (and the designer) since the estimates are being made very early in the design process using approximate methods based only upon the overall dimensions and parameters of the design.

Standard U.S. Navy weight margins have been developed from a careful statistical analysis of past design/build experience (39) following many serious problems with overweight designs, particularly small vessels which were delivered overweight and, thus, could not make speed. These studies quantified the acquisition margin needed to cover increases experienced during preliminary design, contract design, construction, contract modifications, and delivery of Government Furnished Material.

Military ships also include a future growth margin or Service Life Allowance on weight, KG, ship service electrical capacity, chilled water, etc. since the development and deployment of improved sensors, weapons, and other mission systems typically results in the need for these margins during upgrades over the life of the vessel. It is sound design practice to include these margins in initial design so that future upgrades are feasible with acceptable impact. Future growth margin policies vary with country. Watson (18) suggests 0.5% per year of expected ship life. Future growth margins are typically not included in commercial designs since they are developed for a single, specific purpose. Typical U.S. Navy total weight and KG margins are shown in Table 11.VIII.

Table 11.VIII - U. S. NAVAL WEIGHT AND KG MARGINS (39)

Acquisition Margins (on light ship condition)		
Total Design Weight Margin		
mean	5.9%	
mean plus one Standard Deviation	17.0%	
Total Design KG Margin		
mean	4.8%	
mean plus one Standard Deviation	13.5%	
Service Life Allowances (on full load departure)		
Vessel Type	**Weight Margin**	**KG margin**
carriers	7.5%	0.76 m
other combatants	10.0%	0.30 m
auxiliary ships	5.0%	0.15 m
special ships and craft	5.0%	0.15 m
amphibious warfare vessels		
large deck	7.5%	0.76 m
other	5.0%	0.30 m

11.3.5 Summation and Balancing using Spreadsheets

The summation of weights and the determination of the initial transverse metacentric height GM_T and trim, are key to the initial sizing and preliminary arrangement of any vessel. This task can be effectively accomplished using any number of computer tools. Within the teaching of ship design at the University of Michigan extensive use is made of spreadsheets for this purpose. By their automatic recalculation when any input parameter is changed, spreadsheets are valuable interactive design tools since they readily support trade-off and iterative design studies.

The WEIGHTS I spreadsheet for Parametric Stage Weight Summation is shown on the left in Figure 11.18 as an illustration. This spreadsheet is used to the support design iteration needed to achieve a balance between weight and displacement, determine an acceptable initial GM_T, and establish the initial trim. At this stage the longitudinal center of flotation (LCF) is usually not estimated so the trim is not resolved into draft forward T_F and draft aft T_A. The WEIGHTS I spreadsheet supports the inclusion of a design Light Ship weight margin, free surface margin FS in percent, and a design KG_{margin}. The weights and centers are processed to obtain the total VCG and total LCG. The design KG used to establish GM_T is then obtained using,

$$KG_{design} = VCG(1 + FS/100) + KG_{margin} \quad [55]$$

The designer can iterate on the initial estimates of the dimensions and block coefficient C_B. At this stage of design, the hydrostatic properties, BM_T, KB, BM_L, and LCB are selected or estimated using parametric equations as presented in Section 11.2. The trim is obtained from the total LCG using,

$$\text{trim} = T_A - T_F = (LCG - LCB)L/GM_L \qquad [56]$$

To facilitate early design studies, the weights and centers estimation methods outlined in this Section are implemented on the linked Weights and Centers Estimation for Weight I spreadsheet shown on the right in Figure 11.18. The resulting weights and centers are linked directly to the italicized weights and centers entries in the WEIGHTS I spreadsheet summary. Inputs needed for these design models are entered on the linked Weights and Centers Estimation spreadsheet.

11.4 HYDRODYNAMIC PERFORMANCE ESTIMATION

The conceptual design of a vessel must utilize physics-based methods to simulate the propulsion, maneuvering, and seakeeping hydrodynamic performance of the evolving design based only upon the dimensions, parameters, and intended features of the design. An early estimate of resistance is needed in order to establish the machinery and engine room size and weight, which will directly influence the required overall size of the vessel. Maneuvering and seakeeping should also be checked at this stage of many designs since the evolving hull dimensions and parameters will affect this performance and, thus, the maneuvering and seakeeping requirements may influence their selection. This Section will illustrate this approach through public domain teaching and design software that can be used to carry out these tasks for displacement hulls. This available Windows software environment is documented in Parsons et al (40). This documentation and the compiled software are available for download at the following URL:

www-personal.engin.umich.edu/~parsons

11.4.1 Propulsion Performance Estimation

11.4.1.1 Power and Efficiency Definitions

The determination of the required propulsion power and engine sizing requires working from a hull total tow rope resistance prediction to the required installed prime mover brake power. It is important to briefly review the definitions used in this work (41). The approach used today has evolved from the tradition of initially testing a hull or a series of hulls without a propeller, testing an individual or series of propellers without a hull, and then linking the two together through the definition of hull-propeller interaction factors. The various powers and efficiencies of interest are shown schematically in Figure 11.19. The hull without a propeller behind it will have a total resistance R_T at a speed V that can be expressed as the effective power P_E,

$$P_E = R_T V / 1000 \text{ (kW)} \qquad [57]$$

where the resistance is in Newtons and the speed is in m/s. The open water test of a propeller without a hull in front of it will produce a thrust T at a speed V_A with an open water propeller efficiency η_o and this can be expressed as the thrust power P_T,

$$P_T = TV_A / 1000 \text{ (kW)} \qquad [58]$$

These results for the hull without the propeller and for the propeller without the hull can be linked together by the definition of the hull-propeller interaction factors defined in the following:

$$V_A = V(1 - w) \qquad [59]$$

$$T = R_T / (1 - t) \qquad [60]$$

$$\eta_P = \eta_o \eta_r \qquad [61]$$

where w is the Taylor wake fraction, t is the thrust deduction fraction, η_P is the behind the hull condition propeller efficiency, and η_r is the relative rotative efficiency that adjusts the propeller's open water efficiency to its efficiency behind the hull. Note that η_r is not a true thermodynamic efficiency and may assume values greater than one.

Substituting equations. 59 and 60 into equation 58 and using equation 57 yields the relationship between the thrust power and the effective power,

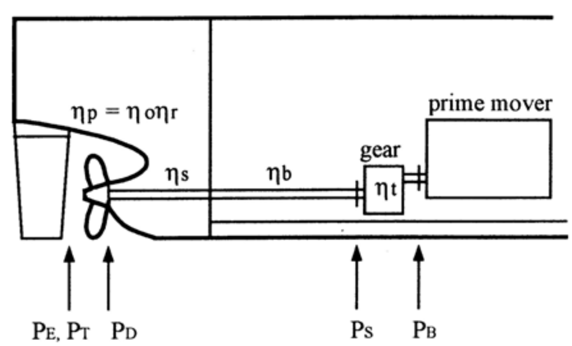


Figure 11.19 - Location of Various Power Definitions

WEIGHTS 1 - PARAMETER STAGE WEIGHT SUMMARY R(11)

	Condition:	Full Load Departure			
DESIGN PARAMETERS					
enter data in boxes					
LWL	132.00	meters		Note: weights and centers in *italics* are linked to models on Sheet 1	
B	22.00	meters			
T	6.90	meters			
Cb	0.630				
Weight Margin	3.00	per cent of Light Ship at CG for Light Ship			
(1 + s)	1.005	shell/appendage allowance			
KG Margin	0.30	meters			
Free Surface Margin	3.00	per cent of KG			
BMT	5.90	meters			
KB = VCB	3.50	meters		estimates from prelim.	
BML	170.00	meters		design equations	
LCB	67.00	meters from the FP			
Water Weight Density	1.025	tonnes/m^3		(SW 1.025; FW 1.000)	
WEIGHT CATEGORY	WT	VCG	product	LCG	product
	[t]	[m abv. BL]		[m from FP]	
*Hull Structure	*3111.6*	*6.36*	19782.8	*67.90*	211273.2
*Superstructures	*144.8*	14.50	2099.3	15.00	2171.7
*Deckhouses	*107.6*	18.00	1936.1	115.00	12369.3
Total Structure	3364.0				
*Outfit	*1016.4*	*14.32*	14554.8	*96.63*	98209.7
*Special Outfit	0.0	0.00	0.0	0.00	0.0
*Machinery	*449.8*	*5.40*	2426.9	115.00	51731.7
*Permanent Ballast	0.0	0.00	0.0	0.00	0.0
*Light Ship Margin	144.9	8.45	1224.0	77.79	11272.7
Light Ship Weight	4975.1	8.45		77.79	
*Cargo Deadweight	7600.0	8.27	62852.0	59.90	455240.0
*Fuel Oil	*213.8*	7.00	1496.5	18.00	3848.1
*Lube Oil	20.0	10.00	200.0	110.00	2200.0
*Water	*183.6*	10.00	1836.0	110.00	20196.0
*Crew and Effects	*4.1*	16.50	67.3	120.00	489.6
*Provisions	*10.8*	14.00	151.2	120.00	1296.0
*Temporary Ballast	0.0	0.00	0.0	0.00	0.0
Total Deadweight	8032.3	8.29		60.17	
Total Weight	13007.4	8.35	total VCG	66.91	total LCG
Displacement	13004.0	0.03	%; + weight exceeds displacement		
GM AND TRIM RESULTS					
Design KG	8.90	meters, including design and free surface margins			
GMT	0.50	meters			
GML	165.15	meters			
Trim	-0.07	meters; + by the stern			

WEIGHTS AND CENTERS ESTIMATION FOR WEIGHTS 1 (R11)

Models from: Watson, D. G. M. and A. W. Gilfillan, "Some Ship Design Methods," Transactions RINA, 1977.
Kupras, L. K., "Optimization Method and Parametric Study in Precontract Ship Design," International Shipbuilding Progress, May, 1971.
Watson, D. G. M., Practical Ship Design, Elsevier Science Ltd, Oxford, UK, 1998.

Additional Parameters	input			
D	13	meters		
superstructures sum(li*hi)	180	m^2		
deckhouses sum(li*hi)	150	m^2		
structural K	0.0336	from Watson & Gilfillan or Watson Table		
distance from LCB to hull LCG	0.680	% LWL positive aft		
outfit Co	0.35	from Watson & Gilfillan or Watson Figure		
fraction of Wo at machinery	0.25	|		
fraction of Wo at amidships	0.375	| fractions need to total one =		1.000
fraction of Wo at deckhouse	0.375	|		check sum
total propulsion MCR	6500	kW		
number of main engines	2			
propulsion engine Ne	450	rpm		
ship type coeff. for Wrem	0.69	[0.69 cargo; 0.72 tankers; 0.83 pass.;		
fuel capacity margin	5	per cent on total		0.19 frigates]
endurance range	2500	nautical miles		
endurance speed	17	knots		
specific fuel rate	0.000213	t/kW*hr [use vendor data + 10%]		
engineroom overhead	13	meters above baseline		
innerbottom height	1.3	meters above baseline		transfer
complement (crew+extras)	24	people		from
endurance days	45	days		Weights I
			L	132
Structural weight estimate			B	22
Cb'	0.6926		T	6.9
Ehull	4499.2		Cb	0.63
Esuperstructure	153.0		LCB	67
Edeckhouse	112.5			
Ws hull+ss+dh	3364.0	tonnes		
Ws hull+ss	3256.4	tonnes		
Ws hull only	3111.6	tonnes		
Ws superstructure	144.8	tonnes		
Ws deckhouse	107.6	tonnes		
Machinery weight estimate				
Wme	127.8	tonnes <- enter actual weight from vendor's		
Wrem	322.0	tonnes	data when available	
Total Wm	449.8	tonnes		
Wfuel	213.8	tonnes		

Figure 11.18 - WEIGHTS I Parametric Stage Weights Summation Spreadsheet

$$P_T = P_E \ (1 - w)/(1 - t) \quad [62]$$

from which we define the convenient grouping of terms called the hull efficiency η_h,

$$\eta_h = (1 - t)/(1 - w) = P_E/P_T \quad [63]$$

The hull efficiency can be viewed as the ratio of the work done on the hull P_E to the work done by the propeller P_T. Note also that η_h is not a true thermodynamic efficiency and may assume values greater than one.

