

2.1.2 Fuel and Miscellaneous Weights

Fuel [5]

$$Wf = \frac{SHP \times Dst \times 1.1 \times SFC}{Vk \times 10^6} \quad (2.15)$$

where

SHP = Maximum continuous shaft horsepower

Dst = Range in nautical miles defined by the user. In this work, it is defined as 7000 nautical miles.

SFC = Specific fuel consumption defined by the user. In this work, it is defined as 120 Gms/ SHP/ hr

Vk = speed in knots

In (2.15), the 1.1 in the numerator indicates that we provide a ten percent allowance to the total round trip distance. The 10^6 in the denominator is the conversion to convert grams to metric tons since the specific fuel consumption is defined in Gms/ SHP/ hr and the fuel weight is expressed in metric tons.

The KG of fuel is approximated assuming fuel in wing deep tanks, using a weighting factor.

$$KGf = Wf \times \left(\frac{6.1}{3385} \right) \quad (2.16)$$

This ratio is an approximation obtained from data [5] that 3385 metric tons of fuel stored in wing deep tanks has a vertical center of gravity of 6.1 meters.

Miscellaneous

Crew and Provisions: [2]

$$Wcp = [(6 \times Dst) + 50] \times Cf \quad (2.17)$$

Freshwater: [2]

We will choose the following approximation over a more accurate relation involving the displacement since we do not want to involve displacement in the weight calculations.

$$Wfw = 280 \times Cf \quad (2.18)$$

Luboil for diesel: [2]

$$Wlo = 50 \times Cf \quad (2.19)$$

Miscellaneous weights when machinery is idle: [2]

$$Whc = 5 \times Pwt \times Cf \quad (2.20)$$

where

Pwt = Port waiting time in days defined by the user. In this work, it is defined as 2 days.

Therefore Total Miscellaneous Weight:

$$W_{misc} = W_{cp} + W_{fw} + W_{lo} + W_{hc} \quad (2.21)$$

Vertical center of gravity of miscellaneous weight [5]

$$KG_{misc} = 0.5 \times D \quad (2.22)$$

2.2 Summary of the Cost Module

The total cost is comprised of building and operating costs. The building cost of the ship can be converted to uniform annual amounts using a capital recovery factor. The operating cost and the fuel cost are calculated on an annual basis. All costs are in U.S. dollars.

2.2.1 Annual Building Costs [6], [2], [10]

Building costs are broken down into steel hull, outfit and hull engineering and machinery costs. Each of these constitutes costs for material and labor. Material costs are a function of the weight. Labor costs are functions of the man-hours that in turn are functions of the weight.

Throughout this module we use a labor cost of 20 dollars per hour. Overheads are calculated as 70 percent of the labor costs. Further, since these formulas were developed in 1962, we use the following approximations to accommodate the present day trends:

- reduce man-hours by sixty percent to account for automation,
- increase material costs by 40 percent .

Steel Hull

$$Man\text{-}hours: Mhs = C_{mhs} \times \left(\frac{W_s}{1000} \right)^{0.85} \quad (2.23)$$

where

C_{mhs} is a coefficient depending on the effectiveness of the yard. We assume a fixed value of $3160 = 7900 \times 0.4$

$$Labor: Lhs = Mhs \times Lc \quad (2.24)$$

where

Lc = Unit labor cost defined by the user. In this work, it is defined as 20 dollars/ hour.

$$\text{Material: Mats} = \text{Csh} \times \text{Ws} \quad (2.25)$$

where

Csh = Cost of hull steel material defined by the user. In this work it is defined as 400 dollars/ metric ton.

Outfit

$$\text{Man-hours: Mho} = \text{Co} \times \left(\frac{\text{Wo}}{100} \right)^{0.9} \quad (2.26)$$

where

Co is a coefficient with a fixed value of $8000 = 20000 \times 0.4$

$$\text{Labor: Lo} = \text{Mho} \times \text{Lc} \quad (2.27)$$

$$\text{Material: Mato} = \text{Cof} \times \text{Wo} \quad (2.28)$$

where

Cof = Cost of outfit material defined by the user. In this work it is defined as 1500 dollars/ metric ton.

