IMO CALLS FOR 50% GHG REDUCTION IN SHIPS BY 2050 COMPARED TO 2008 LEVELS
Cover art by Lily Keyes.

The front cover symbolizes the ravages of climate change, modified by improvements in greenhouse gas emissions, leading to recovery. The back cover illustrates the range of applicability of the code described in this report, including ship types, ballast conditions, and decarbonization methods and technologies.

The bleached coral photo (front cover, bottom left) is courtesy of Vardhan Patankar at Wikimedia Commons licensed under the Creative Commons Attribution-Share Alike 4.0 International license, https://creativecommons.org/licenses/by-sa/4.0/legalcode.

The healthy coral photo (front cover, bottom right) is courtesy of Keith Ellenbogen, MIT Sea Grant Visiting Artist, https://www.keithellenbogen.com. The GHG emissions plot (front cover, top center) is courtesy of Tony Linden, DNV GL. The RTX-5 engine photo (back cover, bottom right) is courtesy of Wärtsilä.
In an effort to combat climate change, the International Maritime Organization (IMO) has set ambitious goals for the reduction of greenhouse gas emissions from ships, with a target of at least a 50% reduction of total annual greenhouse gas (GHG) emissions, including carbon, from 2008 levels by 2050, with a further goal of zero GHG emissions within this century [22]. Numerous interim goals guide the cargo fleet toward the 50% by 2050 target. It will take the combination of a large variety of actions and technology advancements to achieve these goals. Long-term possibilities such as the development and shipboard implementation of new fuels, renewable energy, and energy storage will have a huge impact on shipboard CO2 production, but there is great uncertainty about which of these technologies will become the best option for both the earth and the shipping companies. Numerous actions can be taken immediately to reduce the carbon production and extend the useful life of currently existing ships within the new GHG requirements, allowing ship owners time to assess new technologies before committing to new-construction vessels that incorporate them.

This report describes a methodology and computer code that provide a rapid assessment of the impact of various fuel-saving technologies on a cargo ship’s fuel consumption, thus providing the ship owner fundamental data indicating which technologies and practices warrant further, more detailed investigation. These fuel-saving technologies and practices include slow steaming, engine modifications, bulbous bow removal, propeller optimization, and the installation of energy saving devices that modify flow through the propeller.

The assessment of a ship’s performance uses a small amount of data readily accessible to the ship owner; it is assumed that the data available for the candidate vessel is insufficiently detailed to accomplish a full computational fluid dynamics (CFD) analysis, so various standard estimation methodologies are employed as described herein. The minimum data required include ship type, length, beam, draft, displacement, design speed, number of propellers, engine layout data, and indication of the presence of a bulbous bow or energy-saving device. The accuracy of resistance estimates can be improved by increasing the amount of data provided to the program including information such as bulbous bow dimensions, longitudinal center of buoyancy, hull shape coefficients, surface areas, and propeller details. If these additional data are not provided, the program estimates input values.

Results are provided in terms of fuel usage and savings for each potential modification and for combinations of modifications, showing tonnes/day of fuel over a range of speeds. Estimates for both fully-laden and ballast condition are provided.

The code has been applied to a wide variety of ship types including supertankers, product tankers, bulk carriers and container ships of various sizes, and the results were compared to actual measured data for the ships operating at sea, with very good correlation between the estimates and the measured data. The resistance estimates are better with greater fidelity of input data. They are most accurate within the friction-dominated speeds, showing differences from measured data in the range of three percent. Accuracy of results can drop somewhat at high, wave-dominated speeds, especially for ships with bulbous bows.

The code is written in Matlab and is available online at https://seagrant.mit.edu/decarbonization.

The attached report describes the underlying methodology, provides an overview and user’s guide for the code, presents several examples, and makes some concluding remarks and suggestions for future work.

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Decarbonization of the Cargo Shipping Fleet

I. BACKGROUND

According to the National Oceanic and Atmospheric Administration, the amount of carbon dioxide in the atmosphere has increased by 1.78 ppm per year on average since 1980, and the increase is accelerating. Through the 1980s and 1990s, the increase was around 1.5-1.6 ppm per year, but the growth rate has averaged 2.4 ppm per year since 2010 [24].

Rising levels of carbon dioxide in the atmosphere adversely impact the environment in many ways. For example, increased levels of carbon dioxide dissolving in sea water increase the acidity of the oceans; as pH levels drop, organisms like oysters and corals have trouble maintaining their hard shells and skeletons made from calcium carbonate. If pH levels get too low, the calcium carbonate structures begin dissolving [19]. Another example can be found in the NOAA Arctic Report Card which each year shows an Arctic that is becoming warmer, less frozen and more fragile; the 2020 report includes data on high land-surface air temperatures, low snow extent, low minimum sea-ice extent, and extreme wildfires [25].

Shipping is the most carbon-efficient method of transporting cargo per tonne-km of cargo moved; a very large crude carrier (VLCC) ship emits 3 grams of carbon per tonne-km of cargo, compared to 80 for a 40-tonne truck and 435 for a 747 aircraft [4]. However, the efficiency of cargo shipping is juxtaposed against the sheer quantity of goods transported by ship over vast distances; per the UN Review of Marine Transport [21], approximately 80% of world trade by volume, or 70% by value, is carried by ship. This results in cargo shipping contributing between 2 and 3% of total worldwide carbon emissions per year.

In an effort to combat climate change, the International Maritime Organization (IMO) has set ambitious goals for the reduction of greenhouse gas emissions from ships, with a target of at least a 50% reduction of total annual greenhouse gas (GHG) emissions, including carbon, from 2008 levels, by 2050 [22]. Zero GHG emissions are desired sometime within this century. Numerous interim goals step the cargo fleet toward the 50% by 2050 target.

Combining a large variety of actions and technology advancements will be required to achieve these goals. Long-term possibilities such as the development and shipboard implementation of new fuels, renewable energy, and energy storage will have a huge impact on shipboard CO2 production, but there is great uncertainty about which of these technologies will become the best option for both the earth and the shipping companies.

While the research and development required to bring these new technologies to fruition is being accomplished, numerous actions can be taken immediately to reduce the carbon production and extend the useful life of currently existing ships within the new GHG requirements, thus allowing ship owners time to assess new technologies before committing to new-construction vessels that incorporate them.

II. INTRODUCTION

We have constructed an easy-to-use computer code that provides ship owners fundamental data indicating which technologies and practices are likely to have a significant impact on the owner’s fleet by providing an assessment of the impact of various fuel-saving technologies on a specific cargo ship’s fuel consumption. These fuel-saving technologies and practices include slow steaming, engine modifications, bulbous bow removal, propeller optimization, and energy-saving devices that modify the hull. For each modification or combination of modifications, the code provides quantified impact in terms of specific fuel consumption and tons per day for a given loading condition of a given ship.

The computer code created through this project accomplishes a rapid assessment of a ship’s performance using a small amount of data. The code is designed to be easy to use, depending on ship data that is readily available to the ship owner.

The code calculates the ship resistance over a range of speeds, estimates propeller performance, and predicts engine performance, all at design draft. If ballast draft information is provided, similar calculations are accomplished at ballast condition as well. The code also estimates ship performance with the bulbous bow removed, with an energy saving device installed, with various engine modifications implemented, or with a modified propeller designed for a different design speed, and with combinations of these modifications. The primary metric for comparison is fuel consumption.

This document is arranged as follows. Section III provides an overview of the code structure and input data. Sections IV through VIII provide the theoretical background supporting hull, propeller and engine calculations. Section IX describes the methodology for assessing the impact of ship modifications on fuel consumption. Section X describes the calculations and estimates required to round out the data set. The code is used to analyze various ship types and the results are compared to actual ship performance; these examples are provided in Section XI. A user’s manual is provided in Section XII. Additional discussion of bulbous bows is provided in the Appendix, followed by a glossary of terms, symbols and abbreviations. Conclusions and recommendations for future work are included in Section XIII.

III. CODE OVERVIEW

Following is an overview of the program structure. Theoretical underpinnings of each segment along with a user’s guide can be found in the subsequent sections. The original concept of the code is based on work by Bonfiglio [3].
A. Data Input

Input data are provided by the user in an Excel file. The minimum data required include ship type, length, beam, draft, displacement, design speed, number of propellers, engine layout data, and indication of the presence of a bulbous bow or energy-saving device. The accuracy of resistance estimates can be improved by increasing the amount of data provided to the program including information such as bulbous bow dimensions, longitudinal center of buoyancy, hull shape coefficients, surface areas, and propeller details. If these additional data are not provided, the program estimates input values.

Since full hullform and propeller models of sufficient detail to accomplish a full computational fluid dynamics (CFD) analysis of a hull are not typically available, we use instead various standard estimation methodologies for ship and propeller performance.

Incorporated into the program is a library of engines, including a wide range of MAN B&W and Wärtsilä marine diesel engines plus a few from other manufacturers. The library is stored in an Excel spreadsheet, to which the user may add new engines if desired.

During the data input period, the program reads and parses the input data, estimates missing data as appropriate, and sets constants.

B. As-Built Ship Calculations

For each ship in the input database, the following calculations are conducted:

1) Calculations at Design Draft: 
   a) Ship Resistance: Ship resistance is calculated at design draft using the Holtrop & Mennen procedure for tankers and bulkers or the Hollenbach procedure for container ships, producing curves of resistance and effective power over a range of speeds. Resistance estimates include frictional resistance, form factor, appendage resistance, wave resistance, bulbous bow impact, air resistance, and correlation allowance. Details are provided in Section IV and Section V.
   b) Propeller Performance: Propeller performance is calculated using the Wageningen B-Series propeller regression formulas and the input data. If expanded area ratio (AE/AO) or pitch to diameter ratio (P/D) are not provided by the user, then the program designs a propeller that produces the lowest fuel oil consumption at design speed when coupled with the given engine, while limiting cavitation. Once AE/AO and P/D are set, the program calculates propeller efficiency, estimates hull efficiency and relative rotative efficiency, and uses the input shaft efficiency to calculate delivered and brake power over a range of speeds.
   c) Engine Performance: The engine design operating point, termed specified maximum continuous rating (SMCR), is calculated using the brake power and rotation rate of the propeller at the design speed. Fuel oil consumption is calculated over the full range of speeds supported by the engine, assuming tuning at the SMCR point.

2) Calculations at Ballast Draft: If ballast draft information is provided, then the same ship hull/propeller/engine combination used in the design draft calculations is analyzed at ballast draft as follows:

   a) Ship Resistance: Ship resistance is calculated at ballast draft, producing curves of resistance and effective power over a range of speeds at the appropriate draft.
   b) Propeller Performance: The propeller curves determined at design draft are used to calculate propeller performance at ballast draft, providing estimates of delivered and brake power over a range of speeds.
   c) Engine Performance: Using the SMCR point calculated at design draft, fuel oil consumption is calculated at ballast draft over the full range of speeds supported by the engine.

C. Performance Improvements

The following performance improvements can be calculated individually or in combinations. It is possible to combine any of these major modifications with any other, with the exception that only one engine modification can be selected at a time. Note that the impacts of combinations of improvements are not linear, so to calculate the overall impact, one must accomplish the analysis with multiple improvements selected, rather than summing the results of various individual improvements.

1) Engine Modifications: Estimates of fuel oil consumption for a variety of engine modifications appropriate to the installed engine are provided over the range of speeds available.

2) Propeller Optimization: The propeller may be redesigned for a slower design speed by removing the AE/AO and P/D from the input data and designating a new design speed and maximum speed for cavitation purposes.

3) Bulbous Bow Removal: If a bulbous bow is present, estimates for the impact of removing the bulbous bow are provided by reducing hull wetted surface area by the surface area of the bulb, and eliminating the bulbous bow impact in the resistance calculation.

4) Energy Saving Device Addition: The impact of adding an energy saving device can be estimated by changing the input flag to “yes.”

D. Output Data

Output from the program is provided in numerical tables and in graphical format. Resistance data, propeller data, and fuel usage are provided along with tabulation of input and calculated values for all variables. Examples are provided in Section XI.

IV. RESISTANCE CALCULATION: Holtrop & Mennen

Ship resistance for tankers and bulkers is estimated from basic hullform characteristics using the method developed by Holtrop and Mennen [9]–[12]. This method predicts full-scale ship resistance through a regression analysis of many towing-tank resistance model tests of various hullforms. While a specific range of applicability is not explicitly defined, Birk [1] estimates that the method is applicable to ships with a prismatic coefficient between 0.55 and 0.85, and a length to beam ratio between 3.9 and 9.5. The methodology estimates wave resistance, frictional resistance modified by a form factor, air resistance, a correction factor for roughness and ship form,
and the resistance impacts of appendages and bulbous bow as applicable; these are combined to predict ship resistance in calm water with no wind, referred to herein as ship resistance at trial condition, or \( R_{TC} \). Figure 1 shows the calculated resistance data for an example ship.

In this section, we follow the description of Holtrop & Mennen’s method as described in Birk [1], with some modification where noted due to incorporation of subsequent research.

A. Wave Resistance

Holtrop & Mennen calculate wave resistance as a function of Froude number, \( Fr \), in three regions such that

\[
R_w = \begin{cases} 
R_{Wa}(Fr) & \text{when } Fr \leq 0.4 \\
R_{Wmid}(Fr) & \text{when } 0.4 < Fr \leq 0.55 \\
R_{Wb}(Fr) & \text{when } Fr > 0.55 
\end{cases}
\]

using

\[
R_{Wa}(Fr) = \rho g \lambda Fr c_{Dwa} c_{z} e^{m_{1a} Fr + m_{4a} \cos(\lambda Fr^{-2})} ,
\]

\( R_{Wb}(Fr) = \rho g \lambda Fr c_{Dwb} c_{z} e^{m_{1b} Fr + m_{4b} \cos(\lambda Fr^{-2})} \),

and

\[
R_{Wmid} = R_{Wa}(0.4) + \frac{20Fr - 8}{3} \left[ R_{Wb}(0.55) - R_{Wa}(0.4) \right]
\]

where \( R_{Wa}(0.4) \) indicates \( R_{Wa} \) evaluated at \( Fr = 0.4 \) and \( R_{Wb}(0.55) \) indicates \( R_{Wb} \) evaluated at \( Fr = 0.55 \). The coefficients in these equations can be found in Table I.

B. Bulbous Bow Impact

Holtrop & Mennen account for the impact of the bulbous bow by applying a correction, \( c_2 \), to the wave resistance calculated using (1) and (2), thus reducing wave resistance when a bulbous bow is present. They suggest

\[
c_2 = e^{-1.89 \sqrt{\lambda}}
\]

where

\[
c_3 = \frac{0.56 A_{bt}^{1.5}}{BT(0.31 \sqrt{A_{bt}} + T_f - h_b)},
\]

\( A_{bt} \) is the transverse cross-sectional area of the bulb at the forward perpendicular, \( h_b \) is the height of the centroid of that area above baseline, and \( T_f \) is the draft at the forward perpendicular. This equation applies a reduction in wave resistance due to the bulbous bow; the reduction is a constant percentage of the wave resistance.

The frictional resistance impact of the bulb is inherently included in the frictional resistance calculation of Section IV-C since the ship wetted surface area includes the surface area of the bulb.

Note that the only characteristics of the bulb that are used in this calculation pertain to the area and centroid of the transverse cross-section of the bulb at the forward perpendicular; this is a small set of data to capture an extremely widely varying set of possible shapes and impacts of a bulbous bow, and is thus a very rough approximation of the impact of the bulb on the performance of the ship. See Appendix A for further discussion of the impact of a bulbous bow on ship performance.

