Integrating Seakeeping in the Design of Semi-Displacement and Displacement Monohulls
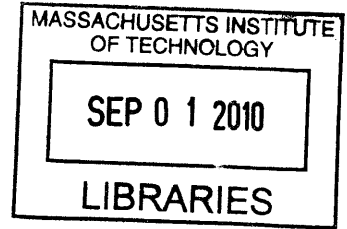
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ABSTRACT

Early stage ship design and assessment continues to be a challenge for naval architects and ocean engineers. The complex and multifaceted interactions between the different components of the ship and the broad spectrum of disciplines required in ship design make it difficult to fully realize the effects of any one change on the entire system. The initial design of smaller patrol craft is especially difficult due to the lack of design tools able to deal with ships of small size operating in the semidisplacement region. Furthermore, seakeeping at high speeds cannot be reliably calculated by traditional methods such as strip theory due to the hydrodynamic effects that occur in the semidisplacement region. Traditional methods have a vessels' response in seas calculated after most initial design decision have been cemented, making changes in design for improved seakeeping difficult at best. This paper puts forth a method for narrowing the design space for semidisplacement and displacement patrol craft operating at Froude numbers up to Fn= 1.0 and incorporating the vessels' response in seas into early stage design. Optimization of the design is done through the use of response surface methodology. Using a systems approach, a Patrol Craft Assessment Tool (PCAT) was created and tested to aide designers in the initial design and assessment of patrol craft of < 90 m. PCAT is an MATLAB code that interfaces with Surface Wave Analysis (SWAN2) to incorporate resistance, engine selection, structures, seakeeping, and mission profiles into one design program to aide a designer in optimizing a patrol craft and understanding the engineering tradeoffs.

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1.0 Introduction

Early stage ship design and assessment continues to be a challenge for naval architects and ocean engineers. The complex and multifaceted interactions between the different systems on the ship and the broad spectrum of disciplines required in ship design make it difficult to fully realize the effects of any one change on the entire system. The initial design of smaller patrol craft is especially difficult due to the lack of design tools able to deal with ships of small size operating in the semi-planing region and the complex body and fluid interactions occurring in the semi-planing region.

While numerous methods have been developed to determine many of a ship's performance metrics (weight, resistance, internal areas) parametrically for semi-displacement ships, calculating seakeeping characteristics of these vessels in early stage design is not usually performed due to the complex nature of the calculations and the time involved in performing them. Strip theory, which is typically used to perform early design seakeeping calculations on displacement vessels, does not produce accurate results above a Froude number of about 0.4 (1) (where the semi-planing region begins). Therefore, seakeeping analysis is put off until later in the design cycle. This is typically mitigated through the use of hull shapes that have historically shown good seakeeping performance. While this method has produced good results, it begs the question, can incorporating seakeeping in to early stage design of semi displacement vessels be done, and if so, does it produce a better ship?

A program such as Surface Wave Analysis (SWAN2), which uses the three dimensional Rankine Panel Method to determine fluid flow around high speed bodies, can accurately calculate seakeeping characteristics of semi-displacement vessels in a timely manner. Additionally, SWAN2 can calculate residual resistance values that incorporate all changes to the shape of the hull, displacements, and trims providing the designer a better comparison of similar hulls than parametric methods that are typically used in early design.

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Using SWAN2 to provide resistance and seakeeping data, the American Bureau of Shipping (ABS) standards to provide structural information, the Society of Allied Weight Engineers (SAWE) standards to provide weight information, the Society of Naval Architects and Marine Engineers (SNAME) for additional resistance and process information, various engine catalogs for information on prime movers, and United States Navy and United States Coast Guard standards, designs, and cost information, it is possible to construct a basic model of ship which can produce performance metrics and cost information. With whole ship, performance and cost, the designer can better understand the effect certain design decisions have on the entire vessel.

However, there are two significant challenges that such a method would present. First is the issue of timeliness. While SWAN2 can produce results for semi-planing vessels more accurately and quicker than many other sources, the calculation of seakeeping for smaller vessels still takes time. Smaller vessels mean resonances in heave occur at shorter wave lengths waves. Shorter wave length ocean waves occur at higher frequencies, which in turn means that to get accurate results for seakeeping, many more calculations have to be performed. This in and of itself is not that difficult to overcome. However, the number of design variables and the scope of the design space in ship design can easily lead to tens of thousands of possible ships, if not more. Therefore, a full factorial exploration of the design space is simply impractical. Instead some optimization must occur. The second issue relates to the detail of the design. In a ship's final design, there are many detailed drawings, arrangements, and analyses, and calculations that need to be performed. To quickly analyze the design space, a design tool such as the one proposed in this paper, could not be used to create such designs. Instead such a tool could be used to eliminate the part of the design space that produces poor results, show portions of the design space where the decision does not produce much change on cost or performance, and most importantly, it can show the design decisions that will drive cost and performance. With this information, the designer can narrow the design space in to allow a more detailed analysis to be performed in areas where the most benefit can be derived.

Current Research

There have been several attempts to solve the complex problem of the design of semiplaning monohulls. Jan Blok and Wim Beukelman looked at calculating seakeeping for frigates and small patrol craft operating in the semidisplacement region, specifically Fr = 0.7 – 1.2. Through model testing of a systematic series, they found that "a hull can be obtained that incorporates a sizeable improvement in the seakeeping at the expense of just a little extra resistance." This finding is extremely important as it shows the importance of understanding the effects of seakeeping early in the design process and the significant impact that it can have on the entire ship design. Additionally they found that for their series, the assumption that strip theory could not be applied to high speed vessels was not entirely accurate. Strip theory did reasonably hold in all motions up to a Froude number of 0.57 (2), but not throughout the entire semi-planing range.

A. M. Wijngaarden and W. Beukelman also used strip theory looked at seakeeping for semiplaning vessels (3). As opposed to looking at a vessel's motion in all six degrees of freedom, they instead created an operability metric that looked at a vessels motion at a specific sea state, a specific heading relative to the seas, and a specific speed. In this way while not capturing the full range of motion for the vessels, they still capture a quick snapshot of seakeeping in a way that can be used for ship design. This method was later used to compare seakeeping in the conceptual phase of design for small warships.

Eames and Drummond's concept exploration paper on the design of small warships (4) looks at many of the same issues that this thesis aims to attack. However, their definition of a vessel is limited. Eames and Drummond originally used a parametric seakeeping perfomance which they readily admit is suboptimal. Their design is limited to 5 independent variables length, length to displacement ratio, prismatic coefficient, breadth to draft ratio, and length to depth ratio, making the calculation of seakeeping for a ship impossible.

1.2 Existing Programs

Several commercial and private programs also perform similar features to the what this thesis is trying to accomplish.

Maxsurf is a suite of products made by Formation Design Systems that aids ship designers in modeling hull forms and determining the full range of naval architectural requirements using a common graphical user environment. Linear strip theory is used extensively as the primary means of analyzing stability, seakeeping, and resistance. Structural analysis can be performed within the suite as well. All modules work consistently on a common ship model (5). Maxsurf would seem to be a very good product for the design of a patrol craft. It uses an interface that allows a smooth transition between modules such as seakeeping and resistance, and it even allows for detailed design. While Maxsurf is an excellent product, it does not allow for gross changes to be applied to a design in a simple manner. For instance, if the designer wanted to look at the performance effects of two different hull forms, the designer would first have to build two separate hull forms (which is a time consuming process), analyze the hull forms separately and then export the analysis information into a separate program for comparison. While an excellent analysis tool and later stage design tool, Maxsurf is not adequate for the early stage design.

The Program of Ship Salvage Evaluation (POSSE) is a structural analysis and salvage response software owned by the U.S. Navy's Supervisor of Salvage and maintained by Herbert Engineering Corporation that provides the capability to perform engineering analyses of complex structural and ship salvage situations, including assessments of ship stability, drafts/trim, intact or damaged structural strength, ground reaction and freeing force, oil outflow and flooding, lightering (weight removal) plan, and tidal effects (6). POSSE is another excellent analysis program, though it is limited in scope to primarily structures. It does not have the resistance or dynamic seakeeping analysis of a program like Maxsurf, but it does allow for easy analysis of ship structures to verify the user specified design requirements were met. This program does not have the breadth of ability to be used in a complete design package, and is sorely lacking the ability to receive a script input to allow for easier interface with other programs. Therefore POSSE was not used for this project.

Paramarine, created by GRC Ltd., is an excellent object oriented program that allows for the designer to go from concept through final detailed design in one program. It is a very powerful

and robust program. However it is not suited to early stage concept analysis. The designer must place every system on the ship from the main machinery all the way down to the fuel pump. This level of detail, while excellent for a complete design, is not ideal early in the design process. Unlike Maxsurf, Paramaine does have the ability to change major variables (such as hull length) with relative ease; however it is not able to compare different variants within the program. Paramarine cannot be used to meet the objective of this project primarily due to the detail required to design a single variant and the time intensive nature of a single design process.

Advanced Surface Ship Evaluation Tool (ASSET) is a synthesis tool developed and maintained by the U.S. Naval Sea Systems Command, Carderock Division. It allows for the designer to input design variables such as hull form, ship subdivisions, and weapon system weights, and attempts to synthesize the design into a single ship. ASSET has the ability to take inputs from other programs such as a spreadsheet, manipulate the information, and return synthesized data. ASSET's capabilities match very closely with the objectives of this thesis. It incorporates all major hull systems and design variables into a program that requires no manipulation of data by the user and displays results in a timely manner. However ASSET has three major drawbacks that limit its use for the purpose of PCAT. It cannot perform analysis of different ships within the program; however this can be accomplished using a scripting function due to ASSET's ability to receive data at any stage of the design. Secondly, and more importantly, ASSET is not designed for patrol craft design. According to the ASSET web site, ASSET's surface combatant module is intended to design ships in between 1000 and 12,000 tons (7). The patrol craft concept will be less than 1000 tons thereby making ASSET unusable for this project. Finally ASSET does not seakeeping analysis for semi-planing patrol craft.