Hull Engineering

$$\text{Man-hours: Mhhe} = \text{Chhe} \times \left(\frac{\text{Whe}}{100} \right)^{0.75} \quad (2.29)$$

where

Chhe is a coefficient with a fixed value of $20400 = 51000 \times 0.4$

$$\text{Labor: Lhe} = \text{Mhhe} \times \text{Lc} \quad (2.30)$$

$$\text{Material: Mathe} = \text{Chull} \times \text{Whe} \quad (2.31)$$

where

Chull = Cost of hull engineering material defined by the user. In this work it is defined as 3500 dollars/ metric ton.

Machinery

$$\text{Man-hours: Mhm} = \text{Chm} \times \left(\frac{\text{SHP}}{1000} \right)^{0.6} \quad (2.32)$$

where

Chm has a fixed value of $6773.33 = 25400 \times 0.4 / 1.5$

$$\text{Labor: } L_m = M_{hm} \times L_c \quad (2.33)$$

$$\text{Material: } M_{atm} = C_{mm} \times \left(\frac{\text{SHP}}{1000} \right)^{0.6} \quad (2.34)$$

where

C_{mm} is a coefficient with a fixed value of $388666.67 = 583000 / 1.5$

Miscellaneous Costs

This involves costs that are not related to any of the weight categories. These include drafting, purchasing, blueprints, scheduling, model tests, material handling, cleaning, launching, staging, dry-dock, tests and trials, classification etc.

It is 10 percent of the subtotal of the material costs.

$$\text{Misc} = 0.10 \times (M_{at} + M_{at0} + M_{at1e} + M_{atm}) \quad (2.35)$$

Accommodation Costs

These are approximated as a function of the number of crew.

$$\text{Accoc} = 180,000 \times N_{crew}^{0.56} \quad (2.36)$$

where

N_{crew} = Number of crew.

N_{crew} is estimated in operating costs (section 2.2.3).

Overhead Costs

These include all costs, which cannot be directly charged to any one contract, such as officers' salaries, taxes, depreciation, watchmen, utilities etc.

This is 70 percent of total labor.

$$\text{Ovhc} = 0.70 \times (L_{hs} + L_o + L_{he} + L_m) \quad (2.37)$$

Yard's total

Y_{tc} ; It is the sum of all the above components.

Yard's Profit

This is 5 percent of the Yard's total.

$$\text{Pr} = 0.05 \times Y_{tc} \quad (2.38)$$

Yard's building price

This is the sum of the Yard's total and Profit.

$$Y_{bc} = Y_{tc} + \text{Pr} \quad (2.39)$$

Owner's expenses

This accounts for the costs involved in surveying and inspection, and is 5 percent of the yard's building price.

$$Owe = 0.05 \times Ybc \quad (2.40)$$

Cost to owner

This is the sum of Yard's building price and Owner's expenses.

$$Owc = Ybc + Owe \quad (2.41)$$

For uniform annual amounts we use a capital recovery factor which is defined as:

$$Cr = \left[\frac{(1 + Ir)^{Sl} \times Ir}{(1 + Ir)^{Sl} - 1} \right] \quad (2.42)$$

where

IR = Interest rate in percentage defined by the user. In this work it is defined as 0.08.

Sl = Ship life in years defined by the user. In this work it is defined as 20.

Therefore Annual Building Cost :

$$Abc = Owc \times Cr \quad (2.43)$$

Before we go on to calculate the operating costs, we need to calculate the number of round trips made annually by the ship. This is required to calculate the cargo handling, port and fuel costs.

2.2.2 Round trip time [11]

The total time for a round trip comprises of the times required for loading and unloading cargo, the waiting time in port and the time spent at sea.

Time for loading/ unloading per round trip

$$Lut = 4 \times \frac{TEU_f}{TSLU \times Ncrane_f} \quad (2.44)$$

where

TEU_f = Total number of TEUs, continuous

TSLU = TEUs loaded/ unloaded per day per crane defined by the user. In this work, it is defined as 1440.

Ncrane_f = Number of cranes, continuous.

A single crane is can handle 1440 TEUs per day [12]. The total number of TEUs loaded/ unloaded per day can be calculated as: TSLU \times Ncrane. The number of cranes can be

calculated based on the formula that one crane can be accommodated every 135 feet over 75 percent of the ship length.

$$N_{\text{crane}_i} = \left\lceil \frac{0.75 \times \text{Loa}}{41.175} \right\rceil + 1 \quad (2.45)$$

where

N_{crane_i} = Number of cranes, integer

The square brackets indicate that the number within is truncated to an integer.