C. Frictional Resistance

The frictional resistance, \( R_f \), is calculated as

\[
R_f = \frac{1}{2} \rho V^2 C_f A_{ws}
\]

where \( \rho \) is the density of seawater, \( V \) is the ship speed, \( A_{ws} \) is the wetted surface area of the bare hull, and \( C_f \) is the non-dimensional coefficient of friction calculated using the ITTC-57 formula,

\[
C_f = \frac{0.075}{(\log_{10}(Re) - 2)^2}.
\]

The frictional resistance coefficient is a function of Reynold’s number, \( Re \), a non-dimensional number indicating the turbulent nature of the flow. \( Re \) is the ratio of the inertial forces to the viscous forces,

\[
Re = \frac{VL_{wl}}{\nu}
\]

where \( V \) is the speed of the ship, \( L_{wl} \) is the length of waterline and \( \nu \) is the kinematic viscosity of seawater, \( 1.1945 \times 10^{-6} \text{ m}^2/\text{sec} \).

The frictional resistance calculated above is the resistance of a flat plate with wetted surface area \( A_{ws} \). This frictional resistance is modified by a form factor, \( (1 + k) \), which accounts
TABLE I: Coefficients for wave resistance equations

\[
c_{1a} = 2223105 \cdot 3.78613 \left( \frac{T}{L_{wl}} \right)^{1.07961} (90 - i_f)^{-1.37565}
\]
\[
c_{1b} = 6919.3C_{fr}^{-1.13346} \left( \frac{L_{wl}}{B} \right)^2 \cdot 0.97977 \left( \frac{L_{wl}}{B} \right) - 2 \cdot 1.40692
\]
\[
c_{2} = 1 - 0.84A_{a} \frac{B}{T}
\]
\[
c_{7} = \begin{cases} 
0.229577 \left( \frac{B}{L_{wl}} \right)^{(1/3)} & \text{when } \left( \frac{B}{L_{wl}} \right) \leq 0.11 \\
0.5 - 0.0625 \left( \frac{B}{L_{wl}} \right) & \text{when } 0.11 < \left( \frac{B}{L_{wl}} \right) \leq 0.25 \\
0 & \text{when } \left( \frac{B}{L_{wl}} \right) > 0.25
\end{cases}
\]
\[
c_{15} = \begin{cases} 
-1.69385 & \text{when } (L_{wl}^{3/5}/\nabla) \leq 512 \\
-1.69385 + ((L_{wl}^{3/5}/\nabla) - 8.0)/2.36 & \text{when } 512 < (L_{wl}^{3/5}/\nabla) \leq 1726.91 \\
0 & \text{when } (L_{wl}^{3/5}/\nabla) > 1726.91
\end{cases}
\]
\[
c_{16} = \begin{cases} 
8.07981C_{p} - 13.8673C_{w}^{2} + 6.984388C_{w}^{3} & \text{when } C_{p} \leq 0.8 \\
1.73014 - 0.7067C_{p} & \text{when } C_{p} > 0.8
\end{cases}
\]
\[
d = -0.9
\]
\[
a = 1 + 0.86C_{w}^{2}
\]
\[
r_{app} = 0.0140407 \left( \frac{L_{wl}}{T} \right) (1 - C_{wp}) 0.30484 \left( \frac{L_{wl}}{B} \right) 0.34574 \left( 1 - C_{p} - 0.0225ld \right) 0.6367 \left( \frac{100\nabla}{L_{wl}^{3/5}} \right) 0.16302
\]
\[
r_{f} = \begin{cases} 
1.446C_{p} - 0.03L_{wl}/B & \text{when } L_{wl}/B \leq 12 \\
1.446C_{p} - 0.36 & \text{when } L_{wl}/B > 12
\end{cases}
\]
\[
L_{r} = L_{wl} \left( 1 - C_{p} + \frac{0.06C_{e}ld}{4C_{p} - 1} \right)
\]

TABLE II: Stern shape parameters

<table>
<thead>
<tr>
<th>Stern Shape</th>
<th>( C_{s} )</th>
</tr>
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<tr>
<td>pram with gondola</td>
<td>-2.5</td>
</tr>
<tr>
<td>( V )-shaped sections</td>
<td>-10.0</td>
</tr>
<tr>
<td>normal sections</td>
<td>0</td>
</tr>
<tr>
<td>( U )-shaped sections</td>
<td>+10.0</td>
</tr>
</tbody>
</table>

D. Appendage Resistance

Each type of appendage has an associated appendage resistance factor as shown in Table III, modified slightly from [1].

TABLE III: Form factors \( (1 + k_{2}) \) for various types of appendages

<table>
<thead>
<tr>
<th>Appendage Type</th>
<th>( k_{2} )</th>
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<tbody>
<tr>
<td>rudder behind skeg</td>
<td>0.35</td>
</tr>
<tr>
<td>rudder behind stern</td>
<td>0.5</td>
</tr>
<tr>
<td>twin screw rudder (slender)</td>
<td>1.5</td>
</tr>
<tr>
<td>twin screw rudder (thick)</td>
<td>2.5</td>
</tr>
<tr>
<td>shaft brackets</td>
<td>3.0</td>
</tr>
<tr>
<td>skeg</td>
<td>0.75</td>
</tr>
<tr>
<td>strut bossing</td>
<td>2.5</td>
</tr>
<tr>
<td>hull bossing</td>
<td>1.0</td>
</tr>
<tr>
<td>exposed shaft (w/b buttoces ( \approx 10^{\circ} ))</td>
<td>1.0</td>
</tr>
<tr>
<td>exposed shaft (w/b buttoces ( \approx 20^{\circ} ))</td>
<td>1.0</td>
</tr>
<tr>
<td>stabilizer fans</td>
<td>1.8</td>
</tr>
<tr>
<td>dome</td>
<td>1.7</td>
</tr>
<tr>
<td>bilge keels</td>
<td>0.4</td>
</tr>
</tbody>
</table>

The total appendage resistance, \( r_{app} \), is

\[
r_{app} = \frac{1}{2} \rho V^{2} C_{f} \sum_{i} (S_{app})_{i} (1 + k_{2})_{i}
\]

where \( C_{f} \) is the frictional resistance coefficient calculated in (4), and \( S_{app} \) is the surface area of the \( i_{th} \) appendage with corresponding appendage resistance factor \( (1 + k_{2})_{i} \).

E. Air Resistance

Total air resistance, \( r_{aa} \), is calculated as

\[
r_{aa} = \frac{1}{2} \rho_a V^{2} C_{aa} A_{exp}
\]
where $\rho_a$ is the density of air; $A_{wexp}$ is the area of the ship exposed to wind, which is area of the ship above the waterline including deckhouse and any loaded cargo, facing forward; and $C_{oa}$ is assumed to be 0.8, an average value for typical ship structures.

**F. Correlation Allowance**

A correlation allowance accounts for differences between model and full scale results for effects such as roughness allowance and the partial dynamic similarity of the model test. While correlation allowances have historically been assigned a constant value of 0.0004, it has been found more recently that the correlation allowance should be varied with size of the vessel. A variety of correlation allowances are proposed by different authors; we use an estimate from Kristensen and Lützen [14]

$$C_a = \frac{0.5(\log_{10}\Delta) - 0.1(\log_{10}\Delta)^2}{1000}$$

where $\Delta$ is the ship displacement in metric tonnes. A lower limit of -0.0001 is placed on $C_a$. The correlation allowance resistance adjustment, $R_a$, is

$$R_a = \frac{1}{2} \rho V^2 C_a \left[ A_{ws} + \sum_i S_{appi} \right].$$

Note that the correlation allowance can be negative, in which case it reduces the total calculated resistance.

**G. Total Resistance**

Total resistance at trial condition, $R_{TC}$, is the total resistance in calm, deep water with no wind, and is merely the sum of the resistance components calculated above:

$$R_{TC} = R_f (1 + k) + R_{app} + R_w + R_a + R_{aa}. \hspace{1cm} (5)$$

Holtrop and Mennen’s original research included values for transom resistance and change in pressure due to the bulbous bow, but subsequent research indicates that both values should be omitted.

**V. RESISTANCE CALCULATION: HOLLÉNBACh**

Ship resistance for container ships is estimated using the method developed by Hollénbach, which is a regression analysis of tow tank data taken in Vienna, Austria. Hollénbach provides a mean estimate of resistance along with an upper and lower bound. For our purposes, we use only the mean value. Hollénbach’s method is applicable to displacement vessels with a length-to-diameter ratio between 4.7 and 7.11, a beam-to-draft ratio from 1.99 to 4.00, and a block coefficient below 0.83. It provides separate analyses for design draft and ballast condition. We follow the description of the method provided by [1]. Figure 2 shows the calculated resistance data for an example ship.

![Fig. 2: Resistance calculated using Hollénbach procedure.](image)

**A. Calculation Length**

A calculation length, $L_c$, is found using

$$L_c = L_{os} \text{ if } L_{os} < L_{bp}$$

$$L_{bp} + \frac{2}{3}(L_{os} - L_{bp}) \text{ if } L_{bp} < L_{os} < 1.1L_{bp}$$

$$1.0667L_{bp} \text{ if } L_{os} > 1.1L_{bp}$$

where $L_{os}$ is the length over waterline.

**B. Residuary Resistance**

Since the frictional resistance calculation does not include a form factor, the residuary resistance, $R_r$, includes the effects of both wave resistance and the viscous pressure resistance. The coefficient of residuary resistance, $C_r$, uses a basis of beam times draft instead of the usual wetted surface area:

$$C_r = \frac{10R_r}{\frac{1}{2} \rho V^2 BT}.$$

We begin by calculating a standard coefficient, $C_{rstd}$,

$$C_{rstd} = b_{11} + b_{12}Fr + b_{13}Fr^2$$

$$+ (b_{21} + b_{22}Fr + b_{23}Fr^2)C_b$$

$$+ (b_{31} + b_{32}Fr + b_{33}Fr^2)C_b^2$$

Note that the Froude number, $Fr$, is calculated using the calculation length, $L_c$, and the block coefficient, $C_b$, is calculated using the waterline length, $L_{wl}$. Coefficient values can be found in Table IV.

The coefficient $b_{11}$ is corrected for single-screw vessels at design draft whose block coefficient is less than 0.6 as follows:

$$b_{11} = -0.87674 \text{ if } C_b < 0.49$$

$$b_{11} = -0.57424 - 25(0.6 - C_b)^2 \text{ if } 0.49 \leq C_b < 0.6$$
Fig. 3: Resistance calculated using Holtrop & Mennen procedure (left) and using Hollenbach procedure (right).

| Table IV: Coefficients for calculation of residuary resistance |
|------------------|------------------|------------------|
|                  | single screw design draft | single screw ballast draft | twin screw design draft |
| $b_{11}$        | -0.57424          | -1.50162          | -5.3475                 |
| $b_{12}$        | 13.3893           | 12.9678           | 55.6532                 |
| $b_{13}$        | 4.6141            | 5.55536           | 19.2714                 |
| $b_{21}$        | -39.721           | -45.8815          | -192.388                |
| $b_{22}$        | -351.483          | 121.82            | 388.33                  |
| $b_{31}$        | -1.14215          | -4.33571          | -14.3571                |
| $b_{32}$        | -12.3296          | 36.0782           | 142.738                 |
| $b_{33}$        | 459.254           | -85.3741          | -254.762                |

| Table V: Coefficient values for additional factors to residuary resistance |
|------------------|------------------|------------------|
|                  | single screw design draft | single screw ballast draft | twin screw design draft |
| $a_1$            | 0.3382            | 0.7139           | 0.2748                  |
| $a_2$            | -0.8086           | -0.2558          | -0.5747                 |
| $a_3$            | -6.0258           | -1.1606          | -6.761                  |
| $a_4$            | -3.5632           | 0.4534           | -4.3834                 |
| $a_5$            | 9.4405            | 11.222           | 8.8158                  |
| $a_6$            | 0.0146            | 0.4562           | -0.1418                 |
| $a_7$            | 0.0               | 0.0              | -0.1258                 |
| $a_8$            | 0.0               | 0.0              | 0.0481                  |
| $a_{10}$         | 0.0               | 0.0              | 0.1699                  |
| $d_1$            | 0.834             | 0.032            | 0.897                   |
| $d_2$            | -1.228            | 0.803            | -1.457                  |
| $d_3$            | 0.497             | 0.739            | 0.767                   |
| $c_1$            | 2.1701            | 1.9994           | 1.8319                  |
| $c_2$            | -0.1602           | -0.1446          | -0.1237                 |

The standard residuary resistance is affected by a multitude of parameters, described below. Coefficients for the equations can be found in Table V.

For speeds above a critical Froude number $F_{rc}$, the high Froude number factor, $k_{Fr}$, is

$$ k_{Fr} = \begin{cases} 1 & \text{if } Fr < F_{rc} \\ \left( \frac{Fr}{F_{rc}} \right)^{c_1} & \text{if } Fr > F_{rc} \end{cases} $$

where

$$ F_{rc} = d_1 + d_2C_b + d_3C_b^2 $$

and $c_1 = Fr/F_{rc}$ for single and twin screw vessels at design draft, and $c_1 = 10C_b((Fr/F_{rc}) - 1)$ for single screw vessels at ballast draft.

The length factor, $k_L$, is

$$ k_L = e_1(L_{bp})^{e_2} $$

in which $L_{bp}$ must be entered in meters.

The beam-to-draft ratio factor, $k_{bd}$, is

$$ k_{bd} = (1.99)^{a_1} \quad \text{if } B/T \leq 1.99 $$

$$ k_{bd} = (B/T)^{a_1} \quad \text{if } B/T > 1.99 $$

The length-to-beam ratio factor, $k_{lb}$, is

$$ k_{lb} = (L_{bp}/B)^{a_2} \quad \text{if } L_{bp}/B \leq 7.11 $$

$$ k_{lb} = (7.11)^{a_2} \quad \text{if } L_{bp}/B > 7.11 $$

The wetted length factor, $k_{ll}$, is

$$ k_{ll} = (L_{os}/L_{wl})^{a_3} \quad \text{if } L_{os}/L_{wl} \leq 1.05 $$

$$ k_{ll} = (1.05)^{a_3} \quad \text{if } L_{os}/L_{wl} > 1.05 $$

The aft overhang ratio factor, $k_{ao}$, is

$$ k_{ao} = (L_{wl}/L_{bp})^{a_4} \quad \text{if } L_{wl}/L_{bp} \leq 1.06 $$

$$ k_{ao} = (1.06)^{a_4} \quad \text{if } L_{wl}/L_{bp} > 1.06 $$

The trim correction factor, $k_{tr}$, is

$$ k_{tr} = \left[ 1 + \frac{T_a - T_f}{L_{bp}} \right]^{a_5} $$
The propeller correction factor, \( k_p \), is
\[
\begin{align*}
    k_p &= (0.43)^{69} & \text{if } D/T_a < 0.43 \\
    k_p &= (D/T_a)^{69} & \text{if } 0.43 \leq D/T_a < 0.84 \\
    k_p &= (0.84)^{69} & \text{if } 0.84 \leq D/T_a
\end{align*}
\]

The standard residuary resistance is then multiplied by several factors for additional influences such that
\[
C_{rbt} = C_{rstd} \cdot k_F \cdot k_L \cdot k_h \cdot k_{tn} \cdot k_{ao} \cdot k_{tr} \cdot k_p \cdot N_{rudder}^{aT} \cdot N_{brackets}^{as} \cdot N_{bossings}^{ao} \cdot N_{thrusters},
\]
where \( N_{rudder} \) is the number of rudders (1 or 2, for twin screw vessels), \( N_{brackets} \) is the number of shaft brackets (0, 1 or 2, for twin screw vessels), \( N_{bossings} \) is the number of shaft bossings (0, 1 or 2, for twin screw vessels), and \( N_{thrusters} \) is the number of side thrusters (between 0 and 4).

Hollenbach’s residuary resistance coefficient, \( C_{rstd} \), is based on a reference surface of \( BT/10 \); this is converted to a wetted surface area basis such that the residuary resistance coefficient used herein, \( C_r \), is
\[
C_r = C_{rbt} \cdot \frac{BT}{10A_{ws}}
\]
and the residuary resistance, \( R_r \), is
\[
R_r = \frac{1}{2} C_r \rho V^2 A_{ws}.
\]

C. Frictional Resistance
Hollenbach uses the ITTC 1957 model-ship correlation line, (4), with no form factor, using a Reynolds number based on \( L_c \).