The above list of design programs was not intended to be exhaustive, but brief look at a range of available tools. While each of the design tools does have its advantages, none are adequately suited to meet the design goal of this project. Therefore a new program had to be developed. Matlab was chosen as the coding environment because the of the ability to handle large amounts of data, the ability to interface with other programs, and the ease of creating graphical interfaces. The program was named the Patrol Craft Assessment Tool or PCAT.

1.3 Major Assumptions

To complete a project of this magnitude some major assumptions needed to be made especially in regard to the weights in the ship. Because every system is not placed on board the ship in PCAT, it is impossible to get an accurate system weight. Doing so would require the program to account for every pump, motor, nut, bolt, and weld. Instead, PCAT uses the common practice of assuming that the weights can be estimated from similar ships. However, when estimating weights, it is difficult to estimate locations of weights. Therefore, the height of the center of gravity (KG) of the ship is not calculated. Instead the user inputs a range of values. In this way, the designer can design to a specific KG, or at the very least understand the effects of changing KG on the ship. Similarly, the longitudinal center of gravity (LCG) is not calculated, but rather is input by the user. It is reasonable to say that the LCG will be very near or directly over the longitudinal center of buoyancy (LCB). Therefore the user can default the LCG to LCB.

In the design of any ship a standard needs to be set for what is allowable and what is not. The U.S. Navy historically uses military specifications detailed in design data sheets (DDS). While using DDS as a standard would be completely justifiable, it is not optimal for this project. The U.S. Navy is moving away from DDS standards and incorporating their standards into the U.S. Naval Vessel Rules which is a controlled document, hence the author was unable to obtain a copy of the Naval Vessel Rules. Therefore with the exception of range calculations, the design standard used was the American Bureau of Shipping (ABS) rules for steel vessels < 90m in length. ABS standards are publicly available and can be downloaded from the ABS web site. A copy of the relevant ABS structural standards is available in Appendix A.

As in any design, the designer cannot go into a project blindfolded. They must have a clear idea of what needs they are trying to fulfill. While not specifically addressed in this paper, accurately determining the needs of the ship owners and operators and involving them in design decisions is vital to the success a ship. If the goal of a project is to provide value to a customer, and the customer needs are not adequately considered, the designer is guaranteed to have a suboptimal product in performance and cost. More information on gathering customer requirements can be found in reference (5).

1.4 SUMMARY

In summary, this thesis intends to put forth a method for exploring the design space in early stage design of patrol craft design. Using a systems approach, a Patrol Craft Assessment Tool (PCAT) will be created and tested to aide designers in the initial design and assessment of patrol craft of < 90 m operating in the semi-displacement or displacement regions. PCAT will be an open source MATLAB code that incorporates resistance, engine selection, structures, mission profiles, seakeeping, cost, and performance into one design program to aide a designer in optimizing a patrol craft.

2.0 Software Architecture

The first step in creating a design tool was to layout the architecture of the program. Using systems engineering, the ship design was broken down into modules that had a specific set of requirements. The interfaces (variables passed to and from modules) were also defined, though they were not controlled as rigorously as they would be on a mechanical project because of the ease in changing the interface. A common heuristic for software architecture is "software architecture should be grown or evolved, not built." (6) This heuristic was used extensively in this program. While clearly laying out the a best guess for the initial function definitions of each module allowed the architect to better understand the requirements of each module and to ensure each module was built as robustly as possible, the architecture was fluid and changed constantly throughout the design process. What follows is the final version of the software architecture.

The software architecture is divided into two equally important areas; the program architecture which details the flow of the program, the purpose of each module, and the interfaces required, and the data architecture which details how the data is stored, retrieved, and used. These two areas are discussed below.

2.1 Program Architecture

The overall flow of PCAT is shown in Figure 2-1. Each of the blocks was in turn divided into functions or modules that executed to create a specific variant.

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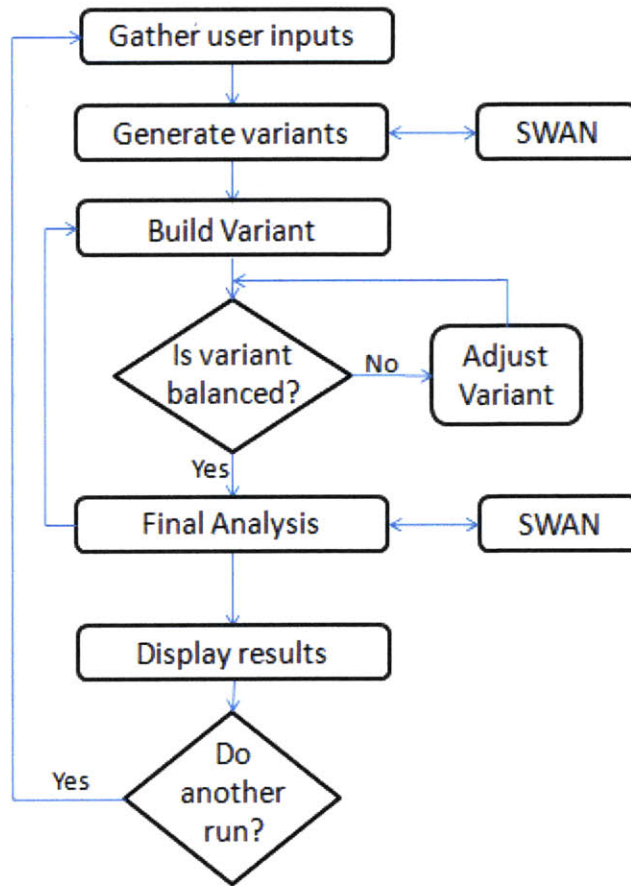
Figure 2-1 Overall Program Architecture

2.1.1 Gathering User Inputs

All user inputs were gathered using a graphical user interface (GUI). Matlab provides a function called *guide* that aides in the building of the GUIs. All GUIs used in PCAT were created using the *guide* function. The purpose of the user inputs section is *to gather user desires and store the information for use later in the program by querying the user for relevant data in an easy to understand format using GUIs.* The user inputs were divided into eight segments: geometry, loading, machinery and manning, weapons, speed, seakeeping, overall measure of effectiveness (OMOE), and cost. Many of the user inputs provide the ability for a range of values. If a range of values is required, the user will be asked for a minimum value, a maximum value, and the number of steps. For instance if the minimum length is 30 m, the maximum length is 50 m, and the number of length steps is 3, ships will be tested with lengths of 30 m, 40 m and 50 m.

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However, the number of steps is ignored is the user desires a response surface model built. Only the minimum and the maximum values are required.

The geometry segment of user inputs is responsible of gathering the user desires for length defined as length between perpendiculars (LBP)[1], length to beam ratio (L/B), length to depth ratio at midships (L/D)[2], the deck height or spacing between internal decks, and the parent hull or hull shape. The geometry segment will gather these variables and store them in a global variable for use later in the program. Figure 2-2 shows a screen shot of the geometry user input page.

Figure 2-2 Geometry Inputs

The next segment is the loading segment. The loading segment is responsible for gathering the user desires for LCG, KG/D, frame spacing, and material used. The properties of the materials

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[1] Throughout the program the ships "length" is the LBP. If length overall (LOA) is required, it is specifically listed as such

[2] In PCAT, depth is defined as the depth at station 10 or depth at midships unless specifically listed otherwise.

used are taken from ABS (7) with the exception of material density. While no specific density was listed in ABS, in a survey of several manufacturing sites, the densities of the steels used were constant at 7850 kg/m^3. This value was used for the density of all three steels. Figure 2-3 shows a screen shot of the loading inputs screen.

	Yield Strength	235 N/mm^2
Ordinary Strength Steel	Ultimate Tensile Strength	460 N/mm^2
	Density	7850 kg/m^3
	Yield Strength	315 N/mm^2
Higher Strength Steel - AH32	Ultimate Tensile Strength	515 N/mm^2
	Density	7850 N/mm^2
	Yield Strength	355 N/mm^2
Higher Strength Steel - AH36	Ultimate Tensile Strength	555 N/mm^2
	Density	7850 kg/m^3

Table 2-1 Material Properties

Figure 2-3 Loading Inputs

The machinery and manning segment gathers data on the number of engines per shaft, the number of shafts, and the number and type of manning on board the ship. Additionally this segment allows the user to specify whether waterjets or propellers will be analyzed used. While the total value of the ship's crew can be changed over the variants, the breakdown is constant over all variants. A screen shot of the machinery and manning input screen is shown in Figure 2-4.

Figure 2-4 Machinery and Manning Input

Figure 2-5 Weapons Input

The weapons segment serves a different function than the other segments. The purpose of the weapons segment is not to receive a range of weights for weapons but rather to receive a list of independent sets of weapons, C4I (command, control, communication, computers, and information), navigation and communication systems to be used on board the ship. Each set of "weapons" will be used on each variant of ship. For each set, the user enters the total weight, required in hull area, required main deck or deckhouse area, power requirement, KG/D, measure of effectiveness for this set of systems (MOE), and cost of this set of systems (the power requirement and the KG/D currently serve no purpose, but are there as place holders for future versions of the program). The user must enter all equipment that would normally be part of SWBS weight groups 400, 700, and variable loads with the exception of fuel loading. This segment is essentially used to capture mission specific equipment that can be estimated b traditional means. A screen shot of the weapons input screen is shown in Figure 2-5.