This number is seen to be a discontinuous function of Loa that induces a discontinuity in the objective function. The following equation obtained through a least squares fit, as shown in Figure 2.1, makes it continuous:

$$N_{\text{crane}_f} = (0.0187 \times \text{Loa}) + 0.3572 \quad (2.46)$$

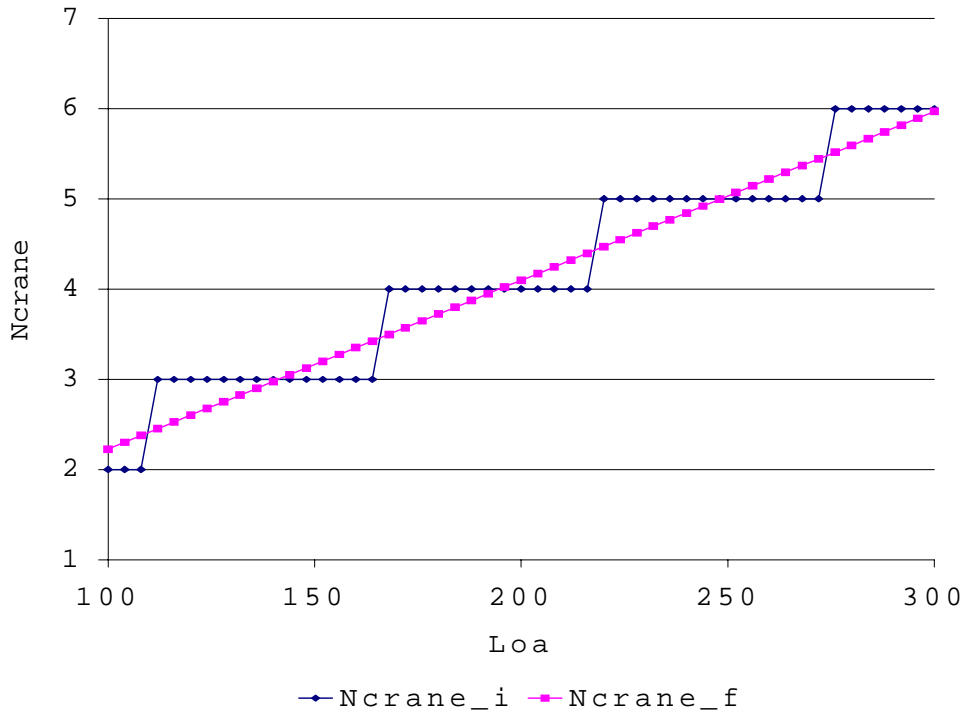


Figure 2.1: Number of cranes as a function of Loa

Waiting time in port

The waiting time in port is assumed to be constant for a given route. It is the time spent in port waiting for availability of cranes and for maintenance. When analyzing different routes, the waiting time will be a function of the number of port calls. In this model we assume a waiting time of two days per round trip.

Time at sea

The time at sea per round trip in days is given by

$$St = \frac{Dst}{24 \times V_k} \quad (2.47)$$

Therefore the total round trip time in days can be calculated as:

$$\mathbf{Rtt} = Lut + Pwt + St \quad (2.48)$$

Therefore the number of trips per year is:

$$\mathbf{NT} = \frac{Ot}{Rtt} \quad (2.49)$$

where

Ot = On-hire time per year in days is defined by the user. In this work it is defined as 350 days.

2.2.3 Annual Operating Costs [6], [10]

Wages

First we estimate the number of crew:

$$N_{crew} = C_{st} \times \left[C_{dk} \times \left(\frac{CN}{1000} \right)^{1/6} + C_{eng} \times \left(\frac{SHP}{1000} \right)^{1/5} \right] \quad (2.50)$$

where

C_{st} = Coefficient for stewards department = 1.25

C_{dk} = Coefficient for the deck department = 15.4

C_{eng} = Coefficient for the engine department = 10

$$Wage = (27000 \times 1.4) \times N_{crew}^{4/5} \quad (2.51)$$

We have accounted for the fact that automation will replace manpower to a large extent, the above relation avoids use of a flat rate per man.