The input power delivered to the propeller P_D is related to the output thrust power from the propeller P_T by the behind the hull efficiency equation 61 giving when we also use equation 63,

$$P_D = P_T / \eta_P = P_T / (\eta_o \eta_r) = P_E / (\eta_h \eta_o \eta_r) \quad [64]$$

The shaft power P_S is defined at the output of the reduction gear or transmission process, if installed, and the brake power P_B is defined at the output flange of the prime mover.

When steam machinery is purchased, the vendor typically provides the high pressure and low-pressure turbines and the reduction gear as a combined package so steam plant design typically estimates and specifies the shaft power P_S, since this is what steam turbine the steam turbine vendor must provide. When diesel or gas turbine prime movers are used, the gear is usually provided separately so the design typically estimates and specifies the brake power P_B, since this is what prime mover the prime mover vendor must provide. The shaft power P_S is related to the delivered power P_D transmitted to the propeller by the sterntube bearing and seal efficiency η_s and the line shaft bearing efficiency η_b by,

$$P_S = P_D/(\eta_s \eta_b) \quad [65]$$

The shaft power P_S is related to the required brake power P_B by the transmission efficiency of the reduction gear or electrical transmission process η_t by,

$$P_B = P_S/\eta_t \quad [66]$$

Combining equations. 64, 65, and 66 now yields the needed relationship between the effective power P_E and the brake power at the prime mover P_B,

$$P_B = P_E / (\eta_h \eta_o \eta_r \eta_s \eta_b \eta_t) \quad [67]$$

11.4.1.2 Power Margins

In propulsion system design, the design point for the equilibrium between the prime mover and the propulsor is usually the initial sea trials condition with a new vessel, clean hull, calm wind and waves, and deep water. The resistance is estimated for this ideal trials condition. A *power design margin* M_D is included within or applied to the predicted resistance or effective power in recognition that the estimate is being made with approximate methods based upon an early, incomplete definition of the design. This is highly recommended since most designs today must meet the specified trials speed under the force of a contractual penalty clause. It is also necessary to include a *power service margin* M_S to provide the added power needed in service to overcome the added resistance from hull fouling, waves, wind, shallow water effects, etc. When these two margins are incorporated, equation 67 for the trials design point (=) becomes,

$$P_B(1 - M_S) = P_E \ (1 + M_D)/(\eta_h \eta_o \eta_r \eta_s \eta_b \eta_t) \quad [68]$$

The propeller is designed to achieve this equilibrium point on the initial sea trials, as shown in Figure 11.20. The design match point provides equilibrium between the engine curve: the prime mover at $(1 - M_S)$ throttle and full rpm (the left side of the equality in equation 68), and the propeller load with $(1 + M_D)$ included in the prediction (the right side of the equality).

The brake power P_B in equation 68 now represents the minimum brake power required from the prime mover. The engine(s) can, thus, be selected by choosing an engine(s) with a total Maximum Continuous Rating (or selected reduced engine rating for the application) which exceeds this required value,

$$MCR \geq P_B = P_E(1 + M_D)/(\eta_h \eta_o \eta_r \eta_s \eta_b \eta_t (1 - M_S)) \quad [69]$$

Commercial ship designs have power design margin of 3 to 5% depending upon the risk involved in not achieving the specified trials speed. With explicit estimation of the air drag of the vessel, a power design margin of 3% might be justified for a fairly conventional hull form using the best parametric resistance prediction methods available today. The power design margin for Navy vessels usually needs to be larger due to the relatively larger (up to 25% compared with 3-8%) and harder to estimate appendage drag on these vessels. The U. S. Navy power design margin policy (42) includes a series of categories through which the margin decreases as the design becomes better defined and better methods are used to estimate the required power as shown in Table 11.IX.

TABLE 11.IX - U.S. NAVY POWER DESIGN MARGINS (42)

Category	Description	M_D
1a	early parametric prediction before the plan and appendage configuration	10%
1b	preliminary design prediction made the model P_E test	8%
2	preliminary/contract design after P_S test with stock propeller and corrections	6%
3	contract design after P_S test with model of actual propeller	2%

Commercial designs typically have a power service margin of 15 to 25%, with the margin increasing from relatively low speed tankers to high-speed container ships. In principle, this should depend upon the dry docking interval; the trade route, with its expected sea and wind conditions, water temperatures, and hull fouling; and other factors. The power output of a diesel prime mover varies as $N' = N/N_o$ at constant throttle as shown in Figure 11.20, where N is the propeller rpm and N_o is the rated propeller rpm. Thus, diesel plants need a relatively larger power service margin to ensure that adequate power is available in the worst service conditions. The service margin might be somewhat smaller with steam or gas turbine prime movers since their power varies as $(2 - N')N'$ and is, thus, much less sensitive to propeller rpm. The power service margin might also be somewhat lower with a controllable pitch propeller since the pitch can be adjusted to enable to prime mover to develop maximum power under any service conditions. Conventionally powered naval vessels typically have power service margins of about 15% since the maximum power is being pushed hard to achieve the maximum speed and it is used only a relatively small amount of the ship's life. Nuclear powered naval vessels typically have higher power service margins since they lack the typical fuel capacity constraint and are, thus, operated more of their life at high powers.

It is important to note that in the margin approach outline above, the power design margin M_D is defined as a fraction of the resistance or effective power estimate, which is increased to provide the needed margin. The power service margin M_S, however, is defined as a fraction of the MCR that is reduced for the design match point on trials. This difference in the definition of the basis for the percentage of M_D and M_S is important. Note that if M_S were 20% this would increase P_B in equation 68 by $1/(1 - M_S)$ or 1.25, but if M_S were defined in the same manner as M_D it would only be increased by $(1 + M_S) = 1.20$. This potential 5% difference in the sizing the main machinery is significant. Practice has been observed in Japan and also occasionally in the UK where both the power design margin and the power service margin are defined as increases of the smaller estimates, so precision in contractual definition of the power service margin is particularly needed when purchasing vessels abroad.

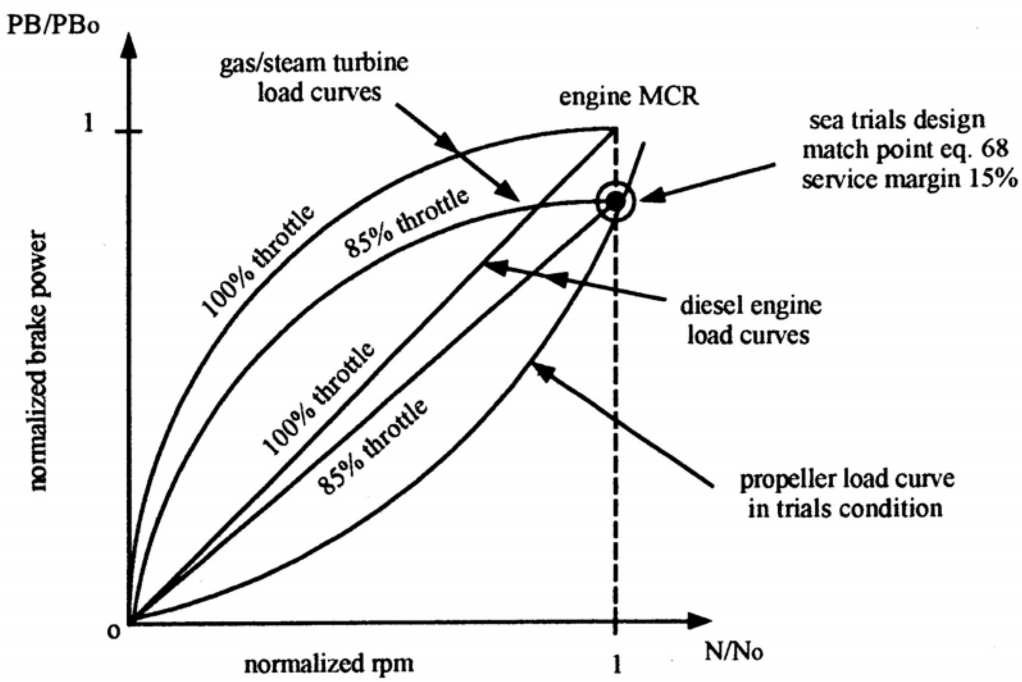


Figure 11.20 - Propulsion Trials Propeller Design Match Point

11.4.1.3 Effective Power Estimation

The choice of vessel dimensions and form parameters will influence and depend upon the resistance of the hull and the resulting choice of propulsor(s) and prime mover(s). The choice of machinery will influence the engine room size, the machinery weight, and the machinery center of gravity. Early estimates of the resistance of the hull can be obtained from SNAME Design Data Sheets, scaling model tests from a basis ship or geosim, standard series resistance data, or one of the resistance estimation software tools available today.

The most widely used parametric stage resistance model for displacement hulls ($F_\nabla \leq \approx 2$) was developed by Holtrop and Mennen at MARIN (43, 44). This model has been implemented in the Power Prediction Program (PPP), which is available for teaching and design (40). This resistance model is used as the principal example here. Hollenbach presents a parametric resistance model intended to improve upon the Holtrop and Mennen method, particularly for modern, shallow draft, twin screw vessels (45).

The Holtrop and Mennen model is a complex, physics-based model for which the final coefficients were obtained by regression analysis of 334 model tests conducted at MARIN. (This particular model applies to displacement monohulls with characteristics in the ranges: $0.55 \leq C_P \leq 0.85$; $3.90 \leq L/B \leq 14.9$; $2.10 \leq B/T \leq 4.00$; $0.05 \leq Fn \leq 1.00$.) The model as implemented in PPP estimates resistance components using a modified Hughes method as follows:

$$R_T = (R_F + K_1R_F + R_W + R_B + R_{TR} + R_{APP} + R_A + R_{AIR})(1 + M_D) \qquad [70]$$

where R_T is the total resistance, R_F is the frictional resistance, K_1R_F is the majority of the form drag, R_W is the wave making and wave breaking resistance, R_B is the added form drag due to the mounding of water above a bulbous bow that is too close to the free surface for its size, R_{TR} is the added form drag due to the failure of the flow to separate from the bottom of a hydrodynamic transom stern, R_{APP} is the appendage resistance, R_A is the correlation allowance resistance, R_{AIR} is the air resistance, and M_D is the power design margin. Holtrop and Mennen added the two special form drag components R_B and R_{TR} to achieve effective modeling of their model tests. The R_{AIR} and the power design margin were incorporated into the PPP program implementation to facilitate design work.

The Holtrop and Mennen model also include three separate models for the hull propeller interaction: wake fraction w, thrust deduction t, and relative rotative efficiency η_r. The user needs to make a qualitative selection between a traditional closed stern or more modern open flow stern for a single screw vessel or select a twin screw model. The method also includes a rational estimation of the drag of each appendage based upon a first-principles drag estimate based upon its wetted surface S_i and a factor $(1 + K_{2i})$ that reflects an estimate of the local velocity at the appendage and its drag coefficient. The PPP program implements both a simple percentage of bare hull resistance appendage drag model and the more rational Holtrop and Mennen appendage drag model.

The input verification and output report from the PPP program are shown in Figure 11.21 for illustration. The output includes all components of the resistance at a series of eight user-specified speeds and the resulting total resistance R_T; effective power P_E; hull propeller interaction w, t, η_h, and η_r; and the thrust required of the propulsor(s) $T_{reqd} = R_T/(1 - t)$. The design power margin as $(1 + M_D)$ is incorporated within the reported total resistance, effective power, and required thrust for design convenience.