The speed segment gathers information on speed requirements. A speed profile is input to aide in lifecycle cost calculation. Additionally, maximum speed (or more accurately, the minimum speed that must be achieved at full power), endurance speed, and range are all gathered in this segment. A default is provided to set the endurance speed to the most efficient speed. Figure 2-6 shows the speed input screen.
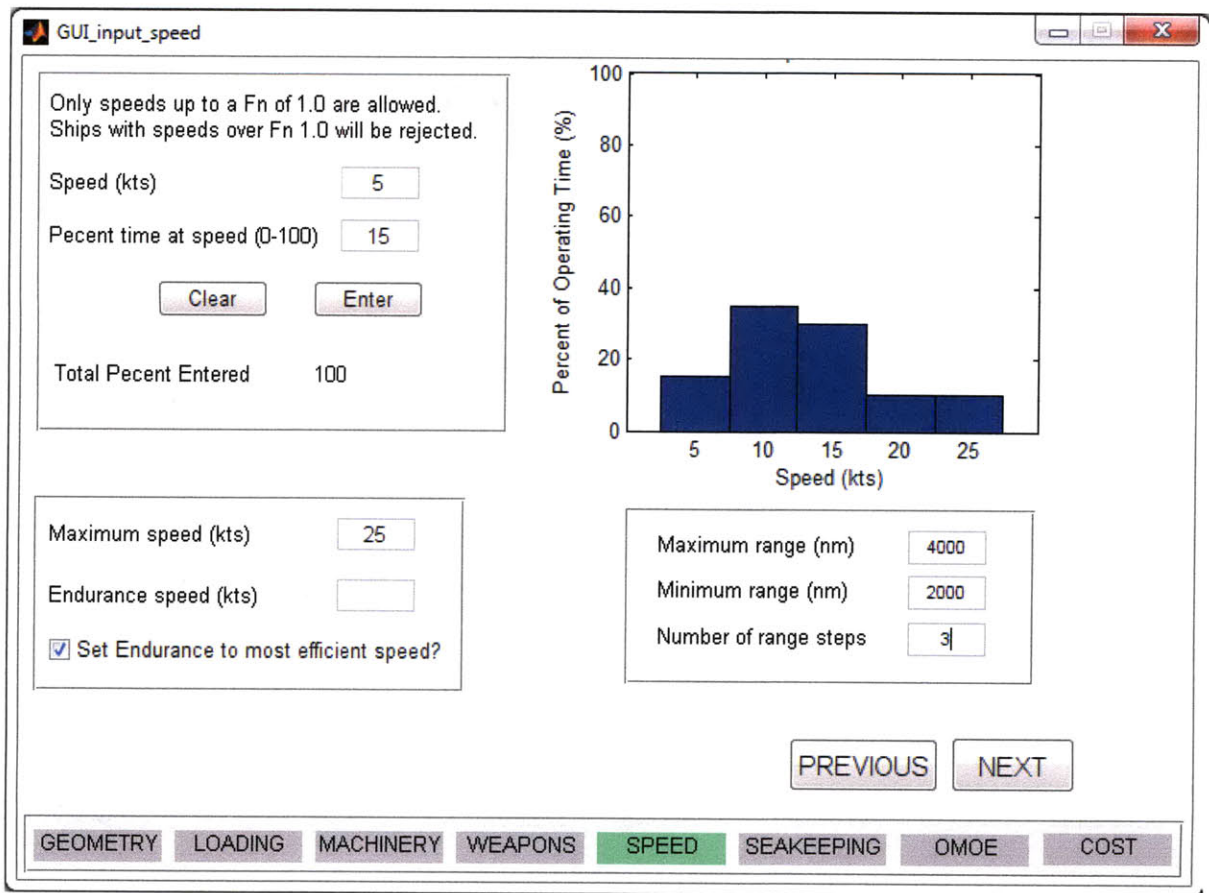
Figure 2-6 Speed Input

The seakeeping segment gathers information on the sea keeping environment for analysis. The sea spectrum used is the Brett Schneider sea spectrum for fully developed seas. This is a two parameter spectrum that requires the modal frequency and the significant wave height to be input. Designer's however, typically define seakeeping requirement in terms of a sea state. The World Meteorological Organization (WMO) publishes information on sea states (or Beaufort Scale) (8) including wave heights for a given sea state. Assuming the peak energy of the spectrum is associated with the mean wave height, the modal frequency can be determined using the dispersion relationship for deep water waves.

$$\omega^2 = gk$$

The remaining inputs are not currently used, but can be used to determine the sea keeping of a vessel over an entire operating range of speeds and headings.

Figure 2-7 Seakeeping Input

The OMOE segment allows the user to vary how performance is calculated. All performance variables are calculated on a linear scale with the threshold being zero and the goal being one. If a value falls below the threshold, it defaults to zero. If a value falls above the goal, it defaults to one. OMOE is divided into three primary groups: Operations, Mobility, and Weapons. The sum of the three primary groups MOE's is typically one. The operations and mobility groups are further sub-divided. Mobility is divided into maximum speed (note this is the actual maximum speed, not the maximum speed entered), the numbers of days the ship can be on patrol, the range of the ship, and the draft of the ship. Operations is divided into main deck space which is the deck area remaining after the weapons are accounted for, in hull space which is the amount of area remaining after the weapons and the prime movers are accounted for, total manning, and sea keeping which is represented by a Motion Sickness Incidence (see seakeeping section for more information). The total MOE of each set of subdivisions usually sums to one. While this is not a requirement, it is a good practice. The OMOE segment allows the user to default goal and

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threshold values to the minimum (or worst) and maximum (or best) values calculated respectively. Figure 2-8 shows the OMOE input.

Figure 2-8 OMOE Input

The final segment of user input is the cost segment. Accurately calculating the cost of a ship is something that even the best ship designers have a difficult time doing. It is common practice to use cost estimating ratios (CERs) to estimate cost in ship design. These ratio's relate the cost of portion og the ship to the weight of that portion. For instance the propulsion group (SWBS 200) includes the weight of the prime mover, the transmission, and the propeller or water jet. This weight is then multiplied by an estimate of the cost that weight group per mton (the CER is in units of $/mton). For this program the cost estimates come from a study done to determine United States Coast Guard CERs.

Life cycle cost encompasses acquisition cost plus the cost of manning and fueling the ship. There for the designer also inputs the cost of manning in $/man-year, the expected life of the hull and the percent of time operating the ship is operating, and the cost of fuel. Unlike other sections, the user is provided with default values because it is not expected that the user will have fuel cost and manning cost available. The cost function is described in more detail in the next chapter.
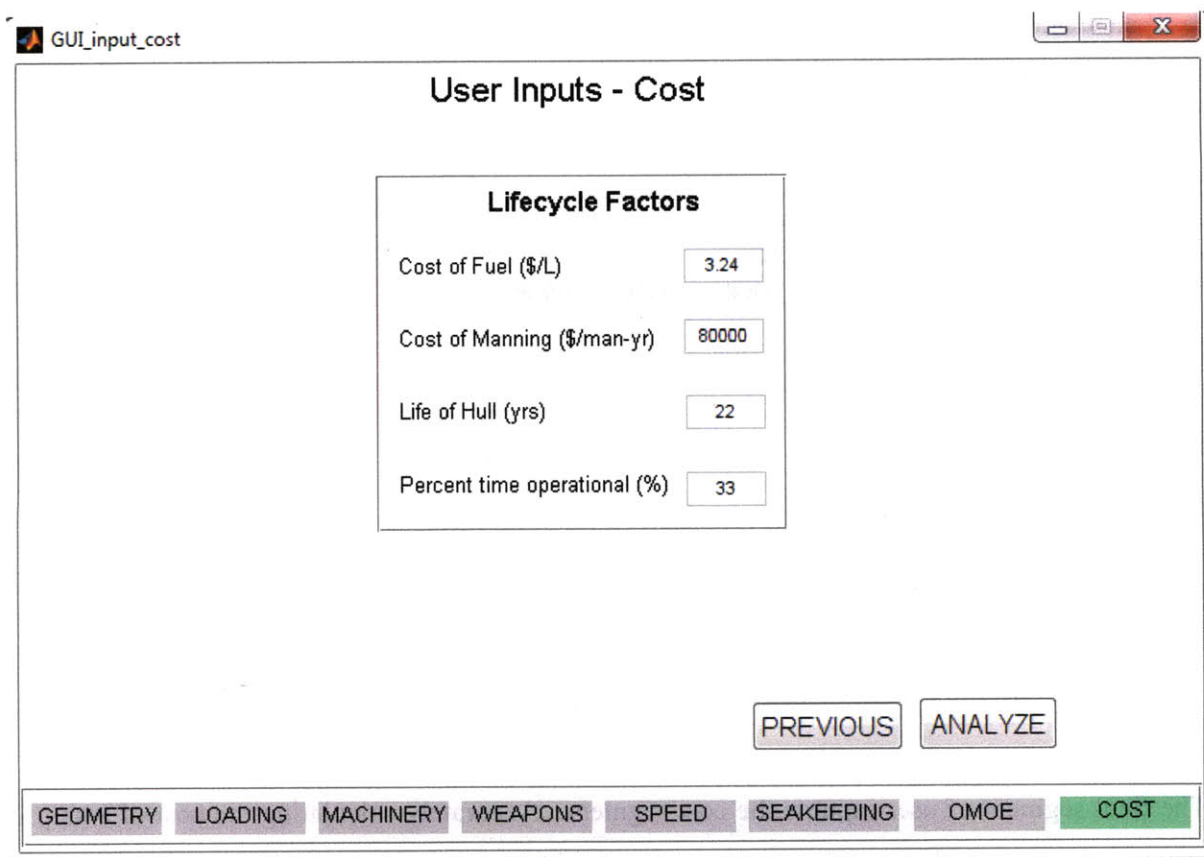
Figure 2-9 Cost Input

2.1.2 Generating Variants

The purpose of the generating variants block is *to take the user inputs and generate the set of hulls that is necessary to explore the user defined design space by assigning parameters to a particular variant in a variable that can be accessed later.*

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This is accomplished in one of two ways. If the user desires to use a response surface model, PCAT will ignore the number of steps input by the user and automatically calculate the correct number of variants to generate using a circumscribed central composite design. If instead the user desires a full factorial run then, nested loops are used to receive data from the user inputs block, such as an array of ship lengths, and assign each length to a different variant. The total number of ships built depends on the number of steps used in the different design variables.