D. Appendage and Air Resistances
The appendage and air resistance values, \( R_{app} \) and \( R_{aa} \), respectively, are calculated using the equations provided by Holtrop & Mennen.

E. Correlation Allowance
The correlation allowance used by Hollenbach coincides with the Vienna Model Basin, such that
\[
C_a = (0.35 - 0.002L_{bp}) \cdot 10^{-3}
\]
and the associated resistance, \( R_a \) is
\[
R_a = \frac{1}{2} C_a \rho V^2 A_{ws}.
\]
Although Hollenbach limits the correlation allowance to a minimum of zero, we extend this for larger ships to allow the correlation allowance to reach a minimum of -0.0001, consistent with the practice we use for Holtrop & Mennen.

F. Total Resistance
Total resistance is the sum of all individual resistances, such that
\[
R_{TC} = R_f + R_r + R_{app} + R_a + R_{aa}.
\]

VI. PROPELLER CALCULATION
Propeller performance characteristics are estimated using the Wageningen B-series propeller data as described in [15]. This regression analysis provides thrust coefficient \( (K_T) \), torque coefficient \( (K_Q) \), and open-water efficiency \( (\eta_o) \) as a function of advance ratio \( (J) \), based on the provided values of diameter \( (D) \), number of blades \( (Z) \), pitch/diameter ratio \( (P/D) \), and expanded area ratio \( (AE/O) \). We address herein only fixed-pitch propellers with one propeller per shaft; counter-rotating propellers and controllable-pitch propellers are not addressed.

A. Resistance Input to Propeller Calculation
Ship resistance versus speed is calculated using the method described in Section IV or V above, producing “trial condition” resistance \( (R_{TC}) \), i.e. resistance in deep, calm water with no wind.

The “heavy running” resistance \( (R_{HR}) \), which includes the impact of wind and waves, is estimated by increasing the calm water resistance by a sea margin, \( sm \), provided by the user
\[
R_{HR} = R_{TC}(1 + sm). \tag{9}
\]
The sea margin can vary depending on the type of ship and the planned operational area, but a typical value is 15%; this is the value assumed if the user does not input a value.

If the ship is not at even keel, then the thrust from the propeller is not directly forward. Therefore, the thrust is increased by a trim factor
\[
F_{trim} = \sqrt{1 - \left(\frac{|T_a - T_f|}{L_{bp}}\right)^2} \tag{10}
\]
where \( T_a \) is draft at the aft perpendicular, \( T_f \) is the draft at the forward perpendicular, and \( L_{bp} \) is the ship length between perpendiculars. For a twin-screw ship, we assume equal loading of the propellers, so the thrust for each propeller is one-half of the total thrust. Thus, the resistance value used in estimating propeller performance, \( R_T \), is
\[
R_T = \frac{R_{HR}}{F_{trim} N_p}. \tag{11}
\]
where \( N_p \) is the number of propellers.

B. Propeller Curves
The non-dimensional advance ratio of the propeller is the ratio of the fluid speed over the propeller tip speed:
\[
J = \frac{V_a}{nD} \tag{12}
\]
where \( V_a \) is the water speed at the propeller, \( n \) is the rotation rate, and \( D \) is the propeller diameter. Since the propeller is located in the wake of the ship, the fluid speed seen by the propeller is most likely not equal to the speed of the ship. The wake fraction, \( w \), accounts for this difference and is used to determine water speed relative to ship speed, \( V \), such that
\[
V_a = V(1 - w). \tag{13}
\]
The defining curves for propeller performance in open water are the non-dimensional thrust coefficient, \( K_T \),

\[
K_T = \frac{T_o}{\rho n^2 D^4}
\]

and the non-dimensional and torque coefficient, \( K_Q \),

\[
K_Q = \frac{Q_o}{\rho n^2 D^5}
\]

where \( Q_o \) is open water torque, \( T_o \) is open water thrust, defined as

\[
T_o = \frac{R_T}{(1 - t)}
\]

where \( t \) is the thrust deduction factor. A propeller operating in close proximity to a hull creates a low pressure region on the intake side near the hull, thus slightly increasing the resistance of the vessel. This effect is accounted for using the thrust deduction factor, \( t \), which is a function of the shape of the hull and the size of the propeller.

The open water efficiency of the propeller is

\[
\eta_o = \frac{JK_T}{2\pi K_Q}.
\] (14)

Propeller curves for a representative propeller are plotted versus \( J \) in Figure 4.

---

The \( K_T \) and \( K_Q \) curves are estimated using

\[
K_T = \sum C_{kt}Z^{zt}(AE/\pi)^{zt}(P/D)^{pt}J^{jt}
\] (15)

\[
K_Q = \sum C_{kq}Z^{zq}(AE/\pi)^{zq}(P/D)^{pq}J^{jq}
\] (16)

where \( Z \) is the number of blades, \( AE/\pi \) is the expanded area ratio, \( P/D \) is the pitch to diameter ratio, and \( C_{kt}, C_{kq}, zt, at, pt, jt, zq, aq, pq \) and \( jq \) are coefficients and terms of the Wageningen B-screw Series found in [15].

If the number of blades is not provided by the user, we assume four. If the pitch to diameter ratio is not provided, we choose the \( P/D \) ratio that produces the best fuel oil consumption at design speed, using the methodology described in Section IX-B. If the expanded area ratio is not provided, we use the formulation proposed by Keller and reported in [1] in which

\[
AE/\pi = \frac{(1.3 + 0.3Z)T_o}{(p_o - p_v)D^2} + k
\] (17)

where \( Z \) is the number of blades, \( T_o \) is the thrust, \((p_o - p_v)\) is the pressure at the centerline of the propeller, and \( k \) is a constant that varies with the type of ship. We use \( k = 0.2 \) for single-screw vessels, \( k = 0.1 \) for high-speed twin-screw vessels (with design speeds greater than 20 knots), and \( k = 0.0 \) for slower twin-screw vessels. The Keller criteria selects an expanded area ratio that is likely to meet cavitation criteria. After calculating propeller performance, we estimate cavitation and adjust \( AE/\pi \) if necessary; please see the discussion of cavitation in Section VI-D.

---

C. Propeller Operating Point

To remove the dependence of the propeller curves on propeller rotation rate, which is unknown at this point, we divide \( K_T \) by \( J^2 \)

\[
\frac{K_T}{J^2} = \frac{T_o}{\rho D^2 V_a^2}
\] (18)

where \( T_o \) and \( V_a \) are calculated as described above, and \( D \) is provided by the user or estimated.

At any given speed and sea state, the intersection of the curve defined by (18) multiplied by \( J^2 \) (for the particulars of the ship), and the propeller \( K_T \) curve defined by (15) (for the particulars of the propeller), determines the \( J \) value at which the propeller will operate when installed in the given ship at the given speed and sea state; an example is shown in Figure 4.

Once \( J \) is determined for a given operating point, the propeller rotation rate and open water propeller efficiency can be calculated at that speed and sea state using (12) and (14). We thus produce, for the trial condition and the heavy running condition, curves of delivered power versus ship speed, propeller rotation rate versus ship speed, and propeller efficiency versus ship speed. Examples are shown in Figure 5.

---

D. Cavitation

Cavitation occurs when the local pressure falls below the vapor pressure, causing bubbles to form and collapse, which
in turn cause noise, vibration, damage to the propeller, and a significant reduction in thrust provided by the propeller. While some small amount of cavitation is acceptable, the propeller must be designed to perform appropriately over the full range of desired speeds. Typically, risk of cavitation is reduced with increased blade area.

Burrill developed a criteria for predicting cavitation in 1943 and revised it in 1962-63. He presented likelihood of cavitation based on a cavitation number and thrust coefficient; the well-known Burrill diagram, shown in Figure 6 from [20], is used in the early stages of propeller design to avoid cavitation. The cavitation number, $\sigma$, is derived from Bernoulli and defined as

$$\sigma = \frac{p_{atm} + \rho gh - p_v}{q_T}$$

where $p_{atm}$ is atmospheric pressure at the surface, $\rho$ is the density of sea water, $g$ is the gravitational constant, $h$ is the distance from the water surface to the centerline of the propeller, $p_v$ is the vapor pressure of sea water, and

$$q_T = \frac{1}{2} \rho (V_R)^2$$

where $V_R$, the relative velocity of water with respect to the propeller at 0.7 radius, is

$$V_R = V (1 - w) \sqrt{1 + (0.7\pi/J)^2}$$

in which $V$ is ship speed, $w$ is wake fraction, and $J$ is propeller advance ratio. The thrust coefficient, $\tau_c$, is used to express the mean thrust loading on the blades [20];

$$\tau_c = \frac{Th}{q_T A_P}$$

where $Th$ is the thrust and $A_P$ is projected blade area. The projected blade area can be estimated from the expanded area, $A_E$, using

$$A_P = A_E (1.067 - 0.229 \frac{P}{D}).$$

Burrill recommended a limit of 5% back cavitation for merchant ship propellers; however, numerous more recent studies of cavitation indicate a higher back cavitation limit is more appropriate; see, for example, [2], [6]. The American Bureau of Shipping (ABS) guidance [20] states that modern merchant ship propellers are designed with airfoil blade sections, making the 10% back cavitation line more appropriate.

Due to these recommendations, we limit ship speed to the speed that corresponds with 10% back cavitation. If this limit falls below the design speed, we increase blade area until the cavitation criteria is met. Figure 7 shows the cavitation limit for a sample ship; the top diagram plots mean thrust loading versus cavitation limit and the bottom diagram plots mean thrust loading versus ship speed. In this example, the cavitation limit occurs at 15.5 knots, which is above the ship design speed of 15.3 knots. The user may input a maximum speed, different from the design speed, which the program will ensure is met without significant cavitation through appropriate selection of $AE/\alpha O$.

### E. Propulsion Power

Having determined the resistance of the ship and the performance of the propeller, we now determine the power required...
to propel the ship through the water.

Effective power, $P_e$, is the power required to overcome the resistance of the ship.

$$ P_e = R_T V. $$

Delivered power, $P_d$, is the power that must be delivered to the propeller in place and incorporates the effects of propeller efficiency, hull efficiency, and relative rotative efficiency.

$$ P_d = \frac{P_e}{\eta_o \eta_h \eta_r} $$

where hull efficiency, $\eta_h$, is

$$ \eta_h = \frac{1 - \omega}{1 - t}. $$

Brake power, $P_b$, is the power that must be produced by the engine; it incorporates the shaft efficiency, $\eta_s$.

$$ P_b = P_d / \eta_s $$

where $\eta_s$ is a scalar value provided by the user. If not provided, we assume $\eta_s = 0.99$. The shaft efficiency accounts for losses along the shaft due to bearings and other frictional losses.

See Figure 8 for a representation of the various power values.

---

**Fig. 8:** Effective power ($P_e$), delivered power ($P_d$), and brake power ($P_b$).

**VII. ENGINE CALCULATIONS**

We assume that all power generated by the engine goes to propulsion and that no reduction gear is used; thus, the rotation rate of the engine is equal to the rotation rate of the propeller and the load on the engine is equal to the load on the propeller, increased by the relevant efficiencies.

Each diesel engine has a characteristic layout diagram defined by four points, $L_1$, $L_2$, $L_3$, and $L_4$; see Figure 9 for examples. The $L_1$ point is the engine’s nominal maximum continuous rating (MCR), which is the rated sustained maximum power produced by the engine at the rated sustained maximum rotation rate; these maximum power and rotation rate values can be exceeded by the engine, but only for a short period of time. The line from $L_1$ to $L_3$ on a log-log plot is a line of constant mean effective pressure (MEP) at the maximum rated MEP for the engine. Lines of constant MEP are parallel to the $L_1 - L_3$ line.

The ship operational design point is the power and rotation rate required to achieve design speed at a selected design sea state including an engine margin, $em$, and a propeller margin, $pm$; this operational design point is termed the specified maximum continuous rating (SMCR). We define brake power at SMCR as

$$ P_{b_{SMCR}} = P_{b_{hrDcs}} (1 + em) $$

where $P_{b_{hrDcs}}$ is the brake power for heavy running at design speed and $em$ is the engine margin, typically 10%. The corresponding engine speed, $N_{SMCR}$, is the value of the
engine speed curve at the SMCR power, $N_{hrDes}$, decreased by a propeller margin, $pm$, typically 5%, such that
$$N_{SMCR} = N_{hrDes}(1 - pm).$$
The SMCR point, defined by the power, $P_{bSMCR}$, and the rotation rate, $N_{SMCR}$, must fall within the engine layout diagram.

To clarify the difference between MCR and SMCR, the MCR is the maximum rated power and speed combination that can be produced by the engine; the SMCR is the maximum rated power and speed combination that can be produced by the engine as installed in the ship and includes such impacts as coupling with the propeller and tuning for the application.

The entire operating curve of the engine at all planned speeds and sea states must fall within an area defined by speed, power, mean effective pressure, and torque limits of the engine as installed. An example plot is shown in Figure 10; note that the trial condition and heavy running propeller curves (solid and dashed black lines) are within the designated limits of the engine as installed. Details for calculation of the limiting curves may be found in [16].

Combining the SFOC versus engine load data with the speed/power curve data determined in Section IV or V above allows us to determine fuel oil consumption (FOC) in tons per day as a function of speed for an engine tuned to the SMCR at high load.
$$FOC = SFOC \cdot P_{b} \quad (19)$$

The engine is typically tuned so that peak fuel efficiency occurs between 70 and 80% engine load; this point is termed the continuous service rating (CSR).

VIII. LIMITS ON SHIP SPEED

The lower bound on ship speed for the resistance and propeller calculations is set to 7 knots, and the upper bound is set to 1 knot greater than design speed, rounded up to the nearest whole knot, or by the Froude number limit from the resistance calculation, whichever is lower. $Fr$ is the Froude number, defined as
$$Fr = \frac{V}{\sqrt{gL}}$$
where $V$ is ship speed, $g$ is the gravitational constant, and $L$ is the characteristic length which, in the case of Holtrop and Mennen, is the waterline length, $L_{wl}$, and in the case of Hollenbach, is the characteristic length, $L_c$. The Holtrop & Mennen method is applicable for $Fr \leq 0.45$. The Froude number limit for the Hollenbach method is dependent upon the type of ship and length;
$$Fr_{max} = g_1 + g_2L_{bp} + g_3L_{bp}^2 \quad (20)$$
where the coefficients are listed in Table VI.

The lower bound on ship speed for the fuel oil consumption calculations is set to the ship speed achievable at 25% of the SMCR (specified maximum continuous rating) of the engine, since extrapolation of our estimate of engine performance is unreliable below 25% engine load. If engine data at a lower
engine load is provided as an input to the program, the lowest load for which data is provided becomes the lower bound on ship speed for fuel oil consumption calculations. The upper limit on speed is restricted to 110% of the SMCR since the engine is not designed to run above 110% engine load.

The propeller cavitation limit of 10% back cavitation can also place an upper limit on the ship speed. While no other limit is explicitly placed on speed by the propeller calculations, an inefficient propeller can cause a limit on maximum speed realized through the engine calculations. If the propeller is designed by the code, a propeller is selected that maintains a reasonable efficiency through the full range of operations. If the propeller design is based on values input by the user and the propeller efficiency for some reason is very low, the limit on speed is realized in the engine calculation portion of the code because the brake power required will be very high.

IX. PERFORMANCE IMPROVEMENTS

A. Engine Modifications

Both Wärtsilä and MAN B&W offer several tuning options for their diesel engines which reduce specific fuel oil consumption at certain engine loads, usually at the expense of greater specific fuel oil consumption at other loads. Carbon production is directly and linearly correlated with fuel consumption; however, NOx production is correlated with temperature and thus can increase with improved fuel consumption. These competing tendencies must be balanced to meet regulatory requirements.