The model includes a regression model for the model-ship correlation allowance. If the user does not yet know the wetted surface of the hull or the half angle of entrance of the design waterplane, the model includes regression models that can estimate these hull characteristics from the other input dimensions and parameters. This resistance estimation model supports design estimates for most displacement monohulls and allows a wide range of tradeoff studies relative to resistance performance. In the example run shown in Figure 11.21, it can be seen that the bulbous bow sizing and location do not produce added form drag ($R_B \approx 0$) and the flow clears off the transom stern ($R_{TR} \to 0$) above about 23 knots. The air drag is about 2% of the bare hull resistance in this case.

11.4.1.4 Propulsion Efficiency Estimation

Use of equation 69 to size the prime mover(s) requires the estimation of the six efficiencies in the denominator. Resistance and hull-propeller interaction estimation methods, such as the Holtrop and Mennen model as implemented in the PPP program, can provide estimates of the hull efficiency η_h and the relative rotative efficiency η_r. Estimation of the open water propeller efficiency η_o in early design will be discussed in the next subsection. Guidance for the sterntube and line bearing efficiencies are as follows (41):

$$\begin{aligned} \eta_s\eta_b &= 0.98, \quad \text{for machinery aft} \\ &= 0.97, \quad \text{for machinery amidship} \end{aligned} \qquad [71]$$

```
              University of Michigan
Department of Naval Architecture and Marine Engineering

 Power Prediction Program (PPP-1.8) by M. G. Parsons

 Source:1. Holtrop,J., & Mennen, G.G.J., "An Approximate
           Power Prediction Method," International Shipbuilding
            Progress, Vol.29, No.335, July, 1982.
        2. Holtrop,J., "A Statistical Reanalysis of
           Resistance and Propulsion Data," International
           Shipbuilding Progress, Vol.31, No.363, Nov., 1984.

Run Identification: SDC Test Powering

Input Verification:

     Length of Waterline LWL (m)              =    205.00
     Maximum Beam on LWL (m)                  =     32.00
     Depth at the Bow (m)                     =     20.00

     Mean Draft (m)                           =     10.00
     Draft Forward (m)                        =     10.00
     Draft Aft (m)                            =     10.00

     Block Coefficient on LWL CB              =    0.5716
     Prismatic Coefficient on LWL CP          =    0.5833
     Midship Coefficient to LWL CM=CX         =    0.9800
     Waterplane Coefficient on LWL CWP        =    0.7500

     Center of Buoyancy LCB (% LWL; + Fwd)    =   -0.7500
     Center of Buoyancy LCB (m from FP)       =    104.04
     Molded Volume (m^3)                      =   37497.0
     Deck House/Cargo Frontal Area (m^2)      =    300.00

     Water Type                               =  Salt@15C
     Water Density (kg/m^3)                   =   1025.87
     Kinematic Viscosity (m^2/s)              =   0.118831E-05

     Appen. Drag (% Bare Hull Resistance)     =      5.00

     Bulb Section Area at Station 0 (m^2)     =     20.00
     Vertical Center of Bulb Area (m)         =      4.00

     Transom Immersed Area (m^2)              =     16.00
     Stern Type                               = Normally Shaped
     Design Margin on RT,PE,REQ.THR (%)       =      5.00
     Propulsion Type                          =  SS, Conv.

     Propeller Diameter (m)                   =      8.00
     Propeller Expanded Area Ratio Ae/Ao      =    0.7393

     Wetted Surface (m^2)                     =   7381.24
     Half Angle of Entrance (deg)             =     12.11
```

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Department of Naval Architecture and Marine Engineering

 Power Prediction Program (PPP-1.8) by M. G. Parsons

 Source:1. Holtrop,J., & Mennen, G.G.J., "An Approximate
           Power Prediction Method," International Shipbuilding
            Progress, Vol.29, No.335, July, 1982.
        2. Holtrop,J., "A Statistical Reanalysis of
           Resistance and Propulsion Data," International
           Shipbuilding Progress, Vol.31, No.363, Nov., 1984.

Run Identification: SDC Test Powering
```

Speed, Resistance Coefficients and Frictional Resistance RF(N):

V(kts)	V(m/s)	FN	SLRATIO	CF	CR	CA	RF
15.00	7.72	0.1721	0.5784	0.001478	0.000441	0.000352	333139.8
17.00	8.75	0.1951	0.6555	0.001455	0.000472	0.000352	421443.8
19.00	9.77	0.2180	0.7326	0.001436	0.000549	0.000352	519426.3
21.00	10.80	0.2409	0.8097	0.001419	0.000674	0.000352	626970.3
23.00	11.83	0.2639	0.8869	0.001404	0.000878	0.000352	743972.3
25.00	12.86	0.2868	0.9640	0.001390	0.001108	0.000352	870339.8
27.00	13.89	0.3098	1.0411	0.001377	0.001260	0.000352	1005989.3
29.00	14.92	0.3327	1.1182	0.001366	0.001465	0.000352	1150844.6

Remaining Resistance Components (N):

V(kts)	Form RF*K1	Appendage RAPP	Wave RW	Bulb RB	Transom RTR	Correlation RA	Air Drag RAIR
15.00	53277.7	21627.6	12091.4	24.6	34017.7	79469.8	13476.4
17.00	67399.9	27907.1	36487.5	30.0	32781.2	102074.5	17309.7
19.00	83069.8	35893.0	88011.8	35.3	27316.6	127504.8	21622.2
21.00	100268.9	46238.6	180775.2	40.2	16717.9	155760.8	26413.8
23.00	118980.5	60471.7	346357.5	44.9	78.7	186842.3	31684.6
25.00	139190.0	78214.1	554702.9	49.2	0.0	220749.4	37434.5
27.00	160883.9	96303.5	759144.4	53.2	0.0	257482.1	43663.6
29.00	184050.0	119248.5	1050018.4	57.0	0.0	297040.4	50371.9

Resistance, Effective Power, Propulsion Factors and Required Thrust

V(kts)	RT(N)	PE(kW)	w	t	REQ.THR(N)	etaH	etaRR
15.00	574481.3	4433.04	0.2402	0.1834	703483.2	1.0748	0.9931
17.00	740705.4	6477.82	0.2397	0.1834	907033.5	1.0741	0.9931
19.00	948023.8	9266.33	0.2393	0.1834	1160906.0	1.0736	0.9931
21.00	1210844.9	13081.05	0.2390	0.1834	1482744.5	1.0731	0.9931
23.00	1562854.0	18491.88	0.2387	0.1834	1913798.5	1.0726	0.9931
25.00	1995714.0	25666.88	0.2384	0.1834	2443858.8	1.0722	0.9931
27.00	2439696.3	33887.09	0.2381	0.1834	2987538.8	1.0718	0.9931
29.00	2994212.3	44669.94	0.2379	0.1834	3666573.5	1.0715	0.9931

Design Margin Has Been Included in RT, PE, and REQ.THR = RT/(1-t).

Figure 11.21 - Sample Power Prediction Program (PPP) Output (40)

The SNAME Technical and Research bulletins can provide guidance for the transmission efficiency with mechanical reduction gears (35),

$$\eta_t = \eta_g = \prod_i (1 - \ell_i) \qquad [72]$$

where $\ell_i =$ 0.010 for each gear reduction

$\ell_i =$ 0.005 for the thrust bearing

$\ell_i =$ 0.010 for a reversing gear path

Thus, a single reduction, reversing reduction gear with an internal thrust bearing used in a medium speed diesel plant would have a gearing efficiency of about $\eta_t = 0.975$. Note that since test bed data for low speed diesels usually does not include a thrust load, η_t = 0.005 should be included in direct connected low speed diesel plants to account for the thrust bearing losses in service. With electric drive, the transmission efficiency must include the efficiency of the electrical generation, transmission, power conversion, electric motor, and gearing (if installed)

$$\eta_t = \eta_{gen}\eta_c\eta_m\eta_g \qquad [73]$$

where η_{gen} = electric generator efficiency

η_c = transmission power conversion efficiency

η_m = electric motor efficiency

η_g = reduction gear efficiency (equation 72)

The SNAME bulletin (35) includes data for this total transmission efficiency η_t depending upon the type of electrical plant utilized. In general, in AC generation/AC motor electrical systems η_t varies from about 88 to 95%, in AC/DC systems η_t varies from about 85 to 90%, and in DC/DC systems η_t varies from about 80 to 86% each increasing with the rated power level of the installation. Further, all the bearing and transmission losses increase as a fraction of the transmitted power as the power drops below the rated condition.

11.4.1.5 Propeller Design Optimization

The open water propeller efficiency η_o is the most significant efficiency in equation 69. The resistance and hull-propeller interaction estimation yields the wake fraction w and the required total thrust from the propeller or propellers,

$$T_{reqd} = R_T / (1 - t) \qquad [74]$$

assuming a conventional propeller is used here. Alexander (46) provides a discussion of the comparable issues when using waterjet propulsion. For large moderately cavitating propellers, the Wageningen B-Screw Series is the commonly used preliminary design model (47). An optimization program which selects the maximum open water efficiency Wageningen B-Screw Series propeller subject to a 5% or 10% Burrill back cavitation constraint (41) and diameter constraints is implemented as the Propeller Optimization Program (POP), which is available for teaching and design (40). This program utilizes the Nelder and Mead Simplex Search with an External Penalty Function (48) to obtain the optimum design. A sample design run with the Propeller Optimization Program (POP) is shown in Figure 11.22. The program can establish the operating conditions for a specified propeller or optimize a propeller design for given operating conditions and constraints. A sample optimization problem is shown. This provides an estimate of the open water efficiency η_o needed to complete the sizing of the propulsion machinery using equation 69.

Useful design charts for the maximum open water efficiency Wageningen B-Screw Series propellers are also available for two special cases. Bernitsas and Ray present results for the optimum rpm propeller when the diameter is set by the hull and clearances (49) and for the optimum diameter propeller when a directly connected low speed diesel engine sets the propeller rpm (50). In using these design charts, the cavitation constraint has to be imposed externally using Keller's cavitation criterion or Burrill's cavitation constraints (41, 51) or a similar result.

Initial propeller design should also consider the trade-off among blade number Z, propeller rpm N_p, open water efficiency η_o, and potential resonances between the blade rate propeller excitation at ZN_p (cpm) and predicted hull natural frequencies. Hull natural frequencies can be estimated in the early parametric design using methods presented by Todd (52).

11.4.2 Maneuvering Performance Estimation

The maneuvering characteristics of a hull are directly affected by its fundamental form and LCG as well as its rudder(s) size and location. Recent IMO requirements mandate performance in turns, zigzag maneuvers, and stopping. Thus, it is incumbent upon the designer to check basic maneuvering characteristics of a hull during the parametric stage when the overall dimensions and form coefficients are being selected. This subsection will illustrate a parametric design capability to assess course stability and turnability. This performance presents the designer with a basic tradeoff since a highly course stable vessel is hard to turn and vice versa.

Clarke et al (53) and Lyster and Knights (54) developed useful parametric stage maneuvering models for displacement hulls. Clarke et al used the

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Propeller Optimization Program (POP-1.5) by M.G. Parsons

  Source:1. Oosterveld, M. W. C., and Van Oossanen, P.,
            "Further Computer-Analyzed Data of the Wageningen
            B-Screw Series", International Shipbuilding
            Progress, Vol. 22, No. 251, July, 1975.
         2. Parsons, M. G., "Optimiztion Methods for Use in
            Computer-Aided Ship Design", Proceedings of the
            First SNAME STAR Symposium, 1975

Wageningen B-Screw Series Propeller Preliminary Design

 *** Eta 0 Reduced by 2% When Controllable Pitch ***

Run Identification:  SDC Test Optimization

 Input Data:

     Optimization Run

     Fixed-Pitch Propeller
     Number of Propeller Blades              =        4
     Required Propeller Thrust (kN)          =    444.8
     Ship Speed Vk (knots)                   =    15.00
     Wake Fraction w                         =    0.115
     Depth of Shaft below Waterline (m)      =     4.40
     Water Type                              =  salt@15C
     Water Density Rho (kg/m^3)              =  1025.87
     Kinematic Viscosity Nu (m^2/sec)        =  0.118831E-05
     Burrill Back Cavitation Constraint      =       5%

     Initial Expanded Area Ratio Ae/Ao       =    0.750
     Initial Pitch Diameter Ratio P/Dp       =    0.900
     Initial Propeller Diameter Dp (m)       =     4.00
     Minimum Diameter Constraint Dpmin (m)   =     1.15
     Maximum Diameter Constraint Dpmax (m)   =     4.60


 Optimal Design Results:

     Propeller Diameter Dp (m)                 =      4.60
     Propeller Pitch P (m)                     =      3.95
     Pitch Diameter Ratio P/Dp                 =    0.8589
     Expanded Area Ratio Ae/Ao                 =    0.6792
     Propeller Revolutions per Minute (rpm)    =    149.46
     Advance Coefficient J                     =    0.5966
     Thrust Coefficient KT                     =    0.1564
     Torque Coefficient KQ                     =   0.02251
     Propeller Open Water Efficiency Eta 0     =     0.660
     Propeller Thrust (kN)                     =     444.8
     Reynolds Number RN                        = 0.406E+08
     Cavitation Number Sigma                   =    0.4152
     Optimization Search Evaluation Count      =        64
```