2.1.3 Build Variants

After the design variables are assigned to a ship, the next step is to use that information to design the ship. The purpose of the building variants block is *to take the user inputs of each variant and construct a model of the ship by systematically adding components to the model.* This is done one variant at a time. The process for building variants is shown in Figure 2-10. Each of the steps is described in more detail in chapter 3.

The output of the build variants block is either a ship with all its design variables calculated, or a ship that has failed to complete and has an error message. With all the design variables calculated, there is one final check: does the weight of the ship equal the displacement? If it does not, the design waterline is adjusted and the build variant process is restarted at a new draft. If the displacement and the draft are equal (or nearly equal) then the ship has "converged" and final analysis can begin.
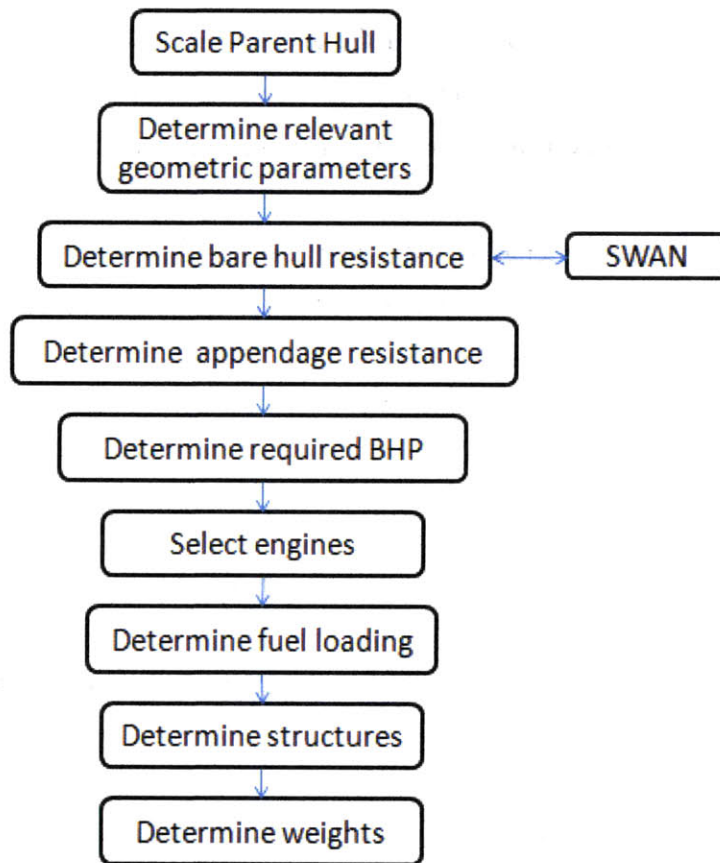
Figure 2-10 Build Variant Process

2.1.4 Final Analysis

After the ship has converged, the final analysis can begin. The final analysis block calculates seakeeping response, life cycle and acquisition cost, and overall effectiveness while rejecting ships that converged to an "unbuildable" variant. Examples of unbuildable variants are ships without adequate internal or external deck space, or ships with a negative metacentric height. The final analysis section also prepares data for use by the display results block.

2.1.5 Display Results

The last block is not one to be overlooked. If the results are not displayed in a manner that is useful to the designer, then PCAT is of little practical value. So the display results block seeks to

aid the user in determining areas for future study, as well as areas that are fairly well resolved by showing comparisons of ships both graphically and listing individual ship results.

2.1.6 Completing Another Run

PCAT allows the user to refine and optimize the results an additional "run" of the program. The results of the first run are not deleted; rather they are kept to allow for comparison with previous results. The results of both runs are displayed simultaneously to allow the user to determine if the changes resulted in an improvement in the ship design over previous runs.

2.2 Data Architecture

In a program designed to run many thousands of ship variants with a few hundred parameters per ship, it is imperative that the data structure be well thought out. Naming of variables must be clear and apparent to allow for future growth of the program. Additionally, the use of global variables must be minimized to keep memory free, though there must be maximum flexibility in the use of variables over numerous functions.

To accomplish these diverse goals, a few key decisions were made. First, there would only be two global variables: the first holding the user inputs (called USER[3]), and the second holding the details of the variants (called HULL). Because there are multiple variants and multiple runs, HULL is a matrix of variables where each variant is represented by an element of hull. The 1st dimension of HULL is the variant number while the 2nd dimension is the run number. For example HULL(35, 1) refers to the 35th variant of the first run.

To keep the naming as clear as possible, structures were used. Matlab describes structures as, "arrays with named data containers' called fields. The fields of a structure can contain any kind of data. For example, one field might contain a text string representing a name, another might contain a scalar representing a billing amount, a third might hold a matrix of medical test results,

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[3] Matlab is a case sensitive code, and in PCAT, HULL and USER are capitalized to bring attention to the global variables. The rest of the variables and fields are in lowercase. To aide a person in editing the code, all variables discussed in this thesis are capitalized in the same way as in PCAT.

and so on." The use of generic named data containers allows the storage of strings, such as the name of the parent hull, matrices, and scalars in a single clearly labeled data structure.

For example, the user inputs for the geometry segment are stored in the USER.geometry structure (note that USER is a structure with field geometry which is also a structure). In this way it is clear where the array of possible lengths is stored (USER.geometry.length). HULL is layed out in the same manner. For example HULL(42,2).geometry.depth holds the midships depth for the 42nd variant on the 2nd run. A detailed description of the two global variables is available in Appendix B.

3.0 Module Creation and Validation

With the process laid out, the next step was to create modules that would build a model of the ship. Each of these modules must be validated to ensure accuracy and then integrated into the program. While the collection of data from the user is not trivial, there is little to describe in the creation or validation process that was not discussed in chapter 2. Therefore this chapter begins with the creation of the variants.

Functions in PCAT are named in a consistent manner to make is easier for a user to improve the code in the future. To ensure the function names are clear, they are marked with italics in this paper. The first executable is *PCAT*, therefore to begin the program the user just types PCAT. The GUIs are divided into two different sections, the GUIs used for receiving data (input) and the GUIs used for displaying data (output). All functions that create GUIs are named *GUI_input (or output)_purpose*. For instance the GUI that gathers data on the geometry of the ship is named *GUI_input_geometry*. *PCAT_execute* is the "main function" that creates the models of the hulls. It calls other functions that are named *PCAT_purpose*. For instance the function that creates the ship's structure is calculated in *PCAT_structures*. All of the functions are described in more detail below.

3.1 Variant Creation

To create a full factorial set of experiments[4], the total number of possible ships is calculated. The user is permitted to allow 15 different variables to take multiple levels: LBP, L/B, L/D, deck height, the parent hull, KG/D, LCG/L, the material used, frame spacing, the use of water jets or propellers, the number of engines per shaft, the number of shafts, the number of weapon groups, range, and total manning. The number of levels of each of these variables (the length of each array) is multiplied together to get the total number of ships to create. The number of possible ship types can grow very quickly with 15 different variables. Even if each variable only takes on 2 possible values, the total number of possible ships will still be 2^{15} or 32,768. Therefore it is necessary for the user to have a rough idea of the boundaries of the design space before

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[4] For information on a reduced set of experiments and response surface modeling see chapter 4.

beginning, though functionality was added to aid the user in narrowing the design space while adding granularity to the possible designs through the use of multiple runs.

With the total number of designs known, PCAT then assigns design variables to each variant. This is done with nested loops running over each of the design variables listed above.

Once the hull parameters are set, the shape of an individual hull will not be changed throughout the program. Therefore, PCAT scales the parent hull before any computations begin. The scaling is done a function called *PCAT_scale*. There are four dimensions that need to be scaled, the longitudinal offsets, the transverse offsets, the depth offsets, and the initial draft of the hull. The transverse and longitudinal offsets are scaled in the following manner (it is important to note that the functions below are not exact Matlab code in PCAT, but rather just show the process used):

offsets.X = desired_lbp * X_o / max(X_o)

offsets.Y = desired_beam/2 * Y_0 / max(Y_o)

where X_o and Y_o are the original X and Y offsets and offsets.X and offsets.Y are the final offsets. The beam is divided by two because the offsets used in PCAT are half breadths.

Scaling the ships depth is slightly more complicated because it is likely that the ships depth is not maximum at the midsection. To account for this, the depth of the parent hull at midships must be determined. The first step is finding the index of the midsection in the longitudinal array (offsets.X). Then, at the ship's midsection, the index of the highest half breadth is found.

```
[temp, mid]=min(abs(X - LBPₒ/2))        %mid is the index of the midsection


for n=length(Z):-1:1
    if ~isnan(Y(mid, n)    %this will break when the half breadth exists
        break              %hence n is the index of the max depth at midships
    end                    %and Z(n) is the maximum depth
end
```