Stores and Supplies

$$S_s = (80 \times 1.4) \times \left(\frac{N_{crew}}{10} \right)^4 \quad \text{if } N_{crew} \text{ is less than 50} \quad \text{OR} \quad (2.52)$$

$$S_s = [50,000 + 4000 \times (N_{crew} - 50)] \times 1.4 \quad \text{otherwise} \quad (2.53)$$

Insurance

Protection and Indemnity:

$$\text{InsPI} = 965 \times 1.4 \times \text{Ncrew} \quad (2.53)$$

Hull and Machinery :

$$\text{InsHM} = [10,000 + 0.007 \times (\text{Mathe} + \text{Mats} + \text{Mato} + \text{Matm} + \text{Lm} + \text{Lhs} + \text{Lo} + \text{Lhe})] \times 1.4 \quad (2.54)$$

Maintenance and Repair

$$\text{Hull:} \quad \text{Mrh} = \left[108000 \times \left(\frac{\text{CN}}{1000} \right)^{\frac{2}{3}} \times 1.4 \right] \quad (2.55)$$

$$\text{Machinery:} \quad \text{Mrm} = \left[10000 \times \left(\frac{\text{SHP}}{1000} \right)^{\frac{2}{3}} \times 1.4 \right] \quad (2.56)$$

Port Expenses

$$\text{Port} = \left[20 + 290 \times \left(\frac{\text{CN}}{1000} \right) \right] \times \text{Pwt} \times \text{NT} \quad (2.57)$$

Cargo handling Costs

$$\text{Chld} = 50 \times \text{Wcargo} \times \text{NT} \times 2 \quad (2.58)$$

where

Wcargo = weight of cargo in metric tons

Therefore Annual Operating Cost :

$$\text{Aoc} = \text{Wage} + \text{Ss} + \text{InsPI} + \text{InsHM} + \text{Port} + \text{Chld} \quad (2.59)$$

2.2.4 Annual Fuel Cost

The annual fuel cost is given by

$$\text{Afc} = \text{Wf} \times \text{Fcost} \times \text{NT} \quad (2.60)$$

where

Fcost = Cost of bunker C fuel oil is defined by the user. In this work, we used 80 dollars/ metric ton.

Therefore Annual Average Cost:

$$Aac = Abc + Aoc + Afc \quad (2.61)$$

2.3 Measures of Merit

2.3.1 Freight Rate

The required freight rate, expressed in dollars per ton per mile, simply stated is the amount the owner charges the customer to break-even. A more precise definition from [7] is: "The required freight for a given rate of utilization produces net profits which exactly cover the operating costs inclusive of calculated interest on the invested capital".

Therefore the required freight rate, RFR, is given by

$$RFR = \frac{Aac}{NT \times W_{cargo} \times Dst} \quad (2.62)$$

2.3.2 Return on Investment

The return on investment, expressed in percentage per year, is defined as the ratio of the difference in the annual gross income and the annual operating costs to the invested capital. The annual gross income is calculated by defining a charge rate expressed in dollars per ton. Five percent of the depreciated value of the investment, which is a reasonable value, is included in the gross income to account for the salvage value of the ship assuming that the ship is in operable condition throughout its expected life-time, which is identified by the user. In this work the ship life is defined as 20 years.

$$ROI = \frac{\text{annual gross income} - \text{annual average cost} + \text{salvage value of the ship}}{\text{invested capital}} \times 100$$

Therefore the return on investment, ROI, is given by

$$ROI = \frac{(\text{Chargerate} \times W_{cargo} \times NT) - Aac + \left[\frac{0.05 \times Ow_c}{(1 + Ir)^{SI}} \right]}{Ow_c} \times 100 \quad (2.63)$$

Charge rate is defined by the user. In this work it is defined as 44.8 dollars/ metric ton.