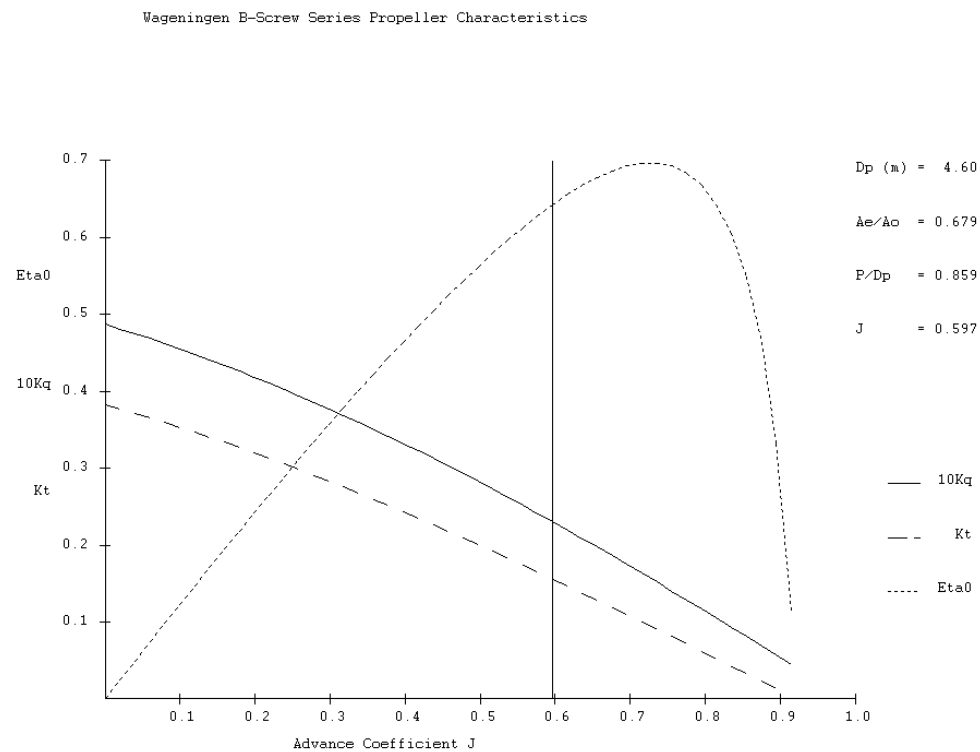

Figure 11.22 - Sample Propeller Optimization Program (POP) Output (40)

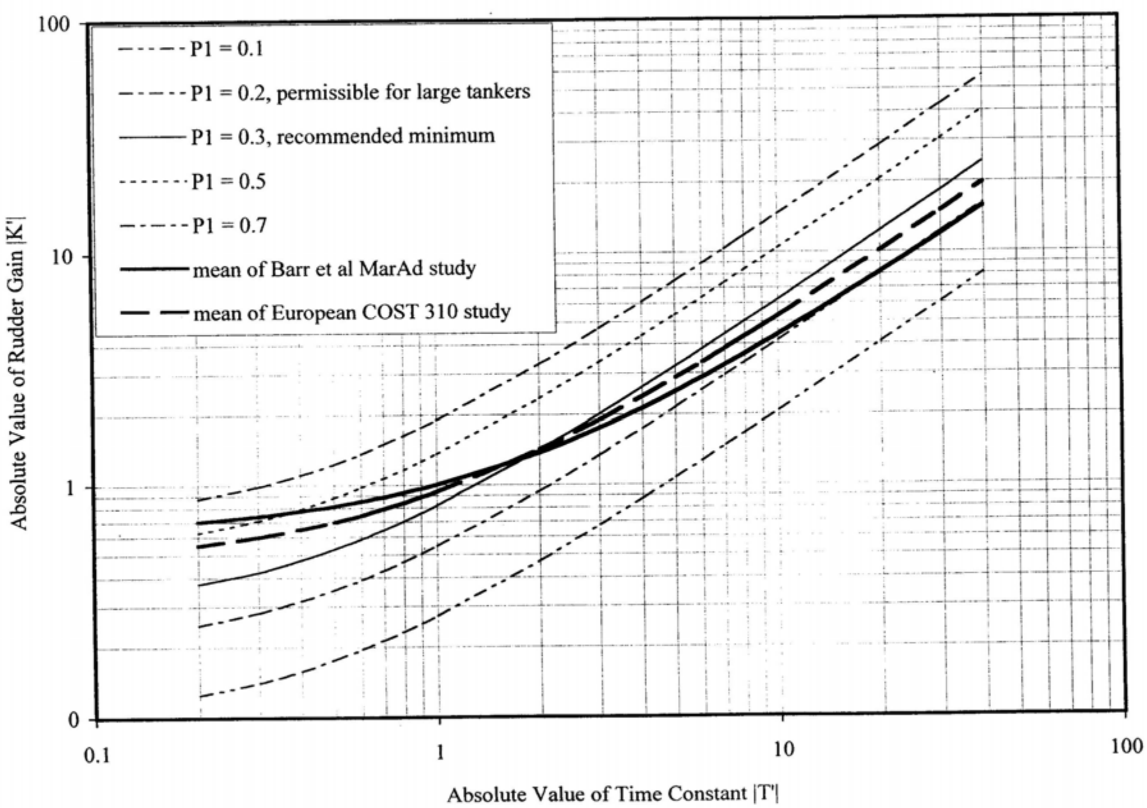

Figure 11.23 - Norrbin's Turning Index versus |K'| and |T'|

linearized equations of motion in sway and yaw to develop a number of useful measures of maneuverability. They estimated the hydrodynamics stability derivatives in terms of the fundamental parameters of the hull form using regression equations of data from 72 sets of planar motion mechanism and rotating arm experiments and theoretically derived independent variables. Lyster and Knights obtained regression equations of turning circle parameters from full-scale maneuvering trials. These models have been implemented in the Maneuvering Prediction Program (MPP), which is also available for teaching and design (40). In MPP, the Clarke hydrodynamic stability derivative equations have been extended by using corrections for trim from Inoue et al (55) and corrections for finite water depth derived from the experimental results obtained by Fugino (56).

Controls-fixed straight-line stability is typically assessed using the linearized equations of motion for sway and yaw (57). The sign of the Stability Criterion C, which involves the stability derivatives and the vessel LCG position, can determine stability. A vessel is straight-line course stable if,

$$C = Y_v' (N_r' - m'x_g') - (Y_r' - m')N_v' > 0 \qquad [75]$$

where m' is the non-dimensional mass, x_g' is the longitudinal center of gravity as a decimal fraction of ship length plus forward of amidships, and the remaining terms are the normal sway force and yaw moment stability derivatives with respect to sway velocity v and yaw rate r.

Clarke (53) proposed a useful turnability index obtained by solving Nomoto's second-order in r lateral plane equation of motion for the change in heading angle resulting from a step rudder change after vessel has traveled one ship length,

$$P_c = | \psi/\delta |_{t' = 1} \qquad [76]$$

This derivation follows earlier work by Norrbin that defined a similar P_1 parameter. Clarke recommended a design value of at least 0.3 for the P_c index. This suggests the ability to turn about 10 degrees in the first ship length after the initiation of a full 35 degree rudder command.

Norrbin's index is obtained by solving the simpler first-order Nomoto's equation of motion for the same result. It can be calculated as follows:

$$P_1 = | \psi/\delta |_{t' = 1} = |K'|(1-|T'| (1-e^{-1/|T'|})) \qquad [77]$$

where K' and T' are the rudder gain and time constant, respectively, in the first-order Nomoto's equation,

$$T'dr'/dt' + r' = K'\delta \qquad [78]$$

where r' is the nondimensional yaw rate and δ is the rudder angle in radians. Values for a design can be compared with the recommended minimum of 0.3 (0.2 for large tankers) and the results of a MarAd study by Barr and the European COST study that established mean lines for a large number of acceptable designs. This chart is presented in Figure 11.23.

Clarke also noted that many ships today, particularly those with full hulls and open flow to the propeller, are course unstable. However, these can still be maneuvered successfully by a helmsman if the phase lag of the hull and the steering gear is not so large that it cannot be overcome by the anticipatory abilities of a trained and alert helmsman. This can be assessed early in the parametric stage of design by estimating the phase margin for the hull and steering gear and comparing this to capabilities found for typical helmsmen in maneuvering simulators. Clarke derived this phase margin from the linearized equations of motion and stated that a helmsman can safely maneuver a course unstable ship if this phase margin is above about –20 degrees. This provides a valuable early design check for vessels that need to be course unstable.

Lyster and Knights (53) obtained regression equations for standard turning circle parameters from maneuvering trials of a large number of both single- and twin-screw vessels. Being based upon full-scale trials, these results represent the fully nonlinear maneuvering performance of these vessels. These equations predict the advance, transfer, tactical diameter, steady turning diameter, and steady speed in a turn from hull parameters.

The input and output report from a typical run of the Maneuvering Prediction Program (MPP) is shown in Figure 11.24. More details of this program are available in the manual (40). The program estimates the linear stability derivatives, transforms these into the time constants and gains for Nomoto's first- and second-order maneuvering equations, and then estimates the characteristics described above. These results can be compared to generalized data from similar ships (57) and Figure 11.23. The example ship analyzed is course unstable since $C < 0$, with good turnability as indicated by $P_c = 0.46$, but should be easily controlled by a helmsman since the phase margin is $2.4^\circ > -20^\circ$. Norrbin's turning index can be seen to be favorable in Figure 11.23. The advance of 2.9 L and tactical diameter of 3.5 L are well below the IMO required 4.5 L and 5.0 L, respectively. If these results were not acceptable, the design could be improved by changing rudder area and/or modifying the basic proportions of the hull.