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```
Z = input.depth * Z_o / Z(n)          %Z_o is the original Z offsets
t = input.depth * t_o / Z(n)
```

This process is spelled out in detail because it arises many times throughout the course of PCAT. The assignment function and the scaling function were validated by inspection. All of this functionality is done in first half of the function *PCAT_execute*.

3.1.1 Possible Parent Hulls

Three parent hulls were loaded into PCAT, the PC-14 hull, the NPL High Speed Round Bilge Hull, and the Series 60 hull form. The NPL High Speed Round Bilge hull was designed for operation in the Froude number (F_N) range of $0.3 - 1.2$. According to Bailey, this hull could be used as a heavily loaded work boat, a fast patrol craft, or a small naval ship. The round bilge of the hull form allows for lower resistance than a flat bottomed planing hull in the semi-displacement region, while still providing more lifting than a typical surface combatant hull. The offsets for the NPL Hull were obtained directly from Bailey's work with the hull (9).

The primary mission of the PC is coastal patrol and interdiction surveillance. These ships also provide full mission support for Navy SEALs and other special operations forces. The PC ships, also known as the cyclone class, provide the U.S. Navy with a fast, reliable platform that can respond to emergent requirements in a low intensity conflict environment(10). The offsets for the PC-14 were taken from a converged ASSET model of the PC-14 created by the U.S. Navy (11).

The Series-60 hull form is a typical merchant hull form. While not ideal for high speed semi displacement craft, the hull offsets were added to allow for an additional hull form for comparison.

Additional parent hulls can be easily inserted into PCAT in the *PCAT_offsets* file. However, the user must also be able to model the hull interaction with the propulsion system to account for

changes in resistance and powering due to changing flow around the hull. More information on this topic can be found in the shaft horse power section below.

3.2 Variant Geometry

With the variant hull defined, the next step is to determine the applicable geometric parameters for use in other modules later in the program. All geometric parameters were determined using techniques described in *Principles of Naval Architecture* (12) and *Introduction to Naval Architecture* (13).

Most of the geometrical parameters apply only to the immersed section of the hull, so the first step is to insert interpolated offsets at the current waterline and shorten the waterline array (Z) and the half breadth array (Y) to include offsets only below the water line.

With no bounds on the spacing of the offsets, it would not be wise to attempt to use Simpson's multipliers to integrate sections and areas. Simpson's technique assumes a quadratic shape to find areas. However, for an arbitrary spacing of the offsets, this would be difficult. Therefore the trapezoidal rule was used for integration and interpolation. The trapezoidal rule assumes a linear shape for integration. This allows the offsets to be entered in whatever spacing is available to the user. The trapezoidal rule is used extensively throughout PCAT.

First the section areas are calculated.

$$Section\ area(x) = 2 * \int_{baseline}^{waterline} Half\ breadth(x,z)dz$$

The displaced volume (∇) is calculated by integrating the section areas.

$$\nabla = \int_{length} Section\ Area(x)dx$$

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The displacement (Δ) is then is calculated using a density of sea water (1025 kg/m^3)

$$\Delta = \nabla * \rho$$

The longitudinal center of buoyancy (LCB) was calculated by integrating the moment of the section areas.

$$LCB = \frac{\int_{length} x * Section\ Area(x)dx}{\nabla}$$

The beam at the water line is simply twice the maximum half breath of the immersed section. The block coefficient (C$_b$) and prismatic coefficient (C$_p$) are also calculated.

$$C_b = \frac{\nabla}{LBP * draft * beam\ at\ waterline}$$

$$C_p = \frac{\nabla}{LBP * maximum\ submerged\ section\ area}$$

The metacentric height (GM) is an excellent measure of initial static stability. GM is defined as the difference between the height of the metacenter (KM) and the height of the center of gravity above the keel (KG). KM can be defined as the height of the center of buoyancy above the keel (KB) plus the height of the metacenter above the center of buoyancy (BM).

$$I_{transverse} = \frac{2}{3} \int_{length} \left(y(x)\right)^3 dx$$

$$BM = \frac{I_{transverse}}{\nabla}$$

To find KB, the moment of areas of the water planes are integrated and divided by the volume.

$$waterplane\ area(z) = 2 \int_{length} y(x,z)dx$$

$$KB = \frac{1}{\nabla} \int_{baseline}^{waterline} z * waterplane\ area(z)dz$$

$$GM = KB + BM - KG$$

The wetted surface area (WSA) is the final variable calculated using the immersed offsets. The WSA is calculated by integrating the length of curves around the hull at a given longitudinal location.

$$length\ of\ curve(x) = \sum_{n=1}^{length(z)} \sqrt{(y(x,n) - y(x,n-1))^2 + (z(n) - z(n-1))^2}$$

$$WSA = \int_{length} length\ of\ curve(x)dx$$

The deck area calculations are also calculated in the geometry sections. The main deck area is calculated as the area of the surface that connects the highest offsets at every station. The user specifies the internal decks spacing (dh). The first internal deck is place dh feet below height of the main deck at midships. All internal decks are parallel with the base line.

$$main\ deck\ area = \sum_{n=1}^{length(x)} \frac{1}{2}(y(n,z_o) + y(n+1,z_1)) * \sqrt{(x(n+1) - x(n))^2 + (z(z_1) - z(z_o))^2}$$

Where z_o is the maximum height at longitudinal point n, and z_1 is the maximum height at the next longitudinal point.

To validate the geometry code, PCAT was run with only a 30.5 m NPL series hull loaded. The actual values in Table 3-1 were gathered directly from the NPL series (9), while the actual values in Table 3-2 were calculated by hand using a quadratic approximation using Simpson's

multipliers. The largest difference error is in the calculation of the wetted surface area. This is primarily due to the linearization of the hull around the curved bilge section.

	PCAT	NPL Series	% difference
Displacement (kg)	101,249	99,105	2.16%
Volume (m^3)	98.74	96.67	2.14%
LCB (m fwd of midships)	-1.966	-1.951	0.77%
C_b	0.396	0.397	-0.25%
C_p	0.690	0.693	-0.43%
WSA (m^2)	116.38	124.43	6.5%

Table 3-1 Validation of Geometric Data

	PCAT	Actual	% difference
Main deck area (m^2)	140.9	138.1	2.03%

Table 3-2 Validation of Geometric Data

The calculation of wetted surface area is performed in the *PCAT_surf_area*. The remainder of the geometry calculations are performed in *PCAT_area_displacement*.

3.3 Bare Hull Resistance

The resistance of each variant is required for several different speeds: the maximum speed, the endurance speed, and each speed entered in the speed profile. But if the user requires the endurance speed to be the most efficient speed, the resistance needs to be calculated at various speeds from minimum to maximum to determine where the maximum speed exists. Even if the user does not have this requirement knowing the fuel efficiency of the ship at different speeds is valuable to the user. To calculate all these resistances in a simple way, elements are added to the speed profile array. Recall that the speed profile array has two components, the speeds at which a ship will operate, as well as the percent of time a ship spends at each speed. Therefore speeds are added in 1 knot increments from a Froude number (Fn) of 0.1 to the maximum speed (as long

as the maximum speed has a Fn < 1.0). For every element that is added to the speed array, a 0 is added to the percentage array in the same location. This represents the ship spending 0% of its time at any new speed added. This process occurs in *PCAT_beefup*.

Froude hypothesized that resistance could be broken down into two basic areas. Frictional resistance which is a function of Reynolds number, and residual resistance which encompasses all other resistance terms, primarily wave making resistance and form drag. The frictional resistance coefficient is calculated using the standard 1957 International Towing Tank Convention (ITTC) formula.

$$C_f = \frac{0.075}{(log_{10}R_N - 2)^2}$$

Where the total frictional resistance is:

$$D_f = \frac{1}{2}\rho S U^2 (C_f + C_a)$$

Where S is the wetted surface area in m^2, U is the ships speed in m/s, ρ is the density of water in kg/m^3, and C$_a$ is the correlation allowance. The correlation allowance is set at 0.0004.

Calculation of the residual resistance can be done using several methods. The most accurate method is to build a model and test the hull; however that is impractical for this project. A discussion of possible methods for calculating residual resistance for patrol crafts follows (14)(15).

Canadian Research Council – Fast Surface Ship – This method is used to calculate residual resistance for ships operating in the displacement region. High speed slender ships that operate at Froude number below 0.83 are a good fit for this method. This method is based on regression analysis of model test data.

Hamburg Ship Model Basin – This method uses Telfer type regression of model data to predict residual resistance for small higher speed ships. This method is good for ships operating up to Froude numbers of 0.83.