2.4 Constraints on the Design

We impose five constraints on the design. The constraint that the displacement equals the weight is mandatory. The inequality constraint involving the length to draft ratio is implied in the formulation and is also mandatory. Mandatory means that the user does not

have the freedom to remove these constraints. The other three constraints involve the Coast Guard Wind heel criterion for metacentric height, the minimum required freeboard from the freeboard tables [5] and a constraint on the rolling period [5]. A description of these constraints is as follows:

$$1) \quad \text{Weight} = \text{Displacement} \quad (2.64)$$

$$2) \quad \frac{Loa}{D} \geq 8.3 \quad \text{implied by (2.2)} \quad (2.65)$$

3) The Coast Guard wind heel criterion for metacentric height [13]

$$GM \geq \frac{P \times LA \times H}{\text{Disp} \times \tan(\hat{\epsilon})} \quad (2.67)$$

where

$$P = 0.036 + \left(\frac{LBP}{1309} \right)^2 \quad \text{metric tons/ meter}^2$$

LA = projected lateral area in meter² of the portion of the vessel and deck cargo above the waterline.

$$= Loa \times (D - T) + (Ntd \times 2.4 \times Loa)$$

H = the vertical distance from the center of A to the center of the underwater lateral area or to the one-half draft point.

$$= \frac{Loa \times 0.5 \times [(D - T)^2 + (Ntd \times 2.4)^2]}{LA}$$

$$\tan(\hat{\epsilon}) = \frac{(D - T)}{\left(\frac{B}{2}\right)}$$

4) Minimum required Freeboard from the freeboard tables [5]

$$\text{Freeboard} \geq \text{Freeboard}_{\min} \quad (2.68)$$

The following expression is obtained by fitting a curve using the method of least squares through the one hundred and fourteen points given in the freeboard tables [5] governed by the code of federal regulations for freeboard (46 CFR 42). The curve is shown in Figure 2.2.

$$\text{Freeboard}_{\min} = 0.025633 \times Loa^{0.9146} \quad (2.69)$$

Correction in (2.69) for the block coefficient.

If $C_b > 0.68$, multiply (2.69) by $\frac{C_b + 0.68}{1.36}$

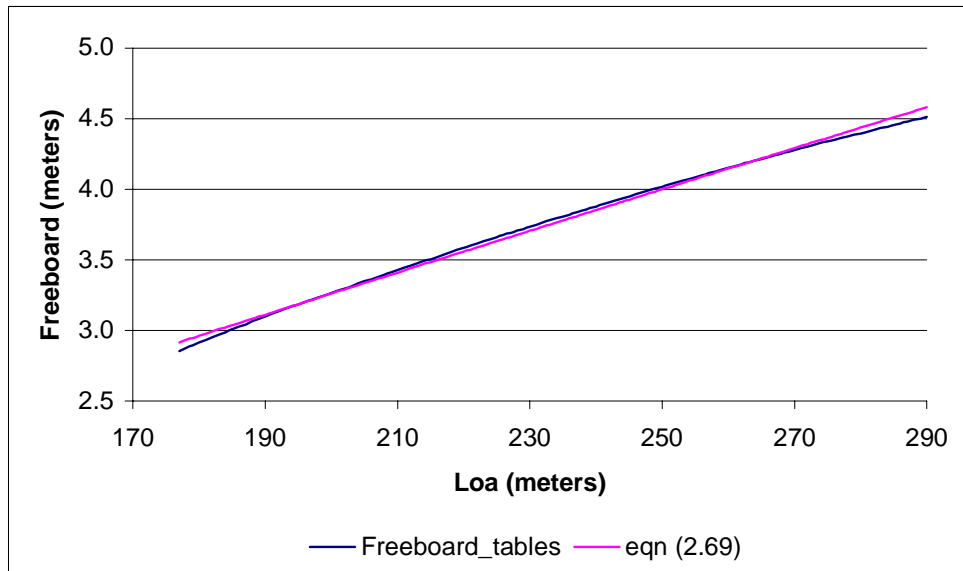


Figure 2.2: Freeboard as a function of Loa

Correction in (2.69) for the length to draft ratio.

If $\frac{L}{D} < 15$, add $\left(D - \frac{L}{15}\right) \times 0.25$ to (2.69)

5) **Minimum Rolling Period [5]**

$$\text{Troll} \geq \text{Troll}_{\min} \quad (2.70)$$

where
an expression for the rolling period [5] is:

$$\text{Troll} = 0.58 \sqrt{\frac{B^2 + (4 \times KG^2)}{|GM|}}$$

and
Troll_{min} is defined by the user. In this work it is defined as 15 seconds.