11.4.3 Seakeeping Performance Estimation

The seakeeping performance (58) can be a critical factor in the conceptual design of many vessels such as offshore support vessels, oceanographic research vessels, and warships. It is only secondary in the parametric design of many conventional commercial vessels. The basic hull sizing and shape will affect the seakeeping capabilities of a vessel as noted in the discussion associated with equation 21. Thus, it may be incumbent upon the designer to check the basic seakeeping characteristics of a hull during the parametric stage when the overall dimensions and form coefficients are being selected. This subsection will illustrate a parametric design capability to assess seakeeping performance in a random seaway. Coupled five (no surge) and six degree-of-freedom solutions in a random seaway are desired. From this, typically only the three restored motions of heave, pitch, and roll and the vertical wave bending moment are of interest in the parametric stage of conceptual design.

11.4.3.1 Early Estimates of Motions Natural Frequencies

Effective estimates can often be made for the three natural frequencies in roll, heave, and pitch based only upon the characteristics and parameters of the vessel. Their effectiveness usually depends upon the hull form being close to the norm.

An approximate roll natural period can be derived using a simple one degree-of-freedom model yielding,

$$T_\phi = 2.007\, k_{11}/\sqrt{GM_T} \qquad [77]$$

where k_{11} is the roll radius of gyration, which can be related to the ship beam using,

$$k_{11} = 0.50\, \kappa\, B \qquad [78]$$

with $0.76 \leq \kappa \leq 0.82$ for merchant hulls
$0.69 \leq \kappa \leq 1.00$ generally.

Using $\kappa = 0.80$, we obtain the easy to remember result $k_{11} \approx 0.40B$. Katu (59) developed a more complex parametric model for estimating the roll natural period that yields the alternative result for the parameter κ,

$$\kappa = 0.724\sqrt{(C_B(C_B + 0.2) - 1.1(C_B + 0.2) \bullet (1.0 - C_B)(2.2 - D/T) + (D/B)^2)} \qquad [79]$$

Roll is a lightly damped process so the natural period can be compared directly with the dominant encounter period of the seaway to establish the risk of resonant motions. The encounter period in long-crested oblique seas is given by,

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Maneuvering Prediction Program (MPP-1.3) by M.G. Parsons

  References:  Clarke,D., Gedling,P., and Hine,G.,
               "The Application of Manoeuvring Criteria in Hull
                Design using Linear Theory," Trans. RINA, 1983
               Lyster, C., and Knights, H. L.,
               "Prediction Equations for Ships" Turning Circles,"
                Trans. NECIES, 1978-1979


 Run Identification: SDC Test Maneuvering


 Input Verification:

      Length of Waterline LWL (m)             =    148.00

      Maximum Beam on LWL (m)                 =     32.28

      Mean Draft (m)                          =      9.00

      Draft Forward (m)                       =      9.00

      Draft Aft (m)                           =      9.00

      Block Coefficient on LWL CB             =    0.7000

      Molded Volume (m^3)                     =  30097.87

      Center of Gravity LCG (%LWL; + Fwd)     =   -0.5000
      Center of Gravity LCG (m from FP)       =     74.74

      Midships to Rudder CE XR (%LWL; + Aft)  =   49.0000
      Rudder Center of Effort XR (m from FP)  =    146.52

      Initial Ship Speed (knots)              =     16.00
      Initial Ship Speed (m/s)                =    8.2310

      Water Type                              =  Salt@15C
      Water Density (kg/m^3)                  =   1025.87
      Kinematic Viscosity (m^2/s)             =   0.118831E-05

      Yaw Radius of Gyration K33/LWL          =    0.2500

      Water Depth to Ship Draft Ratio H/T     =   1000.00

      Steering Gear Time Constant (s)         =      2.50

      Total Rudder Area - Fraction of LWL*T   =    0.0219

      Number of Propellers                    =         2

      Number of Rudders                       =         2

      Submerged Bow Area - Fraction of LWL*T  =    0.0160
```

```
Run Identification: SDC Test Maneuvering

   Linear Maneuvering Derivatives

Nondimensional Mass              M prime     =  0.018569
Nondimensional Mass Moment       I sub zz    =  0.001161

Sway Velocity Derivative         Y sub v     = -0.024483
Sway Acceleration Derivative     Y sub v dot = -0.013466

Yaw Velocity Derivative          N sub v     = -0.006917
Yaw Acceleration Derivative      N sub v dot = -0.001079

Sway Velocity Derivative         Y sub r     =  0.004155
Sway Acceleration Derivative     Y sub r dot = -0.001205

Yaw Velocity Derivative          N sub r     = -0.003398
Yaw Acceleration Derivative      N sub r dot = -0.000628

Sway Rudder Derivative           Y sub delta =  0.003995
Yaw Rudder Derivative            N sub delta = -0.001958


   Time Constants and Gains for Nomoto"s Equation

Dominant Ship Time Constant    T1 prime      =   -7.2207
Ship Time Constant             T2 prime      =    0.4145
Numerator Time Constant        T3 prime      =    0.8821
Numerator Time Constant        T4 prime      =    0.2250

1st Order Eqn. Time Constant   T prime       =   -7.6882
Rudder Gain Factor             K prime       =    4.0253
Rudder Gain Factor             K sub v prime =   -2.2066

Steering Gear Time Constant    TE prime      =    0.1390


   Evaluation of Turning Ability and Stability

Inverse Time Constant          1/|T prime|   =    0.1301
Inverse Gain Factor            1/|K prime|   =    0.2484

Clarke"s Turning Index                   P =    0.4634
Linear Dynamic Stability Criterion       C =-0.0000188