Semi Displacement Double Chine – This method is based on regression data performed by the National Technical University of Athens on double chine, transom stern, semi displacement hull series. This series is intended for large high speed vehicles operating below Froude numbers of 0.53.

Semiplaning Transom Stern - This method is designed for the ships in the displacement and semi-displacement region for Froude numbers up to 0.53. Regression analysis was performed at the U.S. Naval Academy Hydrodynamics Laboratory on various hulls.

Compton – This algorithm is designed for typical coastal patrol, training, or recreational powerboat hull forms with transom sterns operating in the displacement or semi displacement regions. This resistance method is good for Froude numbers from 0.1 to 0.6 (16).

While all of these methods can provide a good estimate for bare hull resistance, they are all parametrically derived and can have difficulty differentiating subtle differences in hull types. Finding a method of calculating resistance accurately from the zero speed (displacement only) through a Fn of 1.0 (semi-displacement) is difficult because of the differences in dynamic support the vessel receives. Additionally, each method has its own set of restrictions where it is valid. The restrictions for the Compton method are shown below as an example.

	Lower Limit	Upper Limit
Speed (kts)/$\sqrt{LWL}$	0.35	2.00
$F_{N\nabla}$	0.3	1.5
$\Delta/(0.01 * LBP)^3$	105	150
LCG/LBP	-0.13	-0.02
LBP/B	4.0	5.2

Table 3-3 Compton Resistance Bounds

To allow the user the widest range of possible inputs and to aide in capturing all differences in hull shape, size, and weight distribution, SWAN2 was used to generate the residual resistance. Being a potential flow model, SWAN2 can accurately provide the resistance generated by the waves, however, SWAN2 cannot derive the form resistance for high speed vessels with transom sterns. Form resistance is highly dependent on the flow separation that occurs at the transom of high speed ships. Because SWAN2 is a potential flow program, it cannot simulate this effect. However, at high Fn (0.5-1.0), the form drag has been shown to be independent of speed and approximately half the frictional drag (17). So the residual resistance coefficient is calculated as follows.

$$C_r = C_w + \frac{1}{2} C_f$$

Where C_w is the wave resistance coefficient provided by SWAN2.

The total resistance (D_T) and bare hull horse power (EHP) are calculated as follows.

$$C_T = C_f + C_a + C_r$$

$$D_T = \frac{1}{2} \rho S U^2 (C_T)$$

$$EHP_{BH}(U) = U * D_T(U)$$

Where S is the wetted surface area in m^2, U is the ships speed in m/s, and ρ is the density of water in kg/m^3. To validate the resistance subroutine, two methods were used. First the results were compared to results of the same ships using Compton method. Additionally, the results were compared to Maxsurf's Hull Speed module which has the ability to calculate residual resistance. The hull used was a 33 ft YP, the same hull used by Roger Compton in his initial study (16).
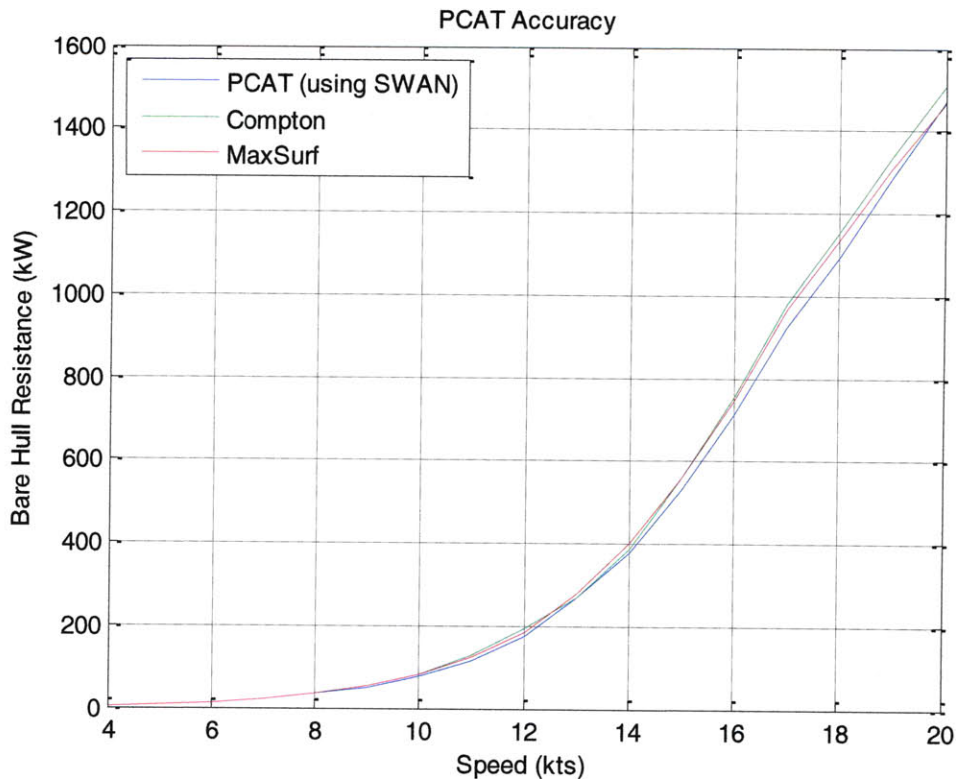
Figure 3-1 Accuracy of PCAT Resistance

The results from this routine were very pleasing. SWAN2 residual resistance provides an accurate measure of resistance, within 10% throughout the design range.

The interface with an external program like SWAN2 is difficult. It requires meticulous coding to ensure all inputs and outputs are in the correct format and can be exchanged between the programs seamlessly. To interface with SWAN2 is a multi-step process. The first step is ensuring that the offsets are formatted correctly for SWAN2. In SWAN2 the offsets are written into a text file with a .pln extension. Therefore *PCAT_writepln* scales the offsets and writes the offsets to the correct format for use in SWAN2.

Next, SWAN2 requires a file to input the job control parameters, a .inp or input file. This file describes the analysis that is required and provides further details about the ship. Information included in the .inp file include: ship length, depth, speed, mass, and radii of gyration as well as water density and information required to set up the free surface boundary and mesh grid. The

.inp file is created in *PCAT_writeinp*. There are a few SWAN2 variables that require specific explanation. The radius of gyration for pitch, yaw, and roll are not known because the designer does not know the location of all the masses on the ship at this stage in the design process. Therefore typical values are assumed for these variables.

Variable	Approximation
Radius of Gyration in pitch	25% Length
Radius of Gyration in yaw	25% Length
Radius of Gyration in roll	35% Beam

Table 3-4 SWAN2 Approximations

Additionally, SWAN2 provides for dynamic trim and sinkage for the vessels. Because SWAN2 is a time domain program, it is important to ensure that the sinkage and trim have achieved steady state values. Therefore PCAT will continue to run SWAN2 on a specific hull until the sinkage and trim have converged or for a maximum of 4 iterations. All of the resistance calculations occur in *PCAT_resistance*.

3.4 Appendage Resistance

Adding in the resistance of the appendages is the next step. Appendage resistance is typically added as a percentage of bare hull resistance (18). This implies that the resistance of an appendage behind a high resistance ship is more than the resistance of an appendage behind a low resistance ship. A second method for calculating resistance suggested by Holtrop and Mennen calculates the appendage resistance based on their wetted surface area using the afore mentioned 1957 ITTC formula frictional resistance formula. The two methods are in reasonable agreement with one another, therefore the appendage resistance is calculated as a percentage of total resistance. The factors used are shown in Table 3-5. These resistance factors only apply to ships with a propeller. Ships with waterjets do not require the external appendages of propeller ships and therefore the resistance is not added for ships with water jets.

Appendage	Fraction of Total Resistance
Twin Rudders	0.015
Twin bossing	0.10
Shaft brackets and open shafts	0.06

Table 3-5 Appendage Resistance Factors

The appendage resistance of the ship is given by

$$R_{appendage} = R_{BH} * (F_{rudders} + F_{bossings} + F_{shaft})$$

The appendage resistance is calculated in *PCAT_appendage*.

3.5 Brake Horse Power for a Ship with a Propeller

Converting the resistance and power of a bare hull (with increased resistance for appendages) to a brake horse power (BHP) is a non-trivial exercise. Changes in flow around the hull, losses due to power transmission, and power conversion all factor into BHP (19). The BHP required is calculated in *PCAT_bhp*.

3.5.1 Wake Factor and Thrust Deduction Factor

The thrust deduction factor (t) is fractional difference in the thrust generated by a ship and the resistance of the same ship.

$$t = \frac{kT - R}{kT}$$

Where k is the number of propellers, R is the ships resistance at a given speed and T is the thrust generated at that speed.

The wake factor accounts for the difference in the ships speed and the inflow to the propeller.

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$$w = \frac{V_s - V_a}{V_s}$$

Where V_s is the ship velocity and V_a is the inflow to the propeller. Together they account for the differences between the testing of a model hull and a propeller separately in open water and integrating them into one unit. The hull efficiency (η_H) is defined as the power required to move a ship at a certain speed ($R*V_s$) divided by the propulsive power generated ($k*T*V_a$).

$$\eta_H = \frac{R*V_s}{k*T*V_a} = \frac{1-t}{1-w}$$

This factor often is near or even exceeds unity. The hull efficiency is different for every hull. Therefore if the user inputs an additional hull, they must also determine the hull efficiency of that hull in different conditions.

3.5.2 Propeller Efficiency

A propeller delivers power in the form of torque (Q) and a rotational speed ($2\pi*n$). So the open water efficiency (η_o) of a ship is defined as the power delivered ($T*V_a$) over the power available ($2\pi*Q*n$). This value typically falls between 0.3 and 0.7.

$$\eta_o = \frac{T*V_a}{2\pi*Q*n}$$

However the actual torque generated (M) differs from the torque generated in a free stream. This difference is captured in the relative rotation coefficient (η_r). Typical values for η_r fall between 0.98 and 1.02.

$$\eta_r = \frac{Q}{M}$$

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3.5.3 Efficiencies for Given Hulls

The wake factor and thrust deduction factor for the PC hull were taken from the ASSET values. Both are assigned values of 0. The relative rotation coefficient is also taken from the ASSET model of the PC and is assigned a value of 1. The open water efficiency of the propeller is assigned a value of 0.65 based on Woud and Stapersma (19).

The hull efficiency and the relative rotation efficiency of the NPL series hull are provided by Bailey in reference (9). Bailey gives the two efficiencies as a function of $\widehat{\mathbb{M}}$, the Froude length constant and Fn.

$$\widehat{\mathbb{M}} = LBP \Bigg/ \left(\Delta * \frac{2240\,lbf}{1LT} \frac{s^2}{32.2\,ft} \frac{ft^3}{1.990\,slugs} \right)^{1/3}$$

The curves for P (which is $\eta_H *\eta_R$) without a wedge from were used from Bailey and linearly interpolated in two dimensions, $\widehat{\mathbb{M}}$ and Fn. Similar to the PC, the open water efficiency is given a value of 0.65 for the NPL series hull.