Changes to the SFOC can be accomplished through various engine tuning methods such as exhaust gas bypass, variable turbine area, electronic control tuning and turbocharger cut-out, each of which can be tuned for partial load (50-85% of SMCR) or low load (25-70% of SMCR). Changes to the SFOC for each tuning method can be applied to the SFOC values determined in Section VII. These methods will typically reduce SFOC at lower engine load ranges while increasing SFOC at higher engine loads. Methods cannot be combined for further fuel consumption improvements.

a) Delta or Electronic Control Tuning (ECT): ECT, also known as Delta tuning, is the adjustment of exhaust valve and injection timing using the electronic controls of the engine to optimize performance at a lower engine load. This tuning method can be applied to any engine with electronic controls (as opposed to camshaft-controlled engines), and does not require any additional equipment or engine component modifications, including turbochargers. Figure 12 provides an example change in engine SFOC with ECT compared to generic SMCR tuning; these values are the default used by the program if specific data pertinent to the selected engine are not available.

b) Variable Turbine Area (VT or VTA): VTA regulates the exhaust gas pressure in order to precisely match the amount of air to the quantity of injected fuel at all points in an engine’s load and speed range. The result is reduced specific fuel consumption, reduced emissions of hydrocarbons and carbon dioxide and improved engine response. VTA requires the replacement of the fixed-vane nozzle rings in standard turbochargers with a nozzle ring equipped with adjustable vanes; altering the pitch of the vanes adjusts the air flow. Figure 13 provides an example change in engine SFOC with VTA compared to SMCR tuning; these values are the default used by the program if specific data pertinent to the selected engine are not available.

c) Bypass or Exhaust Gas Bypass (EGB): EGB allows the use of smaller turbochargers which have higher efficiencies at lower engine loads. To prevent over-speeding of the turbocharger at high engine loads, an exhaust gas bypass is installed which routes some exhaust gas around the turbocharger at high engine loads. This has the added advantage of increasing exhaust gas temperatures at high loads. EGB requires the installation of an exhaust gas bypass system and, possibly, replacement of the turbochargers. Figure 14 provides an example change in engine SFOC with EGB compared to SMCR tuning; these values are the default used by the program if specific data pertinent to the selected engine are not available.

d) Turbocharger Cut-Out (TCCO): TCCO is the blanking of one or more turbochargers at low engine loads, either manually or automatically, to improve efficiency at low loads. Savings depend on the general set up of the engine and the number of turbochargers applied. This method requires installation of a blanking device and is applicable to any engine with multiple turbochargers. Figure 15 provides an example
change in engine SFOC with turbocharger cut-out compared to SMCR tuning; these values are the default used by the program if specific data pertinent to the selected engine are not available.

**B. Propeller Optimization**

The propeller optimization code described in this section is employed when the propeller specifications are not provided in the input data or when a new propeller is desired. The necessary parameters for propeller design using the Wageningen series are number of blades, diameter, pitch-to-diameter ratio (P/D), expanded area ratio (AE/AO) and design speed. If desired, a maximum speed, greater than design speed, may be entered to ensure cavitation-free operation above the design speed.

Using the number of blades and diameter input by the user, we select an expanded area ratio using equation (17), then calculate $K_T$, $K_Q$ and open water efficiency for a range of pitch to diameter ratios (P/D) using the Wageningen equations, presenting a family of appropriate propeller curves. The propeller operating point at design speed is determined for each P/D ratio using the J determined by the intersection of $(K_T/J^2)J^2$ for the ship and $K_T$ for the propeller as shown in Figure 16, following the procedure described in Section VI.

**Fig. 13:** Change in Specific Fuel Oil Consumption (SFOC) as a function of Engine Load for variable turbine area (VTA).

**Fig. 14:** Change in Specific Fuel Oil Consumption (SFOC) as a function of Engine Load for exhaust gas bypass (EGB).

**Fig. 15:** Change in Specific Fuel Oil Consumption (SFOC) as a function of Engine Load for turbocharger cut-out (TCCO) for various numbers of turbochargers.

**Fig. 16:** Intersection of $(K_T/J^2)J^2$ for ship with $K_T$ for propellers at various $P/D$ ratios.

This matrix of P/D values is carried through the engine
efficiency calculation, at which point the optimum P/D, that which produces the lowest fuel consumption at design speed when operated in conjunction with the engine, is selected. Note that the propeller with the highest open water propeller efficiency is not necessarily the most efficient overall choice for a propeller design, because the resulting propeller operating speed may force the engine into a less efficient operating point; therefore, the propeller that results in the best specific fuel oil consumption is selected.

An example is shown in Figure 17. The engine brake power/speed point for a range of pitch-to-diameter ratios is plotted against the engine layout diagram. Only those P/D ratios that fall within the diagram are considered for use; of those, the one selected is the P/D ratio that provides the lowest specific fuel oil consumption. Note that in this example, this is not the one with the highest propeller efficiency.

It is possible that the SMCR point does not fall within the engine layout diagram. The can happen if, for example, reducing design speed or installing an energy saving device causes the brake power at design speed to be well below the engine layout diagram for the originally installed engine. In these instances, we project the propeller curve until it intersects the engine layout diagram and pick that intersection point as the SMCR; in such cases, the design speed will occur at an engine power level lower than 100%. For example, the top plot in Figure 18 presents a case in which the design speed with engine margin and sea margin still falls below the engine load diagram; in this case, design speed in heavy running can be achieved at 86% of SMCR (86% engine load).

In cases where the design speed falls above the engine load diagram, it may not be possible to achieve design speed at heavy running with the currently designed propeller and engine combination. The disparity could be due to a number of causes, e.g. incorrect ship data resulting in a high estimate of resistance, incorrect propeller data resulting in an inefficient propeller design, or high sea or engine margins. See, for
example, the center image in Figure 18, in which design speed occurs at 112% of SMCR.

Occasionally, the propeller curve will not intersect the engine layout diagram at all; see, for example, the bottom image in Figure 18. The program will return an error; it is left to the user to select the proper remedy by either allowing the program to select a propeller instead of inputting propeller specifications, or by increasing propeller margin to shift the curve to the left or decreasing propeller margin to shift the curve to the right. In the example shown at the bottom of Figure 18, increasing the propeller margin to 6% from 5% will cause the propeller curve to intersect the engine load diagram.

C. Bulbous Bow Removal

A properly designed bulbous bow reduces propulsion power at and around the designed operating speed of the ship. When a ship is operated at a speed significantly different from the speed for which the bulb was designed, the bulb can have an adverse effect on the resistance of the ship, increasing propulsion power and, thus, fuel consumption. This variation in the impact of the bulbous bow is shown in Figure 19 from Carlton [5], who states that the positive impact of bulbous bows occurs over a narrow range of ship speeds, so they are usually employed in ships that operate at clearly defined speeds. When the bulb results in less than a 3 cm change in draft without accounting for the change in ship weight due to removal of the steel in the bulb.

Occasionally, the propeller curve will not intersect the engine layout diagram at all; see, for example, the bottom image in Figure 18. The program will return an error; it is left to the user to select a propeller instead of inputting propeller specifications, or by increasing propeller margin to shift the curve to the left or decreasing propeller margin to shift the curve to the right. In the example shown at the bottom of Figure 18, increasing the propeller margin to 6% from 5% will cause the propeller curve to intersect the engine load diagram.

Recalling equation (3), the only characteristics of the bulb that are used by Holtrop and Mennen to calculate the impact of the bulb on the ship performance are the area and centroid of the transverse cross-section of the bulb at the forward perpendicular; a small set of data to capture a widely varying possible performance impact from a bulbous bow. Further, the only characteristic of the bulb that is used by Hollenbach is the length of the bulb forward of the forward perpendicular, and even smaller set of data. Thus, either estimate is merely a rough approximation of the impact of the bulb on the performance of the ship. Since this approximation is so rough, any indication from these calculations that bulb removal may be beneficial is merely a recommendation for further study with more detailed analysis of the specific bulb installed in the ship.

1) Ship Properties with Bulb Removed: Removing the bulbous bow reduces the volume, displacement and wetted surface area of the bulb, and thus has a small impact on the lcb location and the block coefficient as well. The following is a description of the process for calculating the impact of bulb removal.

Assuming the bulb is approximately a half-ellipsoid, the bulb volume, \( V_b \) is calculated as:

\[
V_b = \frac{2}{3} A_b L_b
\]

where \( A_b \) is the transverse cross-sectional area of the bulb at the forward perpendicular and \( L_b \) is the bulb length forward of the forward perpendicular. The bulb surface area is approximated using

\[
A_b = 2\pi \left( \frac{\pi A_b 1.6 + 2(L_b \sqrt{\pi A_b}) 1.6}{3} \right)
\]

The wetted surface area of the ship without a bulb, \( A_{wsnb} \), is thus merely

\[
A_{wsnb} = A_{ws} - A_b,
\]

assuming that the remaining ship structure is reshaped to form the bulb-less bow.

The volume of the ship without the bulb, \( V_{nb} \), is

\[
V_{nb} = V - V_b,
\]

and the displacement of the ship without the bulb, \( \Delta_{nb} \), is

\[
\Delta_{nb} = \rho V_{nb}.
\]

The longitudinal center of buoyancy of the ship without a bulb, \( lcb_{nb} \), is slightly aft of the original \( lcb \) due to the removal of volume forward, thus

\[
lcb_{nb} = \frac{lcb V - lcb_b V_b}{V_{nb}}
\]

where the longitudinal center of buoyancy of the bulb, \( lcb_b \), measured from the aft perpendicular, is

\[
lcb_b = \frac{L_{bp} + 4L_b}{3\pi}
\]

assuming that the bulb is a half-ellipsoid.

The change in draft is negligible since the buoyancy of the bulb relative to the buoyancy of the entire ship is small, and, further, this small loss in buoyancy is partially offset by a reduction in weight due to steel that is removed. For example, a sample container ship bulb displaces 330 tonnes of seawater; with a 120 tons/cm immersion at design draft, removal of the bulb results in less than a 3 cm change in draft without accounting for the change in ship weight due to removal of the steel in the bulb.

Bulb removal does not change \( L_{bp} \) or \( B \) and change to \( T \) is negligible, so there is a very small change in block coefficient, \( C_b \), which is recalculated to be

\[
C_b = \frac{V_{nb}}{L_{bp}BT}
\]
### D. Energy Saving Devices

A variety of energy saving devices can be implemented which, in general, have the effect of modifying flow into or out of the propeller in a manner that improves efficiency through some range of speeds. Examples include propeller boss cap fins, ducted propellers, pre-swirl stators and asymmetric rudders or hulls, among others.

One potential fuel-saving technology is the Mewis duct, which is advertised to achieve a fuel savings in the neighborhood of 5 to 7 percent, depending on the thrust coefficient, $C_{th}$, of the original vessel,

$$C_{th} = \frac{T_o}{\frac{1}{2} \rho \pi D^2 (V_o)^2}$$

where $T_o$ is thrust and $V_o$ is the water speed at the propeller. Since the ship data provided to this program is not particularly detailed, it is not possible to accomplish a full CFD-scale simulation of the Mewis duct; further, we do not have the information necessary to properly modify the wake fraction, $w$, thrust deduction factor, $t$, and relative rotative efficiency, $\eta_r$ for a ship with a Mewis duct installed. Therefore, the process used to estimate the impact of the Mewis duct is to calculate the ship’s thrust coefficient using the standard thrust value, then use the plot shown in Figure 21 to determine a power reduction that is applied to the brake power. Mewis and Guiard [7] also report a slight increase in propeller rotation rate on the order of 1%, so the propeller rotation rate is increased by 1% as well. These modifications to delivered power and rpm are applied before the engine SFOC calculations.

Per [17], impact of the Mewis Duct is even greater in ballast than in loaded condition. For example, the average of 35 model tests with and without a Mewis Duct show an average of a 5.7% power reduction at design draft, and a 7.3% power reduction at ballast draft. We do not currently include this increased impact.
potential energy savings; however, the predictions improve greatly with additional data provided. This section describes the methodologies for estimating any missing input data and cites the sources for the estimates.

A. Displacement

If displacement at design draft is not entered, it can be estimated from deadweight, $DWT$, as [16]

$$\Delta = k_{\Delta} DWT$$

where $k_{\Delta} = 1.17$ for tankers and bulkers, and $k_{\Delta} = 1.33$ for container ships.

If displacement at ballast condition, $\Delta_B$, is not provided, then it is estimated from displacement at design draft using

$$\Delta_B = \Delta - \rho C_{wp} B L_{wl}(T - T_B)$$

where $T$ is mean draft at design draft, $T_B$ is mean draft at ballast, and $C_{wp}$ is the waterplane coefficient. We place a lower limit on this calculation such that ballast displacement must be a minimum of 10% of displacement at design draft.

B. Length

Length at the waterline, $L_{wl}$, and length between perpendiculars, $L_{bp}$, are both required. If neither is provided, then we estimate $L_{wl}$ as [16]

$$L_{wl} = 0.956 L_{oa}$$

where $L_{oa}$ is length overall.

The difference between $L_{wl}$ and $L_{bp}$ is the distance from the aft perpendicular to the aftmost point of the wet hull, $d_{ap}$,

$$L_{wl} = L_{bp} + d_{ap}.$$ 

If $L_{wl}$ and $L_{bp}$ are not provided and $d_{ap}$ is not available, the relationship between $L_{wl}$ and $L_{bp}$ can be estimated as [14]

$$L_{wl} = k_{ll} L_{bp}$$

where $k_{ll} = 1.01$ for tankers and bulkers and $k_{ll} = 1.02$ for container ships.

C. Block Coefficient

Block Coefficient, $C_b$, is defined as the volumetric displacement of the ship divided by the volume of the bounding box around the wetted hull

$$C_b = \frac{\nabla}{L_{wl} B T}.$$ 

(22)

Note that the volumetric displacement and mean draft must correspond with one another; we expect both to be at design draft.

Per [16], block coefficients for tankers and bulkers range 0.80 - 0.85, and for container ships range from 0.50 - 0.70. We assume $C_b = 0.8$ for tankers and bulkers, and $C_b = 0.6$ for container ships if the appropriate dimensions are not provided by the user.

D. Beam

If beam, $B$, is not provided, we calculate beam from the block coefficient, length and draft using (22).

E. Midship Section Coefficient

The midship section coefficient, $C_x$, is defined as the midship section area, $A_x$, divided by the bounding box of that area,

$$C_x = \frac{A_x}{B T}.$$ 

If $C_x$ is not provided by the user, then we estimate it using [1]

$$C_x = \frac{1}{1 + (1 - C_b)^{5.5}}.$$ 

F. Waterplane Area Coefficient

The waterplane area coefficient, $C_{wp}$, is defined as the area of the waterplane, $A_{wp}$, divided by the bounding box of that area,

$$C_{wp} = \frac{A_{wp}}{L_{wl} B}.$$ 

If $C_{wp}$ is not provided, we estimate it using [1]

$$C_{wp} = k_{wp1} (C_p + k_{wp2});$$

where $k_{wp1} = 0.763$ and $k_{wp2} = 0.34$ for tankers and bulkers with $0.56 < C_p < 0.87$, and $k_{wp1} = 3.226$ and $k_{wp2} = -0.36$ for container ships with $0.57 < C_p < 0.62$; otherwise, $C_{wp}$ is assumed to equal 0.907.

G. Wetted Surface Area

If the wetted surface area, $A_{ws}$, is not provided, we use Mumford’s formula as modified by Kristensen and Lützen [14]

$$A_{bh} = k_{ws} \left( \frac{\nabla}{T} + 1.9 L_{wl} T \right)$$

where $k_{ws} = 0.990$ for tankers and bulkers and $k_{ws} = 0.995$ for container ships. This surface area, $A_{bh}$, describes the bare
hull only; to this we add an estimate for wetted surface of appendages
\[ A_{app} = 0.7T + 0.015L_{wl} \]
so that
\[ A_{ws} = A_{bh} + A_{app}. \]
If wetted surface area is not provided but appendage surface areas are provided in the input data, the input appendage surface areas are ignored and the estimate above is used instead.