Vessel is hydrodynamically open loop course unstable

Closed Loop Phase Margin with Steering Engine  =    0.6187 degrees


 Approach Speed                          =     16.00 knots

 Rudder Angle                            =     35.00 degrees

 Steady Turning Diameter                 =    511.02 meters
 Tactical Diameter                       =    531.33 meters
 Advance                                 =    432.71 meters
 Transfer                                =    230.34 meters
 Steady Speed in Turn                    =     10.33 knots
```

Figure 11.24 - Sample Maneuvering Prediction Program (MPP) Output (40)

$$T_e = 2\pi/(\omega - (V\omega^2/g)\cos\theta_w) \quad [80]$$

where ω is the wave frequency, V is ship speed, and θ_w is the wave angle relative to the ship heading with $\theta_w = 0°$ following seas, $\theta_w = 90°$ beam seas, and $\theta_w = 180°$ head seas. For reference, the peak frequency of an ISSC spectrum is located at $4.85T_1^{-1}$ with T_1 the characteristic period of the seaway. An approximate pitch natural period can also be derived using a simple one degree-of-freedom model yielding,

$$T_\theta = 2.007\, k_{22}/\sqrt{GM_L} \quad [81]$$

where now k_{22} is the pitch radius of gyration, which can be related to the ship length by noting that $0.24L \leq k_{22} \leq 0.26L$. An alternative parametric model reported by Lamb (14) can be used for comparison,

$$T_\theta = 1.776\, C_{WP}^{-1}\sqrt{(TC_B(0.6 + 0.36B/T))} \quad [82]$$

Pitch is a heavily-damped (non resonant) mode, but early design checks typically try to avoid critical excitation by at least 10%.

An approximate heave natural period can also be derived using a simple one degree-of-freedom model. A resulting parametric model has been reported by Lamb (14),

$$T_h = 2.007\sqrt{(TC_B(B/3T + 1.2)/C_{WP})} \quad [83]$$

Like pitch, heave is a heavily damped (non resonant) mode. Early design checks typically try to avoid having $T_h = T_\phi$, $T_h = T_\theta$, $2T_h = T_\theta$, $T_\phi = T_\theta$ or $T_\phi = 2T_\theta$ which could lead to significant mode coupling. For many large ships, however, these conditions often cannot be avoided.

11.4.3.2 Vertical Plane Estimates for Cruiser Stern Vessels

Loukakis and Chryssostomidis (60) used repeated seakeeping analyses to provide information for parameter stage estimation of the vertical plane motions of cruiser stern vessels based on the Series 60 family of vessels.

11.4.3.3 General Estimates using Linear Seakeeping Analysis

While most seakeeping analysis codes require a hull design and a set of hull offsets, useful linear seakeeping analysis is still feasible at the parameter stage of early design. The SCORES five degree-of-freedom (no surge) linear seakeeping program (61) has been adapted to personal computers for use in parametric design. This program was specifically selected because of its long period of acceptance within the industry and its use of the Lewis form transformations to describe the hull. The Lewis Forms require the definition of only the Section Area Curve, the Design Waterline Curve, and the keel line for the vessel. Hull offsets are not needed.

The SCORES program was adapted to produce the Seakeeping Prediction Program (SPP), which has been developed for teaching and design (40). This program supports the description of the seaway by a Pierson-Moskowitz, ISSC, or JONSWAP spectrum. It produces estimates of the roll, pitch, and heave natural periods. It also performs a spectral analysis of the coupled five degree-of-freedom motions and the vertical wave bending moment, the horizontal wave bending moment, and the torsional wave bending moment. Since SPP is intended for use in the earliest stages of parametric design, only the results for roll, pitch, heave, and the three moments are output (sway and yaw while in the solution are suppressed). The statistical measures of RMS, average, significant (average of the 1/3 highest), and the average of the 1/10 highest values are produced for all six of these responses. An estimated extreme design value is also produced for the three bending moments using,

$$\text{design extreme value} = \text{RMS}\sqrt{(2\ln(N/\alpha))} \quad [84]$$

where the number of waves N = 1000 is used, typical of about a 3 1/2 hour peak storm, and $\alpha = 0.01$ is used to model a 1% probability of exceedance. These design moments can be used in the initial midship section design.

The Seakeeping Prediction Program (SPP) can be used in two ways in early design. With only ship dimensions and hull form parameters available, the program will approximate the Section Area Curve and the Design Waterline Curve for the hull using 5th-order polynomial curves. In its current form, the model can include a transom stern, but does not model a bulbous bow, which will have a relatively secondary effect on the motions. This modeling is effective for hulls without significant parallel midbody. The program can also accept station data for the Section Area Curve and the Design Waterline Curve if these have been established by hydrostatic analysis in the early design process.

Because the linear seakeeping analysis uses an ideal fluid (inviscid flow) assumption, which will result in serious underprediction of roll damping, the user can include a realistic estimate of viscous roll damping by inputting a fraction of critical roll damping ζ estimate. This is necessary to produce roll estimates that are useful in design. A value of $\zeta = 0.10$ is typical of normal hulls without bilge keels, with bilge keels possibly doubling this value.

The input and selected portions of the output report from a typical run of the Seakeeping Prediction Program (SPP) are shown in Figure 11.25. More details of this program are available in the SCORES documentation (61) and the SPP User's Manual (40). In this particular example, the heave and pitch natural frequencies are almost identical indicating highly coupled vertical plane motions. The vessel experiences a 6° significant roll at a relative heading of $\theta_w = 60°$ in an ISSC spectrum sea with significant wave height $H_s = 2.25$ m and characteristic period $T_1 = 10$ s (Sea State 4). This ship will, therefore, occasionally experience roll as high as 12° in this seaway. If these predicted results were not acceptable, the design could be improved by adding bilge keels or roll fins or by modifying the basic proportions of the hull, particularly beam, C_{WP}, and C_{VP}.

11.5 PARAMETRIC MODEL DEVELOPMENT

The parametric study of ship designs requires models that relate form, characteristics, and performance to the fundamental dimensions, form coefficients, and parameters of the design. Various techniques can be used to develop these models. In pre-computer days, data was graphed on Cartesian, semi-log, or log-log coordinates and if the observed relationships could be represented as straight lines in these coordinates linear ($y = a_0 + a_1x$), exponential ($y = ab^x$), and geometric ($y = ax^b$) models, respectively, were developed. With the development of statistical computer software, multiple linear regression has become a standard tool for developing models from data for similar vessels. More recently, Artificial Neural Networks (ANN) have begun to be used to model nonlinear relationships among design data. This Section provides an introduction to the development of ship models from similar ship databases using multiple linear regression and neural networks.

11.5.1 Multiple Linear Regression Analysis

Regression analysis is a numerical method which can be used to develop equations or models from data when there is no or limited physical or theoretical basis for a specific model. It is very useful in developing parametric models for use in early ship design. Effective capabilities are now available in personal productivity software, such as Microsoft Excel.

In multiple linear regression, a minimum least squares error curve of a particular form is fit to the data points. The curve does not pass through the data, but generalizes the data to provide a model that reflects the overall relationship between the dependent variable and the independent variables. The effectiveness (goodness of fit) of the modeling can be assessed by looking at the following statistical measures:

R = coefficient of correlation which expresses how closely the data clusters around the regression curve ($0 \le R \le 1$, with 1 indicating that all the data is on the curve).

R^2 = coefficient of determination which expresses the fraction of the variation of the data about its mean that is captured by the regression curve ($0 \le R^2 \le 1$, with 1 indicating that all the variation is reflected in the curve).

SE = Standard Error which has units of the dependent variable and is for large n the standard deviation of the error between the data and the value predicted by the regression curve.

The interpretation of the regression curve and Standard Error is illustrated in Figure 11.26 where for an example TEU capacity is expressed as a function of Cubic Number CN. The regression curve will provide the mean value for the population that is consistent with the data. The Standard Error yields the standard deviation σ for the normal distribution (in the limit of large n) of the population that is consistent with the data.

The modeling process involves the following steps using Excel or a similar program:

1. select independent variables from first principles or past successful modeling;
2. observe the general form of the data on a scatter plot,
3. select a candidate equation form that will model the data most commonly using a linear, multiple linear, polynomial, exponential, or geometric equation,
4. transform the data as needed to achieve a linear multiple regression problem (e.g. the exponential and geometric forms require log transformations),
5. regress the data using multiple linear regression,
6. observe the statistical characteristics R, R^2, and SE,
7. iterate on the independent variables, model form, etc. to provide an acceptable fit relative to the data quality.

Univeristy of Michigan
Department of Naval Architecture and Marine Engineering

Seakeeping Prediction Program (SPP-1.5) by M.G. Parsons

Reference: Raff, A. I., "Program SCORES - Ship Structural Response in Waves", Ship Structures Committee Report SSC-230, 1972

Hull Data Identification:

Run Identification: SDC Test Seakeeping

Input Verification:

Length of Waterline LWL (m)	=	38.00
Vessel Displacement (tonnes)	=	499.9
Vertical Center of Gravity VCG (m)	=	3.50
Roll Radius of Gyration k11 (m)	=	3.80
Fraction of Critical Roll Damping	=	0.1300
Ship Speed (knots)	=	12.50
Ship Heading Relative to Waves (deg)	=	60.00
Water Type	=	Salt@15C
Water Density Rho (kg/m^3)	=	1025.87
ISSC Two Parameter Spectrum Excitation		
Significant Wave Height (m)	=	2.25
Characteristic Wave Period (s)	=	10.00
Lower Freq. Integration Limit (rad/s)	=	0.30
Upper Freq. Integration Limit (rad/s)	=	2.00

Sta.	Beam[m]	Area[m^2]	Draft[m]	Weight[t]
0	0.00	0.00	0.00	20.0
1	3.43	3.71	2.50	35.0
2	6.11	10.11	2.50	38.0
3	7.92	16.39	2.50	60.0
4	8.90	20.74	2.50	60.0
5	9.18	22.26	2.50	60.0
6	8.97	20.80	2.50	60.0
7	8.47	16.81	2.50	60.0
8	7.85	11.22	2.50	47.0
9	7.10	5.30	2.50	40.0
10	6.20	0.50	0.13	20.0

Motion Natural Frequencies and Periods:

Heave Natural Frequency = 1.555 rad/s   Heave Natural Period = 4.04 sec.

Pitch Natural Frequency = 1.574 rad/s   Pitch Natural Period = 3.99 sec.

Roll Natural Frequency = 0.697 rad/s   Roll Natural Period = 9.02 sec.

Roll Damping Results:

Roll Wave Damping = 0.844E+01

Added Viscous Roll Damping = 0.152E+03

Seakeeping Response Results:

Ship Speed = 12.5 knots = 6.43 m/s

Wave Angle [with Head Seas 180 deg.] = 60.0 deg.

ISSC Two Parameter Spectrum - Sign.Height = 2.25 m   Char. Period = 10.00 s

Wave Input and Response Amplitude Spectra:

Freq. r/s	Wave Amp. m^2s	Heave m^2s	Pitch deg.^2s	Roll deg.^2s	Vert. Mom. (t-m)^2s	Lat. Mom. (t-m)^2s	Tors. Mom. (t-m)^2s
0.300	0.007	0.007	0.001	0.002	0.121E+00	0.217E+00	0.448E-03
0.394	0.523	0.515	0.113	0.481	0.215E+02	0.492E+02	0.250E+00
0.489	0.933	0.904	0.470	2.455	0.672E+02	0.201E+03	0.228E+01
0.583	0.714	0.674	0.711	4.783	0.768E+02	0.299E+03	0.703E+01
0.678	0.442	0.401	0.771	7.044	0.719E+02	0.322E+03	0.151E+02
0.772	0.263	0.226	0.733	9.454	0.795E+02	0.309E+03	0.277E+02
0.867	0.159	0.126	0.652	12.087	0.109E+03	0.283E+03	0.460E+02
0.961	0.099	0.071	0.556	14.286	0.159E+03	0.253E+03	0.682E+02
1.056	0.063	0.040	0.457	14.422	0.225E+03	0.225E+03	0.842E+02