3.5.4 Shaft and Gearbox Efficiencies for Ships with Propellers

The final step in calculating the BHP of an engine is calculating the shaft and gear box losses. Shaft losses are typically 0.5% to 1% of total power per shaft. Gear box losses are typically 1% to 2% for simple reduction gears, but can be as high as 3% to 5% for more complex reduction gears.

For PCAT, the shaft efficiency was assigned a value of 99.25% per shaft (0.75% loss). The gear box efficiency was set to 97% for two engines per shaft, and 98.5% for one engine per shaft (19).

The total BHP needed by all the engines is given by

$$BHP = \frac{EHP}{\eta_H \eta_r \eta_o \eta_{shaft} \eta_{GB}}$$

3.6 Brake Horse Power for a Ships with a Waterjet

Calculating the overall propulsive coefficient of a ship powered by water jet engines is inherently different than propeller ships. Because the impeller of the water jet exists inside the ship and not in the turbulent area external to the ship terms such as wake fraction have no meaning. Additionally, the relative rotation coefficient and the open water efficiency do not correlate to physical terms in a ship powered by water jets (20).

The water entering the waterjet is accelerated and exerts a momentum drag on the ship. So the net thrust generated (T_N) can be given by

$$T_N = T_G - D_M = \dot{m}_j V_j - \dot{m}_i V_s$$

Where T_G is the thrust generated, D_M is the momentum drag, $\dot{m}_j$ is the mass flow rate out of the jet, V_j is the velocity at the outlet of the jet, $\dot{m}_i$ is the mass flow rate to the inlet of the jet, and V_S is ship speed. Unless some flow is bled off the inlet of the water jet, $\dot{m}_i = \dot{m}_j$. This simplifies the net thrust to

$$T_N = \dot{m}(V_j - V_s)$$

The work done propelling the ship is then

$$W_N = T_N V_s = \dot{m} V_s (V_j - V_s)$$

To calculate the energy lost in the jet it is necessary to assume that the potential energy gained in the elevation of the water is negligible and assume perfect inlet energy recovery. Then the energy added by the pump is the difference in the kinetic energy of the inlet and the outlet of the water jet.

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$$\Delta KE = \frac{1}{2}\dot{m}_j V_j^2 - \frac{1}{2}\dot{m}_i V_s^2$$

Again, assuming the flow rates are equal,

$$\Delta KE = \frac{1}{2}\dot{m}\left(V_j^2 - V_s^2\right)$$

The efficiency of the jet (η_j) is then given by the ratio of useful work done on the ship to useful work done by the jet.

$$\eta_j = \frac{W_N}{\Delta KE} = \frac{\dot{m}V_s\left(V_j - V_s\right)}{\frac{1}{2}\dot{m}\left(V_j^2 - V_s^2\right)} = \frac{2V_s}{V_j + V_s}$$

If a new term μ, is defined as V_s/V_j, then the jet efficiency can be represented as follows.

$$\eta_j = \frac{2\mu}{1 + \mu}$$

However, if a loss coefficient, ζ, is included which represents the total energy lost an a proportion of the ideal inlet energy, then the energy added by the pump is written,

$$\Delta KE = \frac{1}{2}\dot{m}\left(V_j^2 - V_s^2\right) + \zeta\frac{1}{2}\dot{m}V_s^2$$

$$\Delta KE = \frac{1}{2}\dot{m}\left[V_j^2 - V_s^2(1 - \zeta)\right]$$

This changes the jet efficiency to

$$\eta_j = \frac{2\mu(1 - \mu)}{1 - \mu^2(1 - \zeta)}$$

This is the definition of jet efficiency that PCAT uses. In a well designed system, ζ can range from 0.25 to 0.50. In a poorly designed system, ζ can range from 0.5 to 1.0 (20). For consistency, it is assumed that all ships with water jets have a loss coefficient of 0.5.

So the efficiency of the waterjet is now a function of only ships speed and the waterjet outlet velocity.

The quazi propulsive coefficient (QPC) for water jets is then equal to,

$$QPC = \eta_j \eta_p$$

where η_p is the efficiency of the pump[5]. The QPC is nominally 0.53 for ships in PCAT's range (20). Ships with waterjets do not normally require gearboxes, therefore there is no need for a gearbox efficiency, and there is no shaft, so there are no shaft losses. So the total power needed by the engines (BHP) is,

$$BHP = \frac{EHP}{QPC}$$

This calculated in PCAT_bhpwj.

3.7 Engine Selection

With the total load known for the engines, the engines can be selected. To simplify the selection process, it is assumed that all propulsion engines onboard the ship will be the same type. In reality it is likely that if there are two engines per shaft, one will be a cruise engine, and the second, a larger engine to achieve maximum speed. However, most ships of this size analyzed by PCAT only have one engine per shaft, so the simplification does not have that large an impact.

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[5] The QPC for a ship with a propeller is $\eta_H \eta_r \eta_o$.

The smallest engine is selected from the engine library that meets the propulsion requirements of the ship. The engine library is contained in Appendix C.

3.8 Fuel Loading and Efficiency

With the engines selected and the resistance profile known, the total amount of fuel needed to reach a certain range can be calculated as well as the fuel efficiency at all the speeds.

To do this the engines on board the ship are loaded in one knot increments. Starting from the lowest speed, one engine is brought on line. When the BHP required to meet a new speed exceeds the power available of a single engine, an engine from another shaft is brought online. This continues until there is one engine on each shaft. If more than one engine exists per shaft, then the pairs of engines are brought online on each shaft next until the required BHP is met. This continues until the maximum speed is achieved.

At each speed the fuel consumption of the propulsion engines is calculated using the SFC.

$$Propulsion\ Fuel\ Consumption\ Rate\ \left(\frac{kg}{hr}\right)$$

$$= SFC(at\ given\ RPM)\left(\frac{kg}{kW-hr}\right) * BHP(at\ same\ RPM)(kW)$$

In this way the propulsion fuel consumption rate is a function of speed. However there is another component of fuel efficiency, the fuel used to power the electrical system. Because the calculation of the total power load is difficult when many of the systems remain undefined, all variants are assigned the same electrical generators; two Caterpillar 3412 diesel generators providing 400kW each. It is assumed that each variant can cruise on 400kW, the second generator is provided for battle conditions and as a spare for cruising. The electrical generator uses 123.0 liters per hour (lph) (21) when at full load. Assuming a density of fuel of 0.88 kg/L, the electrical generator uses 24.5 kg/hr of fuel.

To get the total fuel efficiency the propulsion fuel consumption rate is added to the electrical fuel consumption rate to get the total fuel consumption rate. Note that the fuel efficiency and the fuel consumption rate are both functions of speed.

$$Fuel\ Efficiency\left(\frac{nm}{mton}\right) = \frac{1000\ kg}{mton}\frac{1}{Fuel\ Conspumtion\ Rate\left(\frac{kg}{hr}\right)}Speed\left(\frac{nm}{hr}\right)$$

At low speeds the propulsion engine uses very little fuel, but the ship moves very slowly, so the hotel loads supplied by the electrical generator use a significant amount of fuel per nm. At high speeds the resistance of the ship increases more than cubically. Therefore it is expected that the most fuel efficient speed be low in the speed range, but not at minimum speed. A typical fuel efficiency curve is shown in Figure 3-2.
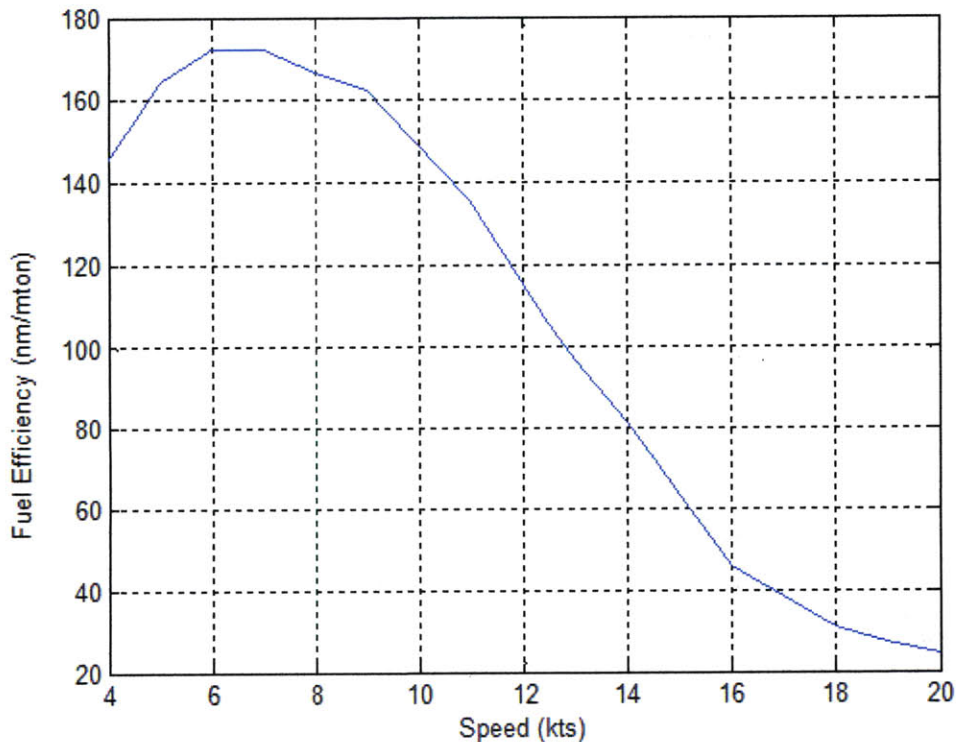
Figure 3-2 Typical Fuel Efficiency

If the user chose to default the endurance speed to the most fuel efficient speed, the endurance speed is chosen as the speed associated with the maximum fuel efficiency.

DDS 200-1, *Endurance Fuel Calculation*(22), was used as the standard for calculating the required fuel loading for the PCAT. The procedure is very similar to what has been done already with the exception of a few additional factors.

- Tailpipe allowance of 0.95 to 0.98 to account for the unavailable fuel remaining in the tank below the tailpipes. (0.95 is used for PCAT).
- Increase in endurance fuel rate by 5% to account for plant deterioration.

DDS 200-1 gives the fuel required to reach a certain range. However, the data sheet assumes that all the fuel is used, which is not realistic for operational purposes. While it is understood in the Navy that the fuel required (or range calculated) is not an accurate value, but rather just a number for comparison, that is not plausible or desirable for this program. Therefore an additional factor of 1.5 is used to ensure the ship can reach the design range with 33% of fuel remaining. The weight of fuel needed is calculated as follows.

$$Fuel\ Weight\ (mton) = \frac{Range(nm) * 1.05}{Efficency\ ar\ endurance\ speed\left(\frac{nm}{mton}\right) * 0.95} * 1.5$$

All of the fuel efficiency and loading calculations are performed in the *PCAT_fuel* function.

3.9 Structures

The calculations of the structures of a variant are performed using the ABS rules for steel vessels < 90m in length. Applicable sections of the ABS rules can be found in Appendix A. In general the ABS rules require each piece to have either a certain thickness (such as deck plating) or a certain section modulus (such as hull girders). For this level of design the following pieces were designed.

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- Bottom shell plating
- Side shell plating
- Main deck plating
- Internal deck plating
- Bottom framing
- Bottom girders
- Side Girders
- Side Framing