If the wetted surface area in ballast, \( A_{wsB} \), is not provided, then it is estimated from wetted surface at design draft using [1]
\[ A_{wsB} = A_{ws} - k_b(T - T_B)(L_{wl} - B) \]
where \( T \) is mean draft at design draft, \( T_B \) is mean draft at ballast, and \( k_b = 2.0 \) for tankers and bulkers and \( k_b = 2.4 \) for container ships.

**H. Longitudinal Center of Buoyancy**

If the distance of the longitudinal center of buoyancy from the aft perpendicular, \( lcb \), is not provided, we use Guldhammer and Harvald’s estimate of the best possible \( lcb \) location, given as a percentage of waterline length forward of the mean of the waterline [8]
\[ lcb = 9.4 - 43.8Fr_{des} \]
where \( Fr_{des} \) is the Froude number at design speed.

**I. Transverse Area Exposed to Wind**

The transverse area exposed to wind, \( A_{exp} \), is the transverse cross-sectional area of the hull and superstructure, including cargo, above the design waterline. This area is in a plane orthogonal to forward motion. Note that a common mistake is to provide the longitudinal windage area, which is the area used to determine heel caused by wind in stability calculations; this value is too large and will result in a very high wind resistance. If \( A_{exp} \) is not provided, we estimate it to be
\[ A_{exp} = BT. \]
If area exposed to wind at ballast, \( A_{expB} \), is not provided, we assume that the exposed area at design draft is increased by the change in trim forward multiplied by the beam:
\[ A_{expB} = A_{exp} + (T_F - T_B)B \]
where \( T_F \) is trim forward at ballast.

**J. Propeller Diameter**

It is strongly encouraged that the propeller diameter, \( D \), be provided by the user. If unavailable, we estimate propeller diameter using [14]
\[ D = k_{d1}T + k_{d2} \]
where \( k_{d1} = 0.395 \) and \( k_{d2} = 1.30 \) for tankers and bulkers, and \( k_{d1} = 0.623 \) and \( k_{d2} = -0.16 \) for container ships.

**K. Propeller Hub Depth**

The depth of the center of the propeller hub, \( h \), can be estimated as
\[ h = T - D/2. \]

**L. Thrust Deduction Factor**

We use Holtrop’s equation to estimate \( t \) for single-screw vessels as [1]
\[ t = \frac{0.25014(B/T_wl)^{0.28956}(\sqrt{BT})^{0.2624}}{(1 - C_p + 0.0225lcb)^{0.01762}} + 0.0015C_{ stern}. \]
For twin-screw vessels [1],
\[ t = 0.325C_b - \frac{0.1885D}{\sqrt{BT}}. \]
In general, \( t \) is a small positive number somewhere around 0.2. We limit the thrust deduction factor to the range of 0.1 to 0.25.

The thrust deduction factor at ballast, \( t_B \) can be determined using [18]
\[ \frac{(1 - t_B)}{(1 - l) = 1 + \left[ \frac{T_B}{T} - 1 \right] (0.4322 + 0.4880C_b). \]

**M. Taylor Wake Fraction**

The wake fraction, \( w \), accounts for differences in the propeller inflow between the propeller in open water and the propeller behind the hull; \( w \) depends on the shape of the hull and the propeller location and size. We calculate wake fraction using a formula from Holtrop & Mennen [1], for a single-screw vessel
\[ w = C_9C_v \frac{L_{wl}}{T_a} \left( 0.0661875 + 1.21756C_{11} \frac{C_v}{1 - C_{P1}} \right) \]
\[ + \frac{0.24558}{0.95 - C_b} \left( \frac{B}{L_{wl}(1 - C_p)} - 0.95 - C_p \right) \]
\[ + \frac{0.11434}{0.95 - C_b} + 0.75C_{ stern}C_v + 0.002C_{ stern} \]
where
\[ C_S = (BA_{ws})/(L_{wl}DT_a) \quad \text{for} \ B/T_a \leq 5 \]
\[ C_b = A_{ws}(7(B/T_a) - 25)(L_{wl}D(B/T_a - 3)) \quad \text{for} \ B/T_a > 5 \]
\[ C_9 = C_S \quad \text{for} \ C_S \leq 28 \]
\[ C_9 = 32 - 16/(C_S - 24) \quad \text{for} \ C_S > 28 \]
\[ C_{11} = T_a/D \quad \text{for} \ T_a/D \leq 2 \]
\[ C_{11} = 0.083333(T_a/D)^3 + 1.33333 \quad \text{for} \ T_a/D > 2 \]
\[ C_{P1} = 1.45C_p - 0.315 - 0.0225lcb \]
and the viscous resistance coefficient, $C_v$, is
\[ C_v = (1 + k)C_f + C_a + C_{app}. \]
Recall that $(1 + k)$ is the form factor, $C_f$ is the coefficient of frictional resistance, $C_a$ is the correlation allowance, and $C_{app}$ is the coefficient of frictional resistance for appendages.

For a twin-screw vessel, the wake fraction is estimated using
\[ w = 0.3095C_b + 10C_vC_b - 0.23\frac{D}{\sqrt{BT}}. \]

For single screw ships, wake fraction is normally in the range of 0.2 to 0.45, with large block coefficient ships having relatively large wake fractions. We limit the wake fraction to the range of 0.1 to 0.5.

Per [18], wake fractions in ballast tend to be 5-15% higher than wake fraction in the loaded condition, resulting in a larger hull efficiency. The revised wake fraction at ballast, $w_B$, can be determined as [18]
\[ \frac{1 - w_B}{1 - w} = 1 + \left[ \frac{T_B}{T} - 1 \right] (0.2882 + 0.1054\Theta) \]
where $\Theta = (100 \cdot \text{trim by bow})L_{bp}$ is the trim angle. Trim by the bow is measured in meters and will typically be a negative number at ballast.

**N. Relative Rotative Efficiency**

Relative rotative efficiency, $\eta_r$, accounts for differences in performance of the propeller behind the hull other than those dealt with by the wake fraction and the thrust deduction, and is generally near unity; typical values range from 0.96 to 1.04. We estimate $\eta_r$ using Holtrop & Mennen’s recommendation referenced in [1] of
\[ \eta_r = 0.9922 - 0.05908(AE/AO) + 0.07424(C_p - 0.0225lc) \]
for single-screw vessels and
\[ \eta_r = 0.9737 + 0.111(C_p - 0.0225lc) - 0.06325(P/D) \]
for twin-screw vessels. Values are limited to a range of 0.95 to 1.05.

**O. Expanded Area Ratio**

As stated in Section IX-B, the propeller expanded area ratio, $AE/AO$, is estimated based on cavitation considerations if it is not provided by the user. The initial rough estimation uses an equation proposed by Keller and referenced in [1]:
\[ \frac{AE}{AO} = \frac{(1.3 + 0.3Z)Th}{(p_0 - p_s)D^2} + K \]
where $Th$ is thrust at design speed, $p_0$ is the hydrostatic pressure at the centroid of the propeller hub, $p_s$ is the saturation pressure of the water which equals 2.291 Pa at 20°C, $D$ is the propeller diameter, and the constant $K$ is

- $K = 0.2$ for single-screw vessels
- $K = 0.1$ for slow twin-screw vessels
- $K = 0.0$ for fast twin-screw vessels.

For the purposes of our code, slow is defined as 20 knots or less and fast is greater than 20 knots. Thrust, $Th$, is calculated as
\[ Th = \frac{R_{hrDes}}{(1 - t)} \]
where $R_{hrDes}$ is the heavy-running resistance at design speed and $t$ is the thrust deduction factor. Hydrostatic pressure, $p_0$, is
\[ p_0 = P_{atm} + \rho gh \]
where $\rho$ is seawater density, $g$ is the gravitational constant, and $h$ is the draft of the centroid of the propeller hub. Note that the full propeller calculation includes a further check on cavitation and, if cavitation levels are exceeded, $AE/AO$ is increased until cavitation requirements are met.

**P. Default Values**

A few parameters have default values included in the program, which are implemented if no values are provided by the user. These defaults include the following:
- **Engine margin, $em = 10\%$**
- **Sea margin, $sm = 15\%$**
- **Propeller margin, $pm = 5\%$**
- **Transmission efficiency, $\eta_s = 99\%$**
- **Number of propellers = 1**
- **Number of propeller blades, $Z = 4$**

**XI. Examples**

In this section we provide examples of a very large crude carrier (VLCC), a product tanker, and a container ship. Where available, we provide data from the actual ship test data or operational data and compare to our calculations. Input data can be seen in Table VII.

**A. Very Large Crude Carrier (VLCC)**

The first example ship is a VLCC. We begin with the resistance calculation using Holtrop & Mennen; results are presented in Figure 22. The majority of the speed range is in the regime dominated by frictional resistance.

The calculated input values for the propeller module are shown in Figure 23. Since the pitch/diameter ratio (P/D) was not provided, the program calculated the P/D to be 0.76 to achieve the minimum specific fuel oil consumption as shown in Figure 24. The resulting propeller curves, shown in Figure 25, generate the open water efficiency shown in Figure 26. Cavitation limits are well above design speed as shown in Figure 27.

The resultant brake power for trial conditions is presented in Figure 28 along with sea trial and log data corresponding to trial condition. The percent difference between the log data and the estimate ranges from 0.3 to 6.2 percent, with the majority being within five percent; see Table VIII. Brake power versus rotation rate is shown in Figure 29.

The engine diagram with SMCR and CSR including corresponding shop test data is shown in Figure 30; test data show excellent correlation with program estimates. Figure 31
<table>
<thead>
<tr>
<th>Ship Name</th>
<th>VLCC</th>
<th>Container</th>
<th>Product Tanker</th>
</tr>
</thead>
<tbody>
<tr>
<td>hullform data</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ship type</td>
<td>tanker</td>
<td>container</td>
<td>tanker</td>
</tr>
<tr>
<td>bulbous bow</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>energy-saving device</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>design speed (knots)</td>
<td>15.6</td>
<td>25.2</td>
<td>14.9</td>
</tr>
<tr>
<td>max speed for cavitation limit (knots)</td>
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<td>–</td>
<td>–</td>
</tr>
<tr>
<td>LBP (m)</td>
<td>324</td>
<td>334</td>
<td>174</td>
</tr>
<tr>
<td>LWL (m)</td>
<td>330</td>
<td>333</td>
<td>–</td>
</tr>
<tr>
<td>LOA (m)</td>
<td>–</td>
<td>–</td>
<td>183</td>
</tr>
<tr>
<td>Beam (m)</td>
<td>60</td>
<td>45.6</td>
<td>32.2</td>
</tr>
<tr>
<td>Design draft forward (m)</td>
<td>20.5</td>
<td>13</td>
<td>11.1</td>
</tr>
<tr>
<td>Design draft aft (m)</td>
<td>20.5</td>
<td>13</td>
<td>11.1</td>
</tr>
<tr>
<td>Displacement at Design Draft (tonnes)</td>
<td>332503</td>
<td>127968</td>
<td>50786</td>
</tr>
<tr>
<td>DWT (tonnes)</td>
<td>266512</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>LCB to AP (m)</td>
<td>173</td>
<td>161</td>
<td>–</td>
</tr>
<tr>
<td>AP to aftmost point of wet hull (m)</td>
<td>7</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>wetted surface area (m²)</td>
<td>28022.8</td>
<td>17734.6</td>
<td>–</td>
</tr>
<tr>
<td>transverse area above water (m²)</td>
<td>1227</td>
<td>1830</td>
<td>608.4</td>
</tr>
<tr>
<td>ballast draft forward (m)</td>
<td>8</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>ballast draft aft (m)</td>
<td>11</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>displacement at ballast (tonnes)</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>LCB to AP at ballast (m)</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>wetted surface at ballast (m²)</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>area above water at ballast (m²)</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>midship section coefficient</td>
<td>0.999</td>
<td>0.9853</td>
<td>–</td>
</tr>
<tr>
<td>water-plane coefficient</td>
<td>0.907</td>
<td>0.8025</td>
<td>–</td>
</tr>
<tr>
<td>block coefficient</td>
<td>0.816</td>
<td>0.6297</td>
<td>0.7981</td>
</tr>
<tr>
<td>longitudinal prismatic coefficient</td>
<td>0.817</td>
<td>0.6391</td>
<td>–</td>
</tr>
<tr>
<td>bulb length from FP (m)</td>
<td>–</td>
<td>12</td>
<td>–</td>
</tr>
<tr>
<td>transverse sectional area of bulb (m²)</td>
<td>–</td>
<td>38</td>
<td>–</td>
</tr>
<tr>
<td>vertical centroid of bulb area (m)</td>
<td>–</td>
<td>7.6</td>
<td>–</td>
</tr>
<tr>
<td>bulb surface area (m²)</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>bulb volume (m³)</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>appendage surface areas (m²)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>rudder behind skeg</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>rudder behind stern</td>
<td>270</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>twin screw rudder (slender)</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>twin screw rudder (thick)</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>skeg</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>shaft brackets</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>strut bossing</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>hull bossing</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>exposed shafts</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>stabilizer fins</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>dome</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>bilge keels</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>engine data</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>engine make</td>
<td>MAN Wärtsilä MAN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>engine model</td>
<td>G80ME-C9-2</td>
<td>RTA96C</td>
<td>S50ME-C8-2</td>
</tr>
<tr>
<td>engine control</td>
<td>Electronic</td>
<td>Electronic</td>
<td>Electronic</td>
</tr>
<tr>
<td>number of cylinders</td>
<td>7</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>number of turbochargers</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>propeller data</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>number of props</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>diameter (m)</td>
<td>10.6</td>
<td>8.8</td>
<td>6</td>
</tr>
<tr>
<td>propeller height above baseline (m)</td>
<td>15</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>number blades</td>
<td>4</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>expanded area ratio</td>
<td>0.4</td>
<td>0.95</td>
<td>0.5411</td>
</tr>
<tr>
<td>pitch/ diameter ratio at 0.7R</td>
<td>0.9895</td>
<td>0.6778</td>
<td></td>
</tr>
<tr>
<td>margins</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>engine margin</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>sea margin</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>shaft efficiency</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>propeller margin</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>
For this ship operating below the design speed of 15.6 knots, the ship resistance is dominated by frictional resistance.

The peak fuel efficiency point is selected, shown as a blue square.

TABLE VIII: Comparison of calculated values to ship measurement data from sea trials and operational logs for the example VLCC brake power in MW at trial condition, as shown in Figure 28.

<table>
<thead>
<tr>
<th>Speed [kt]</th>
<th>Calculated [MW]</th>
<th>Data [MW]</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.38</td>
<td>3.987</td>
<td>4.157</td>
<td>-4.1</td>
</tr>
<tr>
<td>10.25</td>
<td>5.135</td>
<td>5.346</td>
<td>-3.9</td>
</tr>
<tr>
<td>10.63</td>
<td>5.697</td>
<td>5.904</td>
<td>-3.5</td>
</tr>
<tr>
<td>11.01</td>
<td>6.300</td>
<td>6.717</td>
<td>-6.2</td>
</tr>
<tr>
<td>11.54</td>
<td>7.211</td>
<td>7.576</td>
<td>-4.8</td>
</tr>
<tr>
<td>12.00</td>
<td>8.072</td>
<td>8.532</td>
<td>-5.4</td>
</tr>
<tr>
<td>12.50</td>
<td>9.090</td>
<td>9.281</td>
<td>-2.1</td>
</tr>
<tr>
<td>13.00</td>
<td>10.201</td>
<td>10.713</td>
<td>-4.8</td>
</tr>
<tr>
<td>13.69</td>
<td>11.909</td>
<td>11.950</td>
<td>-0.3</td>
</tr>
<tr>
<td>15.51</td>
<td>17.716</td>
<td>17.900</td>
<td>-1.0</td>
</tr>
<tr>
<td>16.17</td>
<td>20.545</td>
<td>20.402</td>
<td>0.7</td>
</tr>
<tr>
<td>16.45</td>
<td>21.851</td>
<td>21.715</td>
<td>0.6</td>
</tr>
</tbody>
</table>
Propeller performance is inhibited by cavitation wherever the mean thrust loading exceeds the 10% back cavitation limit. For this vessel, this occurs at approximately 16.6 knots which is above the design speed.