1.150	0.042	0.023	0.363	11.968	0.297E+03	0.205E+03	0.841E+02
1.244	0.029	0.013	0.275	8.581	0.367E+03	0.192E+03	0.722E+02
1.339	0.020	0.007	0.198	5.756	0.421E+03	0.183E+03	0.577E+02
1.433	0.014	0.004	0.133	3.767	0.450E+03	0.172E+03	0.450E+02
1.528	0.010	0.002	0.081	2.422	0.446E+03	0.159E+03	0.345E+02
1.622	0.008	0.001	0.043	1.501	0.407E+03	0.143E+03	0.253E+02
1.717	0.006	0.000	0.018	0.868	0.336E+03	0.122E+03	0.169E+02
1.811	0.004	0.000	0.005	0.449	0.246E+03	0.988E+02	0.944E+01
1.906	0.003	0.000	0.000	0.219	0.153E+03	0.734E+02	0.363E+01
2.000	0.003	0.000	0.001	0.143	0.748E+02	0.489E+02	0.669E+00

Wave Input and Response Amplitude Statistics:

	m	m	deg.	deg.	t-m	t-m	t-m
R.M.S.	0.562	0.533	0.726	3.083	0.194E+02	0.177E+02	0.753E+01
Ave.	0.702	0.666	0.907	3.853	0.242E+02	0.221E+02	0.941E+01
Signif.	1.123	1.066	1.452	6.165	0.387E+02	0.354E+02	0.151E+02
Ave 1/10	1.432	1.359	1.851	7.861	0.494E+02	0.451E+02	0.192E+02
Design Value with N=1000 and alpha=0.01					0.929E+02	0.849E+02	0.361E+02

Figure 11.25 - Sample Seakeeping Prediction Program (SPP) Output (40)

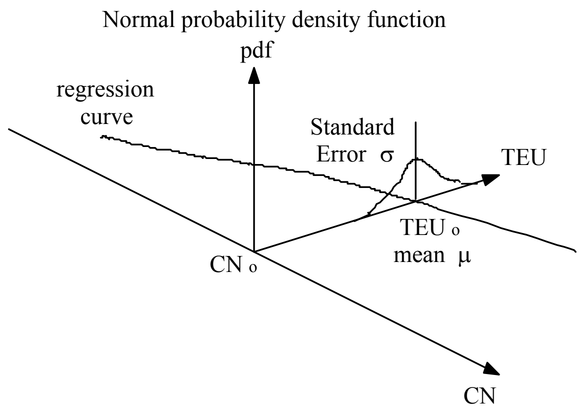

Figure 11.26 - Probabilistic Interpretation of Regression Modeling

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Numerous textbooks and software user's manuals can be consulted for further guidance and instructions if the reader does not currently have experience with multiple linear regression.

11.5.2 Neural Networks

An Artificial Neural Network (ANN) is a numerical mapping between inputs and output that is modeled on the networks of neurons in biological systems (62, 63). An ANN is a layered, hierarchical structure consisting of one input layer, one output layer and one or more hidden layers located between the input and output layers. Each layer has a number of simple processing elements called neurons (or nodes or units). Signal paths with multiplicative weights w interconnect the neurons. A neuron receives its input(s) either from the outside of the network (i.e., neurons in the input layer) or from the other neurons (those in the input and hidden layers). Each neuron computes its output by its transfer (or activation) function and sends this as input to other neurons or as the final output from the system. Each neuron can also have a bias constant b included as part of its transfer function. Neural networks are effective at extracting nonlinear relationships and models from data. They have been used to model ship parametric data (64, 65) and shipbuilding and shipping markets (66).

A typical feedforward neural network, the most commonly used, is shown schematically in Figure 11.27. In a feedforward network the signal flow is only in the forward direction from one layer to the next from the input to the output. Feedforward neural networks are commonly trained by the supervised learning algorithm called backpropagation. Backpropagation uses a gradient decent technique to adjust the weights and biases of the neural network in a backwards, layer-by-layer manner. It adjusts the weights and biases until the vector of the neural network outputs for the corresponding vectors of training inputs approaches the required vector of training outputs in a minimum root mean square (RMS) error sense. The neural network design task involves selection of the training input and output vectors, data preprocessing to improve training time, identification of an effective network structure, and proper training of the network. The last issue involves a tradeoff between overtraining and under training. Optimum training will capture the essential information in the training data without being overly sensitive to noise. Li and Parsons (67) present heuristic procedures to address these issues.

The neurons in the input and output layers usually have simple linear transfer functions that sum all weighted inputs and add the associated biases to produce their output signals. The inputs to the input layer have no weights. The neurons in the hidden layer usually have nonlinear transfer functions with sigmoidal (or S) forms the most common. Neuron j with bias b_j and n inputs each with signal x_i and weight w_{ij} will have a linearly combined activation signal z_j as follows:

$$z_j = \sum_{i=1}^{n} w_{ij}\, x_i + b_j \qquad [85]$$

A linear input or output neuron would just have this z_j as its output. The most common nonlinear hidden layer transfer functions use the exponential logistic function or the hyperbolic tangent function, respectively, as follows:

$$y_j = (1+ e^{-z_j})^{-1} \qquad [86]$$

$$y_j = \tanh(z_j) = (e^{z_j} - e^{-z_j})/(e^{z_j} + e^{-z_j}) \qquad [87]$$

These forms provide continuous, differentiable nonlinear transfer functions with sigmoid shapes.

One of the most important characteristics of neural networks is that they can “learn” from their training experience. Learning provides an adaptive capability that can extract nonlinear parametric relationships from the input and output vectors without the need for a mathematical theory or explicit modeling. Learning occurs during the process of weight and bias adjustment such that the outputs of the neural network for the selected training inputs match the corresponding training outputs in a minimum RMS error sense. After training, neural networks then have the capability to generalize; i.e., produce useful outputs from input patterns that they have never seen before. This is achieved by utilizing the information stored in the weights and biases to decode the new input patterns.

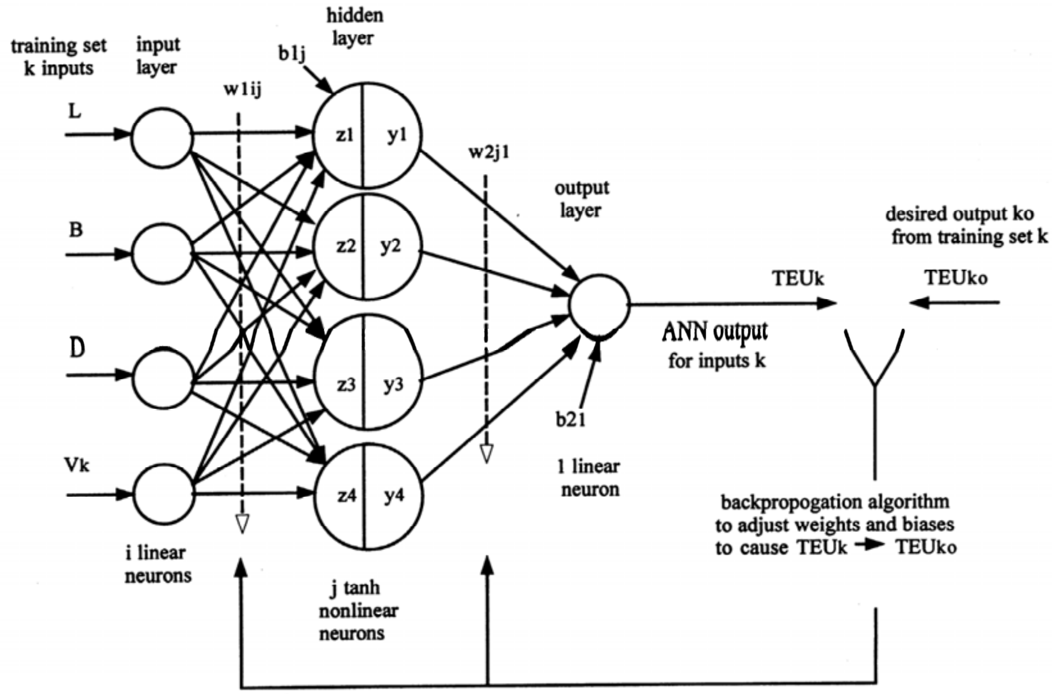

Figure 11.27 - Schematic of (4x4x1) Feedforward Artificial Neural Network

Theoretically, a feedforward neural network can approximate any complicated nonlinear relationship between input and output provided there are a large enough number of hidden layers containing a large enough number of nonlinear neurons. In practice, simple neural networks with a single hidden layer and a small number of neurons can be quite effective. Software packages, such as the MATLAB neural network toolbox (68), provide readily accessible neural network development capabilities.

11.5.3 Example Container Capacity Modeling

The development of parametric models using Multiple Linear Regression Analysis and Artificial Neural Networks will be illustrated through the development of models for the total (hull plus deck) TEU container capacity of hatch covered cellular container vessel as a function of LBP, B, D, and V_k. A mostly 1990's dataset of 82 cellular container ships ranging from 205 to 6690 TEU was used for this model development and testing. To allow a blind model evaluation using data not used in the model development, the data was separated into a training dataset of 67 vessels for the model development and a separate test dataset of 15 vessels for the final model evaluation and comparison. The modeling goal was to develop a generalized estimate of the total TEU capacity for ships using the four input variables: LBP, B, D, and V_k.

The total TEU capacity of a container ship will be related to the overall vessel size and the volume of the hull. Perhaps the most direct approach would be to estimate the total TEU capacity using LBP, B, and D in meters as independent variables in a multiple linear regression model. This analysis was performed using the Data Analysis option in the Tools menu in Microsoft Excel to yield the equation,

$$TEU = -2500.3 + 19.584\ LBP + 16.097\ B + 46.756\ D \qquad [88]$$

(n = 67, R = 0.959, SE = 469.8 TEU)

This is not a very successful result as seen by the Standard Error in particular. Good practice should report n, R, and SE with any presented regression equations.

The container block is a volume so it would be reasonable to expect the total TEU capacity to correlate strongly with hull volume, which can be represented by the metric Cubic Number CN = LBP•BD/100. The relationship between the TEU capacity and the Cubic Number for the training set is visualized using the Scatter Plot Chart option in Excel in Figure 11.28. The two variables have a strong linear correlation so either a linear equation or a quadratic equation in CN could provide an effective model. Performing a linear regression analyses yields the equation,

$$\text{TEU} = 142.7 + 0.02054\ \text{CN} \qquad [89]$$
(n = 67, R = 0.988, SE = 254.9 TEU)

which shows a much better Coefficient of Correlation R and Standard Error.

The speed of vessel affects the engineroom size, which competes with containers within the hull volume, but could also lengthen the hull allowing more deck containers. It is, therefore, reasonable to try as independent variables CN and V_k to see if further improvement can be achieved. This regression model is as follows:

$$\text{TEU} = -\,897.7 + 0.01790\ \text{CN} + 66.946\ V_k \qquad [90]$$
(n = 67, R = 0.990, SE = 232.4 TEU)

which shows a modest additional improvement in both R and SE. Although the relationship between total TEU capacity and CN is highly linear, it is still reasonable to investigate the value of including CN^2 as a third independent variable. This multiple linear regression model is as follows:

$$\text{TEU} = -\,1120.5 + 0.01464\ \text{CN} + 0.000000009557\text{CN}^2 + 86.844\ V_k \qquad [91]$$
(n = 67, R = 0.990, SE = 229.1 TEU)

which shows, as expected, a small coefficient for CN^2 and only a small additional improvement in SE.

To illustrate an alternative approach using simple design logic, the total TEU capacity could be postulated to depend upon the cargo box volume L_cBD. Further, the ship could be modeled as the cargo box, the bow and stern portions, which are reasonably constant fractions of the ship length, and the engine room that has a length which varies as the speed V_k. This logic gives a cargo box length $L_c = L - aL - bV_k$ and a cargo box volume $L_cBD = (L - aL - bV_k)BD = (1 - a)LBD - bBDV_k$. Using these as the independent variables with CN in place of LBD yields the alternative regression equation,

$$\text{TEU} = 109.6 + 0.01870\ \text{CN} + 0.02173\ BDV_k \qquad [92]$$
(n = 67, R = 0.988, SE = 256.1 TEU)

which is possibly not as effective as the prior two models primarily because the largest vessels today are able to carry containers both on top of the engine room and on the stern.

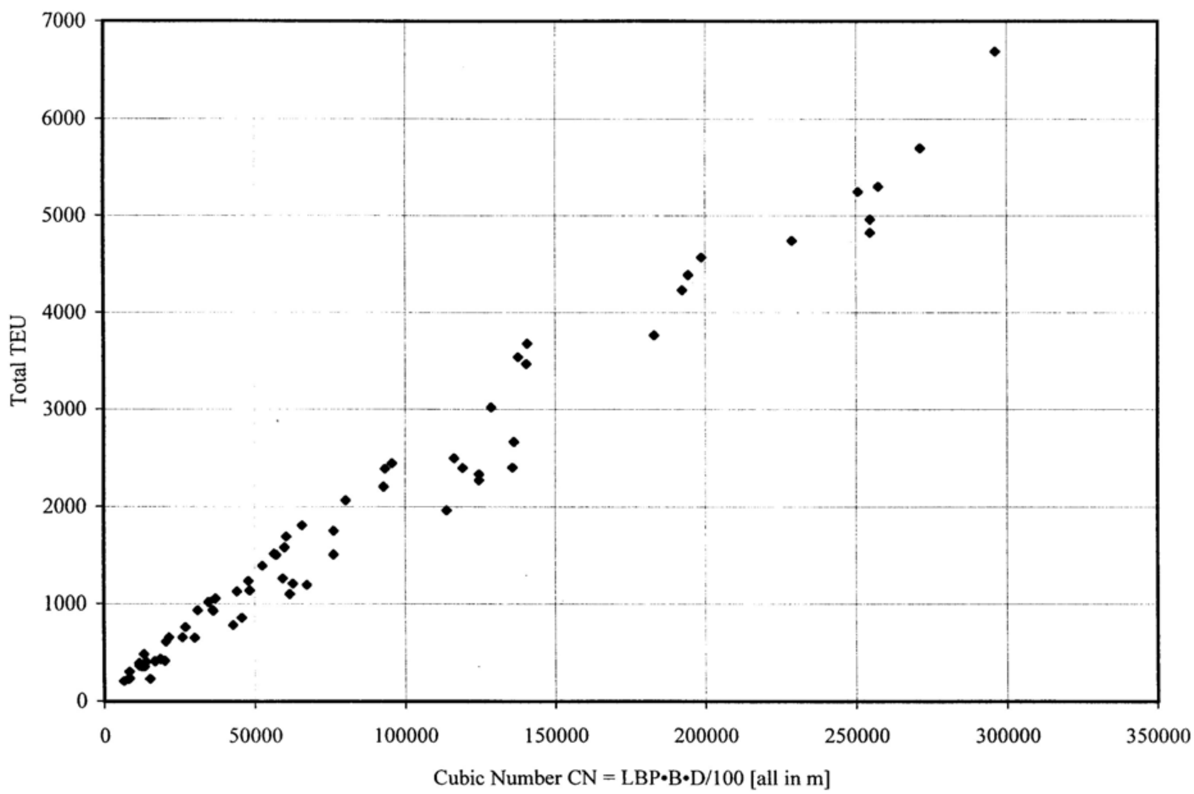

Figure 11.28 - Total TEU Capacity versus Metric Cubic Number

For comparison, a (4x4x1) neural network was developed by David J. Singer using inputs LBP, B, D, and V_k and output TEU. The ANN has four linear neurons in the input layer, one hidden layer with four nonlinear hyperbolic tangent neurons, and a single linear neuron output layer. This neural network was trained with the MATLAB Neural Network Toolbox (68) using the 67 training container ships used to develop the linear regression models. This ANN design evaluated nets with 2, 4, 6, 8, and 10 hidden layer neurons with 4 giving the best results. The ANN was trained for 500 through 5000 epochs (training iterations) with 2500 giving the best results.

To evaluate the performance of the regression equations and neural network using data that was not used in their development, the final 15 test ships were used to test the neural network and the five regression equations presented above. They were compared in terms of their RMS relative error defined as,

$$RMS_i = \{\sum_{j=1}^{15} ((TEU_j - TEU_{ij})/TEU_j)^2/15\}^{1/2} \quad [93]$$

where index i indicates the model and index j indicates the test dataset vessel. A summary of these results is shown in Table 11.X. The most effective regression equation for this test data is equation 90, which had the highest R and nearly the lowest Standard Error. The ANN performed similarly. Note that for this highly linear example, as shown in Figure 11.28, the full capability of the nonlinear ANN is not being exploited.

Table 11.X- MAXIMUM AND RMS RELATIVE ERROR FOR REGRESSIONS AND ANN

Model	Max. Relative Error	RMS Relative Error
Regression Equations		
equation 88	0.771	0.3915
equation 89	0.088	0.1212
equation 90	0.037	0.0979
equation 91	0.059	0.1185
equation 92	0.069	0.1151
Artificial Neural Network		
ANN (4x4x1) trained for 2500 epochs		0.1234

11.6 PARAMETRIC MODEL OPTIMIZATION

The parametric models presented and developed in this chapter can be coupled with cost models and then optimized by various optimization methods for desired economic measure of merit and other cost functions. Methods currently available will be briefly outlined here.

11.6.1 Nonlinear Programming