These pieces were then modeled to determine the overall moment of inertia and section modulus of a section, as well as the weight of the material in the structures weight group.

Several assumptions had to be made to adequately model a particular variant. Some ships use one material for the hull and a second, stronger material for decks or lighter material high in a ship to lower KG. However in PCAT, every variant only uses a single material. For a small hull, bending is not a major structural concern. Therefore, the necessity of strengthening certain sections is diminished, making it reasonable to assume that the hull will be made of a uniform material. Additionally, every frame, girder, and stiffener is a similarly shaped t-beam. This is also a reasonable assumption because t-beams have a high section modulus for the amount of material used and are typically used in the construction of naval vessels.

Each t-beam is shaped as shown in Figure 3-3 with x being the "critical dimension" of the t-beam. With the section modulus of each frame, girder, or stringer limited to one degree of freedom and the required section modulus of each piece given by the ABS rules, each piece can be sized appropriately.
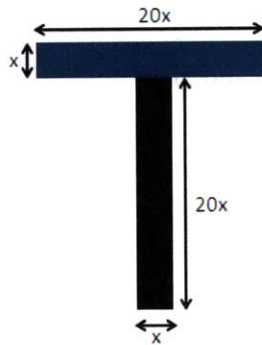
Figure 3-3 Sample t-beam

Calculating the section modulus of a beam requires first knowing the second moment of area, or moment of inertia (I_y) as well as the location of the neutral axis. The neutral axis ($\bar{z}$) is defined as the center of area(23).

$$I_y = \int z^2 dA$$

$$\bar{z} = \frac{\int z dA}{A}$$

For this particular t-beam, I_y and $\bar{z}$ are defined as:

$$\bar{z} = 15.25x$$

$$I_y = \frac{10625}{6} x^4$$

The section modulus is defined as the I_y/c where c is the distance from the extreme fiber to the neutral axis. There are always two section moduli; the section modulus for the upper portion and the section modulus for the lower portion. Because the section modulus (SM) for the lower portion is the limiting case, that is the one used in PCAT. The SM for the t beam is given by:

$$SM = 116.12x^3$$

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But ABS gives formulas for the section modulus. What is needed is the critical dimension, x.

$$x = \sqrt[3]{\frac{SM}{116.12}}$$

Now given a required section modulus from ABS, the size and bending rigidity of each piece is known.

ABS requires minimum section moduli and thicknesses for each piece and each section of hull and deck plating, but there is also a minimum section modulus for the entire section. With the scantlings of each piece known the total moment of inertia of the midsection can be calculated to verify that the variant has enough strength to withstand bending. This is done in 4 steps.

1. The sum of the area of all the pieces is calculated.
2. The sum of the moment of area of all the pieces is calculated.
3. The moment of inertia of each piece about the ships base line is calculated.
4. The total moment of inertia is shifted to the neutral axis.

To complete step 3, each object's moment of inertia has to be calculated about their own horizontal neutral axis. However many of the objects are rotated because they are placed on a round hull. Therefore the moment of inertia must be transformed.

$$I_{y\_new} = \frac{I_y + I_z}{2} - \frac{I_y - I_z}{2} \cos(2\theta)$$

Where θ is the angle of rotation and I_z for the t-beam is the moment of inertia of the t-beam about the vertical plane.

$$I_z = \int y^2 dA = \frac{2005}{3} x^4$$

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To complete steps 3 and 4 the parallel axis therom must be used. The parallel axis theorem states that the moment of inertia for an object about an arbitrary axis is the moment of inertia of the same object about its own neutral axis added to the square of the distance between the neutral axis and the new axis times the area.

$$I_{baseline} = I_y + d^2 A$$

In step 3 the moment of inertia is shifted away from a piece's neural axis to the base line, so the d^2A term is added. In step 4 however, the moment of inertia is shifted toward the section's neutral axis, so the d^2A term is subtracted.

The final section modulus of the midsection is compared to the minimum section modulus. If the calculated section modulus is insufficient, all the scantlings are increased in 1% increments until the section modulus of the section is met. In all test runs performed by the author, it was never necessary to increase the scantlings of the individual pieces to meet the section's section modulus requirement. Stated another way, in all the trial runs preformed, if the minimum scantlings were met for the individual pieces, the minimum section modulus was met for the entire section.

The final calculation done in *PCAT_structures* is the weight of the material used to make the hull. This will feed directly into the weight module. The weight of the material is calculated by finding the weight of the material at each section, and then numerically integrating the section weights along the length of the ship to get the total weight. This is added to the weight of the transverse framing to get the total structure weight. Note that this does not include some of the structural weight such as the transverse bulkheads and the machinery foundations.

To validate the structures calculations, a midsection was built in POSSE's section modulus editor to match the one generated in *PCAT_structures*. Table 3-6 shows the comparison between the POSSE parameters and the PCAT parameters.

55
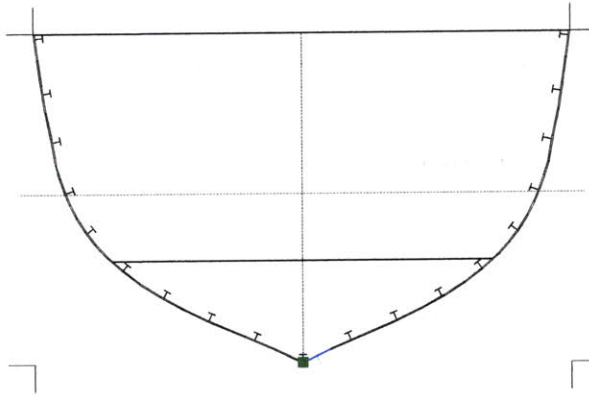
Figure 3-4 Midsection from POSSE

Parameter	POSSE	PCAT	Difference
Area (m^2)	0.269	0.269	0%
I (cm^4)	$4.83*10^7$	$4.87*10^7$	0.82%
SM (top) (cm^3)	$2.49*10^5$	$2.51*10^5$	0.80%
SM (bottom) (cm^3)	$2.38*10^4$	$2.44*10^4$	2.5%
NA(cm)	217.63	217.25	0.17%

Table 3-6 Structural Validation

3.10 Weights

The weights in a ship are broken down into seven groups (called SWBS groups) for lightship and the variable load. The seven groups are shown in Table 3-7.

Group	Description
SWBS 100	Major Hull Structure: shell plating, bulkheads framing, decks, etc.
SWBS 200	Propulsion: Engines, shafting, lube oil
SWBS 300	Electric plant: engines, generators, distribution, switchboards, lighting
SWBS 400	Command and Surveillance: navigation, communication, radars, etc.
SWBS 500	Auxiliaries: freshwater, air systems, HVAC
SWBS 600	Outfit and furnishings: crew berthing, officer spaces, passenger spaces, etc.
SWBS 700	Armament: weapons, ammunition, missiles
Variable Load	Variable load items: Fuel, stores

Table 3-7 Weight Group Descriptions

So far in PCAT only three weight items have been calculated, the fuel loading, most of the structural weight, and the weight of the prime mover. The rest of the weights need to be estimated using the weights of a similar craft. The craft chosen as the baseline for ratios is the PC-14. All of the weights not previously calculated were estimated in accordance with the method put forth by the Society of Allied Weight Engineers (SAWE) (24). All weights are either a ratio of weights from the PC or a function of some parameter generated by PCAT such as manning or shaft horse power.

There are two areas where the changes were made to SAWE procedures. First, because the user input all items for SWBS 400 and 700, they are never separated. All group 400 and 700 items are stored under SWBS 400. Additionally, because very little of the electric system is modeled, the SWBS 300 weights are assumed to be a ratio of the power of the generators.

3.11 Balancing

With the weights of a variant known the next step is checking the balance of the weight of the ship and the displacement at the design draft. If the displacement and the draft are not within 1% of each other, the draft must be adjusted so the displacement more closely matches the weight. In general one of three cases can occur.

1. The variant's weight and displacement agree within 1%. If this occurs, the variant is complete and the final cost, seakeeping, and performance analysis can occur.

2. The variant's weight and displacement are not within 1%, but there is still adequate free board. If this occurs, two adjustments must be made to the variant. First the draft is set to a new level as shown below.

$$draft_{new} = draft_{old} * \left(1 + 0.4 \frac{weight - \Delta}{\Delta}\right)$$

This is an empirical formula that was arrived at through trial and error. It adjusts the draft as a function of the percent difference between the weight and the displacement. Because the engine sizes are not continuous, it is very important to increase the draft slowly so as ensure the smallest engine possible is used to power the variant. Increasing the draft too quickly could cause an unnecessary increase in resistance and hence an unnecessary step increase in weight due to skipping to the next larger engine. The minimum freeboard at midships is set to 6% of ships length (25).

While the vertical and transverse offsets do not need to be adjusted, the longitudinal offsets need to be moved so that the zero point is at the forward perpendicular. Figure 3-5 shows the profile for a nominal hull. Figure 3-6 is the offsets for the same after being adjusted for having a weight that is more than the displacement. It is important to notice that while the size of the hull does not change, the LBP does. So the final LBP will many times not be the original value entered by the user, but the Overall length of the ship will not change.
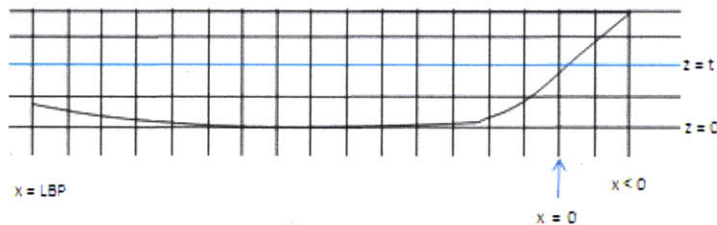
Figure 3-5 Original Profile