Fig. 27: Propeller cavitation limits for the example VLCC.

Fig. 28: Engine brake power versus ship speed at trial condition for the example VLCC. Operational data at trial condition is plotted as magenta stars. A numerical comparison of this data is provided in Table VIII.

Fig. 29: Engine brake power versus propeller rotation rate for the example VLCC.

Fig. 30: Log-log plot of the engine load diagram for the example VLCC with calculated and data values for SMCR and CSR denoted.

Specific fuel oil consumption for the engine tuned to SMCR and for various engine modifications is plotted in Figure 32. From the test data plotted in the figure, it appears that the engine is tuned for lower engine loads, most likely using the ECT low-load modification. Change in fuel oil consumption from the baseline engine tuned to SMCR is shown in Figure 33. Fuel oil consumption in tonnes/day is plotted versus speed for trial condition and heavy running in Figure 34.

B. Product Tanker

The next example is a product tanker. Figures 35 and 36 display the resistance and brake power estimates respectively. The brake power estimate is quite good (less than 3% difference) for the regime dominated by frictional resistance, but begins to diverge a bit as the wave resistance regime is entered, reaching 9.6% difference at 15 knots, where the bulbous bow impacts resistance. This is above the design speed. See Table IX for pertinent data.

We next investigate the impact of various modifications to the ship. Using the baseline data entered for any ship as shown in Table VII, the program generates estimates for the baseline ship, possible engine modifications, ballast condition, and bulb
Fig. 31: Engine load diagram for the example VLCC with calculated propeller curves and trial data denoted. Note that highest log data point occurs at 110% of engine load, and therefore should fall outside the operating polygon, as it does.

Fig. 32: Specific fuel oil consumption for various engine modifications for the example VLCC along with engine test data.

Fig. 33: Change in fuel oil consumption in tonnes/day for various engine modifications for the example VLCC.

Fig. 34: Fuel oil consumption for the example VLCC as a function of speed for heavy running and trial condition.

Fig. 35: Resistance calculation results for the example product tanker.

TABLE IX: Comparison of sea trial data and estimated data for product tanker brake power in MW as plotted in Figure 36.

<table>
<thead>
<tr>
<th>Speed</th>
<th>Estimate</th>
<th>Log Data</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>2.465</td>
<td>2.500</td>
<td>-1.4</td>
</tr>
<tr>
<td>12</td>
<td>3.223</td>
<td>3.200</td>
<td>0.7</td>
</tr>
<tr>
<td>13</td>
<td>4.187</td>
<td>4.100</td>
<td>2.1</td>
</tr>
<tr>
<td>14</td>
<td>5.445</td>
<td>5.250</td>
<td>3.7</td>
</tr>
<tr>
<td>15</td>
<td>7.123</td>
<td>6.500</td>
<td>9.6</td>
</tr>
<tr>
<td>16</td>
<td>9.403</td>
<td>8.050</td>
<td>16.8</td>
</tr>
</tbody>
</table>
Fig. 36: Engine brake power as a function of ship speed for the example product tanker. Note that the estimate is very close to sea trial data through design speed, but begins to diverge at higher speeds where the bulbous bow estimate is less reliable. See Table IX for a numerical comparison.

TABLE X: Changes to input data for additional runs on example product tanker.

<table>
<thead>
<tr>
<th>Run</th>
<th>Original Add Mewis Design Mewis and Mewis Propeller Duct and VT New Prop Propeller</th>
<th>Speed</th>
<th>Load</th>
<th>VT Low</th>
<th>New Propeller</th>
<th>Mewis Duct</th>
<th>Mewis and VT</th>
<th>Mewis, Prop and VT</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy-saving device</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>design speed (knots)</td>
<td>14.9</td>
<td>14.9</td>
<td>12</td>
<td>12</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>expanded area ratio</td>
<td>0.5411</td>
<td>0.5411</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>pitch/ diameter ratio at 0.7R</td>
<td>0.6778</td>
<td>0.6778</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

removal if a bulb is present. In order to estimate the impact of an energy-saving device, a separate run is conducted with the ESD flag toggled to “yes.” In order to estimate the impact of a new propeller design, a separate run is conducted with the propeller specifications for expanded area ratio and pitch to diameter ratio removed from the input, and a new design speed entered. If a maximum speed above the design speed is desired, that value must be entered as well in order to raise the cavitation limit appropriately. The changes to the product tanker input data to calculate the impact of all these modifications is summarized in Table X.

Figures 37, 38, and 39 show the change in fuel consumption in tonnes/day for the example product tanker for each of several possible modifications. Figure 37 shows modifications to the ship structure, and Figure 38 shows engine modifications. While the engine modifications cannot be combined with each other, any one of them can be combined with the hullform or propeller modifications, and the hullform and propeller modifications can in general be combined with one another. Their effect is not linearly additive, as seen in Figure 39 and Table XI. Note that the new propeller is designed for a speed of 12 knots, and hits a cavitation limit above 13 knots, so is not operated above 13 knots.

TABLE XI: Change in fuel consumption in tonnes/day for various modifications and combinations of modifications to the example product tanker.

<table>
<thead>
<tr>
<th>Speed</th>
<th>VT Low</th>
<th>New Propeller</th>
<th>Mewis Duct</th>
<th>Mewis and VT</th>
<th>Mewis, Prop and VT</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.5</td>
<td>-0.3</td>
<td>-0.3</td>
<td>-0.7</td>
<td>-0.9</td>
<td>-1.2</td>
</tr>
<tr>
<td>11</td>
<td>-0.3</td>
<td>-0.4</td>
<td>-0.8</td>
<td>-1.1</td>
<td>-1.4</td>
</tr>
<tr>
<td>11.5</td>
<td>-0.4</td>
<td>-0.5</td>
<td>-0.9</td>
<td>-1.3</td>
<td>-1.6</td>
</tr>
<tr>
<td>12</td>
<td>-0.4</td>
<td>-0.6</td>
<td>-1</td>
<td>-1.5</td>
<td>-1.8</td>
</tr>
<tr>
<td>12.5</td>
<td>-0.5</td>
<td>-0.6</td>
<td>-1.2</td>
<td>-1.6</td>
<td>-2.1</td>
</tr>
<tr>
<td>13</td>
<td>-0.5</td>
<td>-0.6</td>
<td>-1.4</td>
<td>-1.9</td>
<td>-2.3</td>
</tr>
<tr>
<td>13.5</td>
<td>-0.7</td>
<td>--</td>
<td>-1.7</td>
<td>-2.3</td>
<td>--</td>
</tr>
<tr>
<td>14</td>
<td>-0.4</td>
<td>--</td>
<td>-1.9</td>
<td>-2.3</td>
<td>--</td>
</tr>
<tr>
<td>14.5</td>
<td>0</td>
<td>--</td>
<td>-2.2</td>
<td>-2.2</td>
<td>--</td>
</tr>
<tr>
<td>15</td>
<td>0.1</td>
<td>--</td>
<td>-2.6</td>
<td>-2.5</td>
<td>--</td>
</tr>
<tr>
<td>15.5</td>
<td>0.1</td>
<td>--</td>
<td>-3</td>
<td>-2.9</td>
<td>--</td>
</tr>
</tbody>
</table>

Fig. 37: Change in fuel consumption due to various possible modifications to the example product tanker.

Fig. 38: Change in fuel consumption due to various possible modifications to the engine in the example product tanker.
C. Container Ship

The final example is a container ship. Container ships typically operate at higher speeds than tankers and thus operate in a regime that includes wave resistance; this can be seen in Figure 40, where wave resistance begins to become significant at about 20 knots. The estimated resistance has quite good correlation with the model test data in this figure, ranging from 0.1 to 6.7 percent difference at any point, even extending into the wave resistance regime. The close correlation is especially notable in view of the uncertainty involved in estimating the impact of the bulbous bow.

Another area of interest in this example is the propeller curves. Container ships tend to have more complex propellers with greater skew and rake than a tanker propeller, so there was some concern that using the Wageningen B-Series as an estimate of propeller performance might be a source of error; however, we find good correlation between the estimated propeller and propeller test data provided by the ship owner. In Figure 41, the calculated propeller data is shown using solid lines and the corresponding actual propeller data is plotted using squares. In the operational regime for this vessel, $J$ is between 0.64 and 0.685, and the calculated propeller efficiencies in this range are within 2% of the actual values, as shown in Table XII.

### Table XII: Comparison of log data and estimated data for container ship propeller curves.

<table>
<thead>
<tr>
<th>Advance Ratio $J$</th>
<th>0.60</th>
<th>0.65</th>
<th>0.70</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_T$ Calculated</td>
<td>0.244</td>
<td>0.218</td>
<td>0.191</td>
</tr>
<tr>
<td>$K_T$ Data</td>
<td>0.251</td>
<td>0.223</td>
<td>0.196</td>
</tr>
<tr>
<td>$K_T$ % Difference</td>
<td>2.7</td>
<td>2.4</td>
<td>2.8</td>
</tr>
<tr>
<td>$K_Q$ Calculated</td>
<td>0.408</td>
<td>0.373</td>
<td>0.337</td>
</tr>
<tr>
<td>$K_Q$ Data</td>
<td>0.423</td>
<td>0.388</td>
<td>0.353</td>
</tr>
<tr>
<td>$K_Q$ % Difference</td>
<td>3.6</td>
<td>3.9</td>
<td>4.6</td>
</tr>
<tr>
<td>$\eta_o$ Calculated</td>
<td>0.572</td>
<td>0.604</td>
<td>0.630</td>
</tr>
<tr>
<td>$\eta_o$ Data</td>
<td>0.565</td>
<td>0.595</td>
<td>0.620</td>
</tr>
<tr>
<td>$\eta_o$ % Difference</td>
<td>1.2</td>
<td>1.5</td>
<td>1.6</td>
</tr>
</tbody>
</table>

The resulting speed-power curve, shown in Figure 42, has quite close correlation with model test data, showing a maximum of 6.7 percent difference through the entire speed range, even in the wave-dominated regime, as shown in Table XIII.

This ship employs a Wärtsilä engine, so a different array of tuning technologies are available than for the MAN B&W engines used by the previous two example vessels. The impacts of these technologies on fuel consumption for this example ship are shown in Figure 43.

D. Example Summary

We have presented example calculations for three types of ships: a container ship, a product tanker, and a VLCC. These examples thoroughly demonstrate the capabilities of the code. Further, the comparison of each ship to operational or test data shows exceptional correlation between the program’s calculations and actual ship data, especially given the simplicity of the inputs provided.
XII. User’s Manual

This section provides instructions on the use of the program including input data, running the program, modifying default values, and output data.

A. Input Data

Ship data is input via an excel spreadsheet, and is divided into four tabs: hull, engine, prop and conditions. There is a minimum set of mandatory data, without which the program cannot run. The remainder of the data is optional; however, the more data that is input, the more accurate the estimates of performance will be. It is extremely important that data is self-consistent; e.g., draft, displacement and wetted surface area must all correspond to the same draft value. Data descriptions can be found in Tables XIV through XVII. The minimum input data required is summarized in Table XVIII.

B. Basic Program Setup and Running

The program is started in Matlab by running AA0_StartHere.m. Prior to running, a few steps should be checked:

a) Folder Setup: First, ensure that there is a folder named “RESULTS” in the active directory, and within the RESULTS folder, there is a folder named “FIGS”. Output will be placed in these folders.

b) Plotting Flag: Within the AA0_StartHere.m file, line 12 has a plotting flag, named “constants.yesPlot”. If yesPlot is equal to zero, no plots will be created. Setting yesPlot equal to two yields verbose mode with 20 plots presented, and setting yesPlot equal to one yields nine plots.

c) Input Data: The program takes input from two files: input.xlsx and engineData.xlsx. The user should place ship data in each tab of input.xlsx and ensure that the ship name is consistent on each of the four tabs in the input file.

An engine library containing data on a wide range of engines is provided with the program. The user should ensure that the engine model placed on the engine tab of input.xlsx matches the model name of one of the engines in engineData.xlsx. It is possible to add new engines to the engineData library if needed. Two formats are provided; either entry on a single line in the first tab of the spreadsheet, or entry as a full page of data in its own tab. Example sheets are provided for copying.

C. Advanced Program Modifications

Within the AA0_StartHere.m file, line 10 contains the input file name; it is set to “inputs.xlsx”, but can be changed by the user.

Several limits are set within INPUT_Data.m. While we have selected values appropriate to most applications, and do not recommend changing these limits, it is possible for the user to modify these values in the code prior to running. Specific limits follow; all are values in the struct “constant”:

- *lowspeed* is the lowest speed that is calculated by the program. This is set to 7 knots.
### TABLE XIV: Hull Data, entered on the “hull” tab of inputs.xlsx

<table>
<thead>
<tr>
<th>Abbr</th>
<th>Name</th>
<th>Required?</th>
<th>Units or Enumeration</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flags</td>
<td>Ship Type</td>
<td>yes</td>
<td>enumeration</td>
<td>Class or type of ship, enumeration choices: tanker / container / bulker</td>
</tr>
<tr>
<td></td>
<td>Bulbous Bow Flag</td>
<td>yes</td>
<td>yes / no</td>
<td>Indicates whether a bulbous bow is present</td>
</tr>
<tr>
<td></td>
<td>Energy Saving Device</td>
<td>yes</td>
<td>yes / no</td>
<td>Indicates whether a Mewis duct is installed</td>
</tr>
<tr>
<td>Hull Data</td>
<td>Design Speed</td>
<td>yes</td>
<td>[knots]</td>
<td>The design speed</td>
</tr>
<tr>
<td></td>
<td>$L_{bp}$ Length Between Perpendiculars</td>
<td>yes</td>
<td>[m]</td>
<td>Some indication of length is required. The preference is for both $L_{bp}$ and $L_{wl}$ to be provided, but any one of $L_{bp}$, $L_{wl}$ or $L_{oa}$ will suffice.</td>
</tr>
<tr>
<td></td>
<td>$L_{oa}$ Length Overall</td>
<td>yes</td>
<td>[m]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$B$ Beam</td>
<td>yes</td>
<td>[m]</td>
<td>Extreme breadth at waterline</td>
</tr>
<tr>
<td>Data at Design Draft</td>
<td>$T_f$ Draft Forward</td>
<td>yes</td>
<td>[m]</td>
<td>Design draft at the forward perpendicular</td>
</tr>
<tr>
<td></td>
<td>$T_a$ Draft Aft</td>
<td>yes</td>
<td>[m]</td>
<td>Design draft at the aft perpendicular</td>
</tr>
<tr>
<td></td>
<td>$\Delta$ Displacement</td>
<td>yes</td>
<td>[tonnes]</td>
<td>Displacement at design draft. Either Displacement or DWT must be provided.</td>
</tr>
<tr>
<td></td>
<td>DWT Deadweight</td>
<td></td>
<td></td>
<td>Provided, displacement is preferred.</td>
</tr>
<tr>
<td></td>
<td>$lcb_{a,p}$ Longitudinal Center of Buoyancy</td>
<td></td>
<td>[m]</td>
<td>Distance from longitudinal center of buoyancy to the aft perpendicular</td>
</tr>
<tr>
<td></td>
<td>$A_{ws}$ Wetted Surface Area</td>
<td></td>
<td>[m$^2$]</td>
<td>Area of the bare hull at design draft</td>
</tr>
<tr>
<td></td>
<td>$A_{exp}$ Area exposed to wind</td>
<td></td>
<td>[m$^2$]</td>
<td>Athwartships cross-sectional area above the waterline, orthogonal to the direction of travel</td>
</tr>
<tr>
<td></td>
<td>$d_{ap}$ AP to athmost point</td>
<td></td>
<td>[m]</td>
<td>Distance from aft perpendicular to athmost point of wet hull at design draft</td>
</tr>
<tr>
<td>Data at Ballast Draft</td>
<td>$T_{f,B}$ Draft Forward</td>
<td>see note</td>
<td>[m]</td>
<td>Draft at the forward perpendicular in ballast condition</td>
</tr>
<tr>
<td></td>
<td>$T_{a,B}$ Draft Aft</td>
<td>see note</td>
<td>[m]</td>
<td>Draft at the aft perpendicular in ballast condition</td>
</tr>
<tr>
<td></td>
<td>$\Delta_{B}$ Displacement</td>
<td></td>
<td>[tonnes]</td>
<td>Displacement at ballast draft</td>
</tr>
<tr>
<td></td>
<td>$lcb_{B}$ Longitudinal Center of Buoyancy</td>
<td></td>
<td>[m]</td>
<td>Distance from longitudinal center of buoyancy at ballast to the aft perpendicular</td>
</tr>
<tr>
<td></td>
<td>$A_{ws,B}$ Wetted Surface Area</td>
<td></td>
<td>[m$^2$]</td>
<td>Area of the bare hull at ballast</td>
</tr>
<tr>
<td></td>
<td>$A_{exp,B}$ Cross-sectional Area</td>
<td></td>
<td>[m$^2$]</td>
<td>Athwartships cross-sectional area above the waterline, orthogonal to direction of travel at ballast</td>
</tr>
</tbody>
</table>

Note: if ballast condition is to be calculated, ballast draft forward and aft must be provided

### Hullform Coefficients
- $C_{x}$ Midship Section Coefficient: non-dimensional
- $C_{wp}$ Waterplane Coefficient: non-dimensional

### Bulbous Bow Data
- $L_b$ Bulb Length: [m]
- $A_{kt}$ Bulb Transverse Area: [m$^2$]
- $h_b$ Vertical Centroid of $A_{kt}$: [m]
- $A_s$ Bulb Surface Area: [m$^2$]
- $V_b$ Bulb Volume: [m$^3$]

### Appendage Wetted Surface Area
- $A_{app,i}$ Appendage Wetted Surface Area: [m$^2$]

### TABLE XV: Engine Data, entered on the “engine” tab

<table>
<thead>
<tr>
<th>Name</th>
<th>Required?</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Make</td>
<td></td>
<td>Make of the engine, MAN, Wartsila or other</td>
</tr>
<tr>
<td>Engine Model</td>
<td>yes</td>
<td>Engine model. Must match data in engine library</td>
</tr>
<tr>
<td>Engine Control</td>
<td>yes</td>
<td>Engine control methodology, ‘camshaft’ or ‘electronic’</td>
</tr>
<tr>
<td>Number of Cylinders</td>
<td>yes</td>
<td>Number of cylinders in engine</td>
</tr>
<tr>
<td>Number of Turbochargers</td>
<td></td>
<td>Number of turbochargers</td>
</tr>
</tbody>
</table>
TABLE XVI: Propeller Data, entered on the “prop” tab

<table>
<thead>
<tr>
<th>Abbr</th>
<th>Name</th>
<th>Required?</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_p$</td>
<td>Number of Propellers</td>
<td>yes</td>
<td></td>
<td>Number of propellers</td>
</tr>
<tr>
<td>$D$</td>
<td>Diameter</td>
<td></td>
<td>[m]</td>
<td>Diameter of the propeller</td>
</tr>
<tr>
<td>$h_e$</td>
<td>Propeller Height</td>
<td></td>
<td>[m]</td>
<td>Height of the center of the propeller above the baseline</td>
</tr>
<tr>
<td>$Z$</td>
<td>Number of Blades</td>
<td></td>
<td></td>
<td>Number of blades on each propeller</td>
</tr>
<tr>
<td>AE/AO</td>
<td>Expanded Area Ratio</td>
<td>non-dimensional</td>
<td></td>
<td>Propeller blade expanded area divided by the area of the propeller disk</td>
</tr>
<tr>
<td>P/D</td>
<td>Pitch to Diameter Ratio</td>
<td>non-dimensional</td>
<td></td>
<td>Propeller pitch at 0.7 radius, divided by propeller diameter</td>
</tr>
</tbody>
</table>

TABLE XVII: Conditions and Margin Data, entered on the “conditions” tab

<table>
<thead>
<tr>
<th>Name</th>
<th>Required?</th>
<th>Default Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Margin</td>
<td></td>
<td>10%</td>
<td>Percent increase in propulsion power for engine design point calculations</td>
</tr>
<tr>
<td>Sea Margin</td>
<td></td>
<td>15%</td>
<td>Percent increase in propulsion power due to high sea state</td>
</tr>
<tr>
<td>Shaft Efficiency</td>
<td></td>
<td>99%</td>
<td>Transmission efficiency between engine and propeller</td>
</tr>
<tr>
<td>Propeller Margin</td>
<td></td>
<td>5%</td>
<td>Percent decrease in propeller rotation rate used for engine design point calculations</td>
</tr>
</tbody>
</table>

TABLE XVIII: Minimum Required Input Data

- Displacement or Deadweight
- Length
- Beam
- Draft
- Design Speed
- Number of Propellers
- Ship Type Indicator (Tanker, Container)
- Bulbous Bow Indicator (yes, no)
- ESD Indicator (yes, no)
- Engine Layout Diagram including for each corner: Rotation Rate, Brake Power, Mean Effective Pressure, Specific Fuel Oil Consumption

- percentloadmin is the minimum engine load for which fuel consumption is calculated, set to 25%.
- percentloadmax is the maximum engine load for which fuel consumption is calculated, set to 110%.
- $w_{min}$ is the minimum value that the wake fraction, $w$, is allowed to take, set to 0.1.
- $w_{max}$ is the maximum value that the wake fraction, $w$, is allowed to take, set to 0.5.
- $tm_{in}$ is the minimum value that the thrust deduction factor, $t$, is allowed to take, set to 0.1.
- $tm_{ax}$ is the maximum value that the thrust deduction factor, $t$, is allowed to take, set to 0.25.
- $etarmin$ is the minimum value that the relative rotative efficiency, $\eta_r$, is allowed to take, set to 0.95.
- $etarmax$ is the maximum value that the relative rotative efficiency, $\eta_r$, is allowed to take, set to 1.05.

D. Numerical Output

Each time it is run, the program places a time-stamped output file in “../RESULTS”. In this excel file, there will be a separate tab for each ship and each condition. For example, if the input data contains a ship named “thisShip”, output tabs will be named “thisShip”, “thisShip BALLAST”, “thisShip NO BULB”, and “thisShip BALLAST NO BULB”, assuming that input contains ballast data and that the ship has a bulbous bow that is removed.

Each tab contains in the first three columns a tabulation of input data. The first column contains the variable name, the second column contains data values input by the user and the third column contains data values used by the program, thus providing the user any values that were estimated by the program. As an example, in the screenshot shown in Figure 44, note that the user did not input values for the expanded-area ratio or the pitch-to-diameter ratio of the propeller, so the program calculated them; thus, column B reads zero for each value whereas column C reads 0.371 and 0.77 respectively.

![Fig. 44: Output File listing of data input (column B) and data used (column C).](image)
brake power for trial condition and heavy running over a full range of speeds. Specific fuel oil consumption (SFOC) and fuel oil consumption (FOC) for the engine tuned to SMCR are provided for speeds corresponding to a range of 25-110% engine power; see Figure 45. Next, FOC and SFOC for the heavy running case with each applicable engine modification are tabulated as shown in Figure 46. Farther to the right in the output file, details of the propeller calculations and the resistance calculations are tabulated as shown in Figures 47 and 48 respectively.

**E. Graphical Output**

Graphical output includes the following plots, examples of which can be found throughout this report.

- Resistance (Figure 1)
- Propeller design points for various pitch to diameter ratios (Figure 16)
- Propeller selection plotted on engine diagram (Figure 17)
- Engine operating point (Figure 18)
- Brake power vs. ship speed (Figure 28)
- Propeller input data (Figure 23)
- Propeller curves and operating point (Figure 25)
- Propeller rotation rate vs. ship speed (Figure 5 center)
- Engine brake power vs. propeller rotation rate
- Propeller efficiency vs. ship speed (Figure 5 right)
- Engine load diagram, log-log plot (Figure 30)
- Engine load diagram with propeller curves and engine operating polygon (Figure 10)
- Cavitation limit as a function of cavitation number (Figure 7 top)
- Cavitation limit vs. ship speed (Figure 7 bottom)
- Daily fuel consumption vs. percent engine load, heavy running, for various tuning technologies
- Specific fuel oil consumption vs. ship speed for heavy running and various tuning technologies (Figure 32)
such as timely hull cleaning with low cost and high impact.

be useful to parse voyage data for prediction of maintenance

ships, but have the potential to provide significant energy

incorporation of renewable resources such as wind power.

ods that are not examined in the current project such as waste-

warrant further investigation as well.

be to improve twin-screw estimates and add capability for

reduction gears, controllable-pitch propellers, and electric drive

or power-take-off configurations.

Additional energy saving devices beyond the Mewis Duct

warrant further investigation as well.

There are a number of quite interesting energy-saving meth-

ods that are not examined in the current project such as waste-

heat recovery, energy storage, air lubrication of the hull, or

incorporation of renewable resources such as wind power.

These would likely require significant modification to existing

ships, but have the potential to provide significant energy

savings.

Machine-learning techniques and the use of big data would

be useful to parse voyage data for prediction of maintenance

and repair needs which can unearth energy-saving methods

such as timely hull cleaning with low cost and high impact.

ACKNOWLEDGEMENTS

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Hauke Kite-Powell of Marsoft, Inc., used the code exten-
sively, providing testing and feedback on all features. His

testing has greatly improved the robustness of the code.

Lily Keyes conceptualized and implemented the cover art.

REFERENCES


Ship Resistance and Propulsion. John Wiley & Sons Ltd, Hoboken,

[2] Scott D. Black. Thrust breakdown characteristics of conventional pro-
Warfare Center Carderock Division, September 2007.

[3] Luca Bonfiglio and Dario Boote. Progetto di massima di una portacon-

[4] Ø Buhauge, JJ Corbett, O Endresen, V Eyring, J Faber, S Hanayama,
D Lee, H Lindstad, A Mjelde, C Palsson, et al. Second IMO greenhouse

Heinemann, 2018.


a series of 16 inch model propellers. Royal Institute of Naval Architects,

1957.


Mewis Duct® - challenges in full-scale design and new developments for

fast ships. In Third International Symposium on Marine Propulsors

(SMP’13), Launceston, Tasmania, Australia, May 2013.


and principal dimensions (revised). Danish Technical Press, Danmark,

Danmarks Tekniske Højskole, kademisk Forlag, St. kannikestrade 8, DK

1169 Copenhagen, 1974.

[9] J. Holtrop. Statistical re-analysis of resistance and propulsion data. Inter-


dependent form factor. In Proceedings of SMSSH (Scientific and

Methodological Seminar on Ship Hydrodynamics), pages 1–7, Varna,


[14] Hans Otto Kristensen and Marie Lützen. Prediction of resistance and


of Naval Architects and Marine Engineers, Jersey City, NJ, USA, second


[16] MAN Diesel & Turbo. Basic principles of ship propulsion. Technical

report, MAN Diesel & Turbo, 2011.

[17] Friedrich Mewis and Thomas Guida. Mewis duct – new developments,
solutions and conclusions. In Second International Symposium on

Marine Propulsors (SMP’11), Hamburg, Germany, June 2011.

[18] Anthony F Molland, Stephen R Turnock, and Dominic A Hudson. Ship


[19] National Oceanic and Atmospheric Administration. Ocean acidifica-
tion, 2020. https://www.noaa.gov/education/resource-collections/ocean-
coasts/ocean-acidification.


[22] International Maritime Organization. Reducing greenhouse gas emissions

from ships, 2020. https://wwwIMO.org/en/MediaCentre/HotTopics/Pages/Reducing-

[23] Herbert Schneecluth and Volker Bertram. Ship design for efficiency and


[24] Pieter Tans, Ed Dlugokencky, and Ben Miller. The power of greenhouse


Arctic Report Card 2020. National Oceanic and Atmospheric Admin-


APPENDIX

A. Bulbous Bow Effects

A properly designed bulbous bow reduces propulsion power at and around the designed operating speed of the ship. When a ship is operated at a speed significantly different from the speed for which the bulb was designed, the bulb can have an adverse effect on the resistance of the ship, increasing propulsion power and, thus, fuel consumption. This variation in the impact of the bulbous bow is shown in Figure 19 from Carlton [5], who states that the positive impact of bulbous bows occurs over a narrow range of ship speeds, so they are usually employed in ships that operate at clearly defined speeds for much of their time. If a ship is operated consistently off-design, e.g. due to a new operational profile, it may be cost effective to modify the bulb’s shape or to remove the bulb entirely.

The main effect of a bulbous bow is to reduce the ship's bow wave by creating a wave that is out of phase with the bow wave. The bulb also has some less pronounced positive effects due to changing the flow of water past the hull, e.g. reduction of the breaking of the bow wave, changes in the energy in the vortices originating at the bow, and changes in the streamlines at the bow. The change in flow pattern persists to the stern and the propeller, and thus impacts the wake fraction and thrust deduction factor, affecting the propulsive efficiency of the propeller. Kracht [13] provides diagrams of the impact of two specific bulbs on the wake fraction and thrust deduction factor, shown in Figure 49.

The advantages of a bulbous bow are somewhat reduced by an increase in frictional resistance due to the increased surface area of the hull; therefore, at slow speeds where wave resistance is very small relative to frictional resistance, the bulbous bow can increase resistance. Further, at some non-optimum higher speeds, it is possible that the bulbous bow may increase wave resistance if the wave created by the bulb is not out of phase with the ship’s bow wave.

It is definitely agreed upon that the impact of the bulbous bow increases with increasing Froude number to a maximum value, then decreases again to zero at very high Froude numbers. The performance of the bulbous bow is different at laden and ballast drafts; the impact is generally greater, i.e. more beneficial, at ballast, especially for ships with large block coefficients.

B. Bulbous Bow Ranges of Applicability

Figure 50 from Watson [26] shows the combinations of Froude number and block coefficient for which a bulb is likely to be advantageous at full load draft. For finer ships, the bulb is advantageous at high speeds, whereas for ships with a high block coefficient, the bulb is advantageous over a wider range of Froude numbers. Although he does not provide an equivalent diagram for a ship operating at ballast, Watson does state that a bulb is advantageous at ballast even if not advantageous when laden if the ship operates at full power and thus higher speeds (on the order of two knots greater) at ballast than laden. This advantage at ballast condition is greatest on ships with block coefficients greater than 0.75.

Guldhammer and Harvald [8] present a modification to the ship resistance for a bulbous bow which varies with Froude number and block coefficient of the ship and with the transverse cross-sectional area of the bulb at the forward perpendicular relative to the area of the maximum section. The numerical values ($\times 10^3$) of the bulbous bow resistance coefficient are shown in Table XIX. Note the greater impact at higher speeds and lower block coefficients. They further
state that the impact relative to block coefficient is reversed at ballast condition: full forms, with block coefficients greater than 0.70, show a large decrease in resistance with two to three times the values shown in Table XIX, and fine forms, with block coefficients less than 0.6, will tend to increase.

Table XIX: Bulbous bow impact coefficient of resistance \( \times 10^3 \) for fully laden ships as a function of Froude number, \( Fr \), and block coefficient, \( \phi \), for a bulbous bow with transverse sectional area greater than or equal to ten percent of the ship maximum sectional area [8].

<table>
<thead>
<tr>
<th>Fr</th>
<th>0.165</th>
<th>0.180</th>
<th>0.245</th>
<th>0.275</th>
<th>0.308</th>
<th>0.335</th>
<th>0.360</th>
<th>( \phi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta C )</td>
<td>0.2</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>0.60</td>
<td>0.70</td>
<td>0.80</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Data on several pertinent ships with bulbous bows is plotted on the chart provided by Watson in Figure 51. It is interesting that several ships with bulbous bows fall within the area of the plot described as not advantageous for bulbous bows. All of these ships are newer than the original plot, which was published in 2002. These same ships are plotted using the resistance coefficients provided by Guldhammer and Harvald in Figure 52, and again we see that several ships fall into the area in which Guldhammer and Harvald predict an increase in resistance at design speed. One must surmise that either the ship designers purposefully created ships with poor performance, or that progression in bulbous bow design has changed the performance of ships with bulbs since Watson, Guldhammer and Harvald made their assessments.

C. Methods of Estimating Bulbous Bow Effect

a) Schneekluth and Bertram: Schneekluth and Bertram [23] provide a thorough description of the methodology by which a bulbous bow reduces ship resistance. They describe the estimation of the impact of a bulbous bow by using a power-equivalent length. In this methodology, resistance is calculated using a bulb-less ship with all the same properties of the ship with a bulb, except that the characteristic length (\( L_{bp} \) or \( L_{wl} \)) is increased to match the power requirements of the ship with a bulb. This length increase varies with Froude number. Per [23], for Froude numbers between 0.22 and 0.25, the ship’s length is increased by about half of the length that the bulb projects forward of the forward perpendicular; for Froude numbers between 0.3 and 0.33, the ship’s length should be increased by up to three times the length of the bulb. This methodology has a great deal of error inherent in it, mainly because the forms of bulbs vary greatly and it is difficult to capture the interaction of the bulb with the hullform using this rather coarse tool.

b) Hollenbach: Hollenbach [1] addresses the bulbous bow by increasing ship length by the length of the bulb, similar to the method suggested by Schneekluth and Bertram, except the added length is not modified for various speeds. This method does not allow comparison of hullforms with and without a bulb, as the hullform without a bulb demonstrates higher resistance even at very low speeds where frictional resistance is dominant and thus where the bulb should increase ship resistance.

c) Kracht: Kracht [13] performed an in-depth study of the performance of various bulbous bow forms and the impact that several parameters have on the performance of the bulb. These parameters include length, width, height, volume, and position and shape of the bulb, all related to equivalent data of the bare ship hull. Kracht defines a residual power reduction coefficient, \( \Delta C_{P\nabla R} \), to capture the change in residual resistance for a ship with and without a bulb,

\[
\Delta C_{P\nabla R} = 1.0 - \frac{C_{Rwith}}{C_{Rwithout}},
\]

where \( C_{Rwith} \) and \( C_{Rwithout} \) are residual resistance coefficients of equivalent ships with and without a bulb. Figure 53 shows the variation of \( \Delta C_{P\nabla R} \) with Froude number for various bulb shapes and baseline hulls. All of these example ships have a block coefficient of approximately 0.7. Note the variation of impact of the bulb with Froude number, and thus
with speed of the ship.

Kracht produced a set of design curves that assist in the selection of the properties of a bulb for a given application. We find that using these curves to predict bulb size on modern cargo ships significantly under-predicts the size of the bulb that is actually installed on the ships we tested, possibly due to the amount of noise in the prediction charts, due to advances in bulb design, or due to changes in ship design and performance over the years.

Fig. 53: Residual power reduction coefficient as a function of Froude number for various ship-bulb combinations [13]. All ships have a block coefficient very close to 0.7.

d) Kristensen and Lützen: Kristensen and Lützen [14] provide separate equations to estimate the resistance impact of bulbous bows for container ships and for bulk carriers and tankers, derived from the examination of several model test results for ship hulls with bulbous bows, compared to equivalent bulb-less hull resistance calculated by Harvald’s method. They argue that the impact of a bulbous bow depends primarily on three parameters: the length-displacement ratio, the prismatic coefficient, and the Froude number, \( Fr \). They further argue that, for tankers, the length-displacement ratio and Froude number vary within a very tight range, so they present an equation for estimating resistance impact of a bulbous bow for a tanker as a function of Froude number only

\[
\Delta C_{R,bulb} = \max(-0.4, -0.1 - 1.6 Fr).
\]  

(24)

This bulb correction is negative, thus reducing resistance, for all vessels at all speeds. For a container ship, the correlation is found to be

\[
\Delta C_{R,bulb} = (250 Fr - 90) \cdot \frac{C_{R,HarvaldNOBulbousBow}}{100}.
\]  

(25)

where \( C_{R,HarvaldNOBulbousBow} \) is the coefficient of resistance for the equivalent ship without a bulbous bow calculated using the Harvald estimation process. This bulb correction is negative for expected Froude numbers.

The data upon which Kristensen and Lützen based their equations are shown in Figure 54 for equation (24) and Figure 55 for equation (25). One can see that there is significant noise in the data.

e) Holtrop and Mennen: Holtrop & Mennen multiply the wave resistance by a constant value, \( c_2 \), where \( 0 < c_2 \leq 1 \), thus reducing the wave resistance by a constant percentage across the full range of ship speeds. The coefficient \( c_2 \) is a function of bulbous bow transverse cross-sectional area at the forward perpendicular, \( A_{bt} \); height of the centroid of this area, \( h_b \), compared to ship draft forward, \( T_f \); and ship beam, \( B \); and draft, \( T \), as follows:

\[
c_2 = e^{-1.89\sqrt{c_3}}
\]

where

\[
c_3 = \frac{0.56A_{bt}^{1.5}}{BT(0.31\sqrt{A_{bt}} + T_f - h_b)}
\]

Although the Holtrop & Mennen method does not fully
capture the change in effect of a bulbous bow with Froude number around design speed, the estimation is a reasonable approach because at low speeds, the wave resistance is very low, so the bulb impact is low; and the ship does not typically move at speeds significantly above the design speed, so the inaccuracies at very high speeds are not pertinent.

D. Bulbous Bow Conclusions

The conclusions we have drawn from our review of bulbous bow analysis and estimation criteria are as follows:

- It is clear that a properly designed bulbous bow can reduce ship resistance.
- The reduction in wave resistance due to the bulb peaks at a specific Froude number and drops off with speeds both higher and lower than the peak, as shown in Figure 53.
- This reduction in ship resistance occurs within a window of speeds centered around the speed for which the bulb is designed. Outside this window, the bulb has very little effect and can even have an adverse effect as shown in Figure 19.
- No simple estimation method exists that can accurately calculate the impact of the bulb on the ship’s resistance, especially over a range of speeds and loading conditions. Bulb performance varies widely as shown in Figures 53, 54 and 55. This is because the bulb shape is designed in conjunction with the ship hull to tailor flow to a specific operational condition. Accurate estimation of the ship’s resistance with a bulb requires model testing or CFD analysis of the ship’s lines.
- Recommendations for a new bulb tailored to a new operating speed cannot be accomplished using standard-series-level or regression-analysis-level data; it requires either model testing or CFD.
- We find that Holtrop’s method works as well as any of the methods available for estimating the impact of the bulbous bow on resistance, and better than many, and has the further recommendation that it is in keeping with the remainder of the Holtop resistance estimation method that we employ.
- We provide a ballpark-level estimate of savings found through removal of the bulb. If this appears advantageous, we recommend more detailed analysis prior to committing to any structural changes.
GLOSSARY

\( \Delta \) displacement at design condition
\( \Delta_B \) displacement at ballast condition
\( \nabla \) volumetric displacement at design condition
\( \nabla_b \) bulbous bow volumetric displacement
\( \nu \) kinematic viscosity of sea water
\( \rho \) density of sea water
\( \rho_a \) density of air
\( \eta_p \) propeller hull efficiency
\( \eta_o \) open water propeller efficiency
\( \eta_r \) propeller relative rotative efficiency
\( \eta_s \) shaft efficiency
\( \sigma \) local cavitation number
\( \tau_c \) cavitation thrust coefficient
\( A_b \) surface area of the bulbous bow
\( A_{bt} \) transverse cross-sectional area of the bulbous bow at the forward perpendicular
\( A_E \) propeller expanded area
\( A_{exp} \) the transverse cross-sectional area of the hullform and cargo above the waterline
\( A_P \) propeller projected blade area
\( A_{wp} \) waterplane area
\( A_{ws} \) wetted surface area of the hull
\( A_{wsB} \) wetted surface area of the hull at ballast
\( A_x \) transverse area of midship section below waterline
\( AE/AO \) propeller expanded area ratio
\( B \) beam at waterline
\( C_{a} \) correlation allowance
\( C_{aa} \) air resistance coefficient
\( C_{app} \) coefficient of frictional resistance for appendages
\( C_b \) block coefficient
\( C_f \) coefficient of frictional resistance
\( C_p \) prismatic coefficient
\( C_r \) coefficient of residual resistance
\( C_{stern} \) Holtrop stern shape parameter
\( C_{th} \) thrust coefficient
\( C_v \) viscous resistance coefficient
\( C_{wp} \) waterplane area coefficient
\( C_x \) midship section coefficient
\( CSR \) engine continuous service rating
\( D \) propeller diameter
\( d_{ap} \) distance between aft perpendicular and aftmost point of the wet hull
\( ECT \) diesel engine electronic control tuning
\( EGB \) exhaust gas bypass, a diesel engine tuning methodology
\( e_m \) engine margin
\( F_{trim} \) trim factor
\( Fr \) Froude number
\( Fr_c \) critical Froude number
\( FOC \) fuel oil consumption
\( g \) gravitational constant
\( h \) depth of center of propeller hub below water surface
\( h_o \) height of the centroid of \( A_{bt} \) above the baseline
\( h_z \) height of the center of the propeller hub above the baseline
\( i_e \) entrance half-angle
\( J \) propeller advance ratio
\( K_{Q} \) propeller torque coefficient
\( K_T \) propeller thrust coefficient
\( L_b \) length of bulbous bow extending forward of forward perpendicular
\( L_{hp} \) ship length between perpendiculars

\( \Delta \) \( \rho \)

\( \Delta B \) \( \rho_a \)

\( \nabla \) \( \nu \)

\( \nabla_b \) \( \nu \)

\( \nu \) \( 1.1945 \cdot 10^{-6} (m^2/s) \)

\( \rho \) \( 1026 \text{ kg/m}^3 \)

\( \rho_a \) \( 1.225 \text{ kg/m}^3 \)

\( \eta_p \) \( (1-w)/(1-t) \)

\( \eta_o \) \( (1-w)/(1-t) \)

\( \eta_r \) \( (1-w)/(1-t) \)

\( \eta_s \) \( (1-w)/(1-t) \)

\( \sigma \) \( (1-w)/(1-t) \)

\( \tau_c \) \( (1-w)/(1-t) \)

\( A_b \) \( (1-w)/(1-t) \)

\( A_{bt} \) \( (1-w)/(1-t) \)

\( A_E \) \( (1-w)/(1-t) \)

\( A_{exp} \) \( (1-w)/(1-t) \)

\( A_P \) \( (1-w)/(1-t) \)

\( A_{wp} \) \( (1-w)/(1-t) \)

\( A_{ws} \) \( (1-w)/(1-t) \)

\( A_{wsB} \) \( (1-w)/(1-t) \)

\( A_x \) \( (1-w)/(1-t) \)

\( AE/AO \) \( (1-w)/(1-t) \)

\( B \) \( (1-w)/(1-t) \)

\( C_{a} \) \( (1-w)/(1-t) \)

\( C_{aa} \) \( (1-w)/(1-t) \)

\( C_{app} \) \( (1-w)/(1-t) \)

\( C_b \) \( (1-w)/(1-t) \)

\( C_f \) \( (1-w)/(1-t) \)

\( C_p \) \( (1-w)/(1-t) \)

\( C_r \) \( (1-w)/(1-t) \)

\( C_{stern} \) \( (1-w)/(1-t) \)

\( C_{th} \) \( (1-w)/(1-t) \)

\( C_v \) \( (1-w)/(1-t) \)

\( C_{wp} \) \( (1-w)/(1-t) \)

\( C_x \) \( (1-w)/(1-t) \)

\( CSR \) \( (1-w)/(1-t) \)

\( D \) \( (1-w)/(1-t) \)

\( d_{ap} \) \( (1-w)/(1-t) \)

\( ECT \) \( (1-w)/(1-t) \)

\( EGB \) \( (1-w)/(1-t) \)

\( F \) \( (1-w)/(1-t) \)

\( Fr \) \( (1-w)/(1-t) \)

\( Fr_c \) \( (1-w)/(1-t) \)

\( FOC \) \( (1-w)/(1-t) \)

\( g \) \( (1-w)/(1-t) \)

\( h \) \( (1-w)/(1-t) \)

\( h_o \) \( (1-w)/(1-t) \)

\( h_z \) \( (1-w)/(1-t) \)

\( i_e \) \( (1-w)/(1-t) \)

\( J \) \( (1-w)/(1-t) \)

\( K_{Q} \) \( (1-w)/(1-t) \)

\( K_T \) \( (1-w)/(1-t) \)

\( L_b \) \( (1-w)/(1-t) \)

\( L_{hp} \) \( (1-w)/(1-t) \)
\( L_c \) Hollenbach characteristic length
\( L_{oa} \) ship length overall
\( L_{os} \) overall length of wetted surface
\( L_r \) Holtrop & Mennen length of run of ship
\( L_{wl} \) ship waterline length
\( lcb \) longitudinal center of buoyancy with respect to \( \frac{1}{2}L_{wl} \) as percent of \( L_{wl} \), positive forward
\( lcb_{ap} \) longitudinal center of buoyancy of the ship measured from the aft perpendicular
\( lcb_b \) longitudinal center of buoyancy of the bulbous bow
\( \text{MCR} \) engine maximum continuous rating
\( \text{MEP} \) engine mean effective pressure
\( N \) engine rotation rate
\( N_{\text{SMCR}} \) engine rotation rate at SMCR
\( N_p \) number of propellers
\( n \) rotation rate of propeller
\( P_b \) brake power
\( P_d \) delivered power
\( P_e \) effective power
\( P_{b\text{SMCR}} \) engine brake power at SMCR
\( P/D \) propeller pitch-to-diameter ratio at 70% of the radius
\( p_{atm} \) atmospheric pressure
\( p_v \) vapor pressure of seawater
\( p_0 \) hydrostatic pressure
\( p_m \) propeller margin
\( Q_o \) open water torque
\( R_a \) correlation allowance resistance adjustment
\( R_{aa} \) air resistance
\( R_{app} \) total frictional resistance of all appendages
\( R_f \) frictional resistance
\( R_r \) residuary resistance
\( R_T \) total resistance
\( R_{TTC} \) total resistance at trial condition
\( R_{HR} \) total resistance at heavy running condition
\( R_w \) wave resistance
\( Re \) Reynold’s number
\( S_{app} \) appendage surface area
\( \text{SFOC} \) specific fuel oil consumption
\( \text{SMCR} \) engine specified maximum continuous rating
\( T \) mean draft at design condition
\( T_a \) draft at the aft perpendicular at design condition
\( T_f \) draft at the forward perpendicular at design condition
\( T_B \) mean draft at ballast condition
\( T_{aB} \) draft at the aft perpendicular at ballast condition
\( T_{fB} \) draft at the forward perpendicular at ballast condition
\( T_b \) thrust
\( T_o \) open water thrust
\( \text{TCCO} \) turbocharger cut-out, a diesel engine tuning methodology
\( t \) thrust deduction factor
\( t_B \) thrust deduction factor at ballast condition
\( V \) ship speed
\( V_a \) water speed at the propeller
\( V_R \) relative velocity of water at 0.7 of the propeller radius
\( \text{VITA} \) variable turbine area, a diesel engine tuning methodology
\( w \) wake fraction
\( w_B \) wake fraction at ballast condition
\( Z \) number of propeller blades
\( (1 + k) \) frictional form factor
\( (1 + k_2) \) appendage resistance factor
\[ P_d / \eta_s \]
\[ P_e / \eta_o \eta_h \eta_r \]
\[ p_0 = p_{atm} + \rho g h \]
\[ VL/\nu \]
Representative engine load and operating limits for an engine installed in a ship

SHIPPING ACCOUNTS FOR 80% OF GLOBAL TRADE