Classical nonlinear programming methods were reviewed in Parsons (48). Nonlinear programming is usually used in early ship design with a scalar cost function such as the Required Freight Rate. A weighted sum cost function can be used to treat multiple objective problems by converting the multiple objectives $f_i(\mathbf{x})$ to a single scalar cost function. These methods can also be used to obtain a Min-Max solution for multicriterion problems.

The phrase Multi-discipline Optimization (MDO) is often used to apply to optimization problems involving various disciplinary considerations such as powering, seakeeping, stability, etc. Nonlinear programming applications in early ship design have done this for over 30 years. Note that MDO is not synonymous with the Multicriterion Optimization described below.

The typical formulation for nonlinear programming optimization with λ objectives would be as follows:

Formulation:

$$\min_{\mathbf{x}} F = \sum_{i=1}^{\lambda} w_i \; f_i(\mathbf{x}) \quad [94]$$

subject to

equality constraints $h_j(\mathbf{x}) = 0, \quad j = 1,\ldots, m$

inequality constraints $g_k(\mathbf{x}) \geq 0, \quad k = 1,\ldots, n$

with

$f_i(\mathbf{x})$ = cost or objective function i

w_i = weight on cost function i

This optimization problem can be solved by many numerical procedures available today. An example of the one of the most comprehensive packages is LMS OPTIMUS (69). It has a convenient user interface for problem definition and uses Sequential Quadratic Programming (SQP) for the numerical solution.

Small design optimization problems such as that implemented in the Propeller Optimization Program (40) can utilize much simpler algorithms. In this particular example, the Nelder and Mead Simplex Search is used with the constrained problem converted to an equivalent unconstrained problem min $P(\mathbf{x},r)$ using an external penalty function defined as,

$$P(\mathbf{x},r) = f(\mathbf{x}) - r \sum_{k=1}^{n} \min(g_k(\mathbf{x}), 0) \quad [95]$$

where r is automatically adjusted by the code to yield an effective penalty (48). If the equality constraints can be solved explicitly or implicitly for one of the x_i

this allows the number of unknowns to be reduced. Alternatively, an equality constraint can be replaced by two equivalent inequality constraints: $h_j(\mathbf{x}) \leq 0$ and $h_{j+1}(\mathbf{x}) \geq 0$.

11.6.2 Multicriterion Optimization and Decision Making

An effort in recent years has been directed toward methods that can be applied to optimization problems with multiple criteria that can appear in marine design (70, 71, 72). In most cases this is a matter of formulation where issues previously treated as constraints are moved to become additional criteria to be optimized.

11.6.2.1 The Analytical Hierarchy Process

There are a number of ship design optimization and design selection problems that can be structured in a hierarchy of influence and effects. The Analytical Hierarchy Process (AHP) introduced by Saaty (73) can be used to treat these problems. This method is well presented by Saaty (73) and Sen and Yang (72) and will not be presented further here. Marine applications are given by Hunt and Butman (74). AHP has also been used in ship design tradeoff studies to elicit relative values, see Singer et al (75).

11.6.2.2 Pareto and Min–Max Optimization

The optimization with multiple criteria requires a careful definition of the optimum. The classical approach seeks a Pareto optimum in which no criterion can be further improved without degrading at least one of the other criteria. In general, this logic results in a set of optimum solutions. This situation is shown for a simple problem that seeks to maximize two criteria subject to inequality constraints in Figure 11.29. The figure shows the objective function space with axes for the two criteria $f_1(\mathbf{x})$ and $f_2(\mathbf{x})$. The feasible constrained region is also shown. The set of solutions that provides the Pareto Optimum is identified. At ends of this set are the two separate solutions f_1° and f_2° that individually optimize criteria one and two, respectively. Engineering design typically seeks a single result. The Min-Max solution provides a logical way to decide which solution from the Pareto optimum set to use.

A logical engineering solution for this situation is to use the one solution that has the same relative loss in each of the individual criteria relative to the value achievable considering that criterion alone f_i°. The relative distance to the f_i° are defined by the following ,

$$z_i'(\mathbf{x}) = |\, f_i(\mathbf{x}) - f_i^\circ \,| / |f_i^\circ| \qquad [96]$$

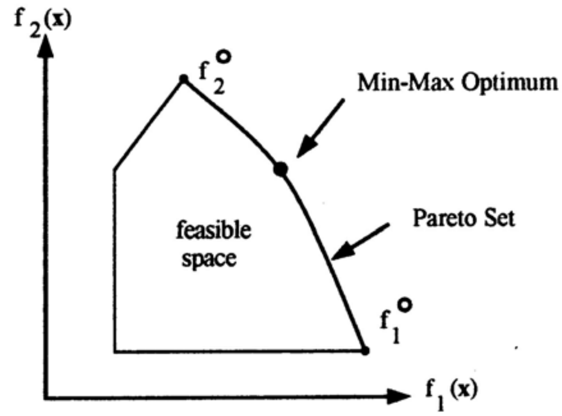

Figure 11.29 - Illustration of Pareto and Min-Max Optima

$$z_i''(\mathbf{x}) = |\, f_i(\mathbf{x}) - f_i^\circ \,| / |f_i(\mathbf{x})| \qquad [97]$$

where the first will govern for a minimized criterion and the latter will govern for a maximized criterion. The algorithm uses the maximum of the these two measures,

$$z_i(\mathbf{x}) = \max(z_i'(\mathbf{x}), z_i''(\mathbf{x})) \qquad [98]$$

The Min-Max optimum $y(\mathbf{x}^*)$ is then defined by the following expression,

$$y(\mathbf{x}^*) = \min_{\mathbf{x}} \max_{i} (z_i(\mathbf{x})) \qquad [99]$$

where the maximization is over the objective criteria i and the minimization is over the independent variable vector $\mathbf{x}$. The resulting solution is shown in Figure 11.29. This solution cannot achieve any of the f_i°, but is a compromise solution that has the same relative loss with respect to each of the f_i° that bound the Pareto set. This yields a reasonable engineering compromise between the two competing criteria.

11.6.2.3 Goal Programming

An alternative optimization formulation for multiple criterion problems is called goal programming (70, 71, 72, 76). This approach treats multiple objective functions and selected constraints as goals to be approached or met in the solution. There are two approaches for formulating these problems: Preemptive or Lexicographical goal programming and Archimedian goal programming. These two can be blended into the same formulation when this is advantageous (72).

Preemptive or Lexicographical goal programming solves the problem in stages. The solution is obtained for the first (most important) goal and then the problem is solved for the second goal with the added constraint that the first goal result cannot be degraded, etc. The process continues until all goals are treated or a single solution results. The approach restates the traditional objective functions as goals that are treated as additional equality constraints using positive slack or deviation variables $d_k^{\pm}$ defined to achieve the equalities. The cost function Z then involves deviation functions h_i that are selected to produce the desired results relative to satisfying these goals.

Formulation:

$$\min_{\mathbf{x}} Z = (P_1\, h_1(d_1^-, d_1^+), P_2\, h_2(d_2^-, d_2^+), \ldots, P_{n+m}\, h_{n+m}(d_{n+m}^-, d_{n+m}^+)) \qquad [100]$$

subject to goal achievement

$$f_i(\mathbf{x}) + d_i^- - d_i^+ = b_i, \qquad i = 1,\ldots, n$$

and constraints

$$g_j(\mathbf{x}) + d_j^- - d_j^+ = 0, \qquad j = 1,\ldots, m$$

with

$f_i(\mathbf{x})$ = goal i

b_i = target value for goal i

$g_j(\mathbf{x})$ = constraint j ≥ 0, ≤ 0, or $= 0$

d_k^- = underachievement of goal i $\geq b_i$, or constraint j, k= i or n + j, $d_k^- \geq 0$

d_k^+ = overachievement of goal i $\geq b_i$, or constraint j, k= i or n + j, $d_k^+ \geq 0$

P_i = priority for goal i achievement, $P_i >> P_{i+1}$

The priorities P_i are just symbolic meaning the solution for goal 1 is first, with the solution for goal 2 second subject to not degrading goal 1, etc. The numerical values for the P_i are not actually used. The deviation functions $h_i(d_i^-, d_i^+)$ are selected to achieve the desired optimization result, for example,

desired result form of $h_{i \text{ or } j}$	function
goal/constraint reached exactly	
$h_i(d_i^-, d_i^+) = (d_i^- + d_i^+)$	(= b_i goal or = 0 constraint)
goal/constraint approached from below	
$h_i(d_i^-, d_i^+) = (d_i^+)$	($\leq b_i$ goal or ≤ 0 constraint)
goal/constraint approached from above	
$h_i(d_i^-, d_i^+) = (d_i^-)$	($\geq b_i$ goal or ≥ 0 constraint)

Archimedian goal programming solves the problem just a single time using a weighted sum of the deviation functions. Weights w_i reflect the relative importance and varying scales of the various goals or constraints. The deviation functions are defined in the same manner as in the Preemptive approach.

Formulation:

$$\min_{x} Z = (h_1(w_1^- d_1^-, w_1^+ d_1^+) + h_2(w_2^- d_2^-, w_2^+ d_2^+) + \ldots + h_{n+m}(w_{n+m}^- d_{n+m}^-, w_{n+m}^+ d_{n+m}^+)) \qquad [101]$$

subject to goal achievement

$$f_i(\mathbf{x}) + d_i^- - d_i^+ = b_i, \qquad i = 1,\ldots, n$$

and constraints

$$g_j(\mathbf{x}) + d_j^- - d_j^+ = 0, \qquad j = 1,\ldots, m$$

with

$f_i(\mathbf{x})$ = goal i

b_i = target value for goal i

$g_j(\mathbf{x})$ = constraint j ≥ 0, ≤ 0, or $= 0$

d_i^- = underachievement of goal i $\geq b_i$, or constraint j, k= i or n + j, $d_k^- \geq 0$

d_k^+ = overachievement of goal i $\geq b_i$, or constraint j, k= i or n + j, $d_k^+ \geq 0$

$w_k^{\pm}$ = weights for goal i or constraint j, k = i or n + j, underachievement or overachievement deviations

In formulating these problems care must be taken to create a set of goals, which are not in conflict with one another so that a reasonable design solution can be obtained. Refer to Skwarek (77) where a published goal programming result from the marine literature is shown to be incorrect primarily due to a poorly formulated problem and ineffective optimization stopping.

11.6.3 Genetic Algorithms

The second area of recent development in design optimization involves genetic algorithms (GA's), which evolved out of John Holland's pioneering work (78) and Goldberg's engineering dissertation at the University of Michigan (79). These optimization algorithms typically include operations modeled after the natural biological processes of natural selection or survival, reproduction, and mutation. They are probabilistic and have the major advantage that they can have a very high probability of locating the global optimum and not just one of the local optima in a problem. They can also treat a mixture of discrete and real variables easily. GA's operate on a population of potential solutions (also called individuals or chromosomes) at each iteration (generation) rather than evolve a single solution, as do most conventional methods. Constraints can be handled through a penalty function or applied directly within the genetic operations. These algorithms require significant computation, but this is much less important today with the dramatic advances in computing power. These methods have begun to be used in marine design problems including preliminary design (80), structural design (81), and the design of fuzzy decision models for aggregate ship order, second hand sale, and scrapping decisions (66, 82).

In a GA, an initial population of individuals (chromosomes) is randomly generated in accordance with the underlying constraints and then each individual is evaluated for its fitness for survival. The definition of the fitness function can achieve either minimization or maximization as needed. The genetic operators work on the chromosomes within a generation to create the next, improved generation with a higher average fitness. Individuals with higher fitness for survival in one generation are more likely to survive and breed with each other to produce offspring with even better characteristics, whereas less fitted individuals will eventually die out. After a large number of generations, a globally optimal or near-optimal solution can generally be reached.

Three genetic operators are usually utilized in a genetic algorithm. These are selection, crossover, and mutation operators (66 & 79). The selection operator selects individuals from one generation to form the core of the next generation according to a set random selection scheme. Although random, the selection is biased toward better-fitted individuals so that they are more likely to be copied into the next generation. The crossover operator combines two randomly selected parent chromosomes to create two new offspring by interchanging or combining gene segments from the parents. The mutation operator provides a means to alter a randomly selected individual gene(s) of a randomly selected single chromosome to introduce new variability into the population.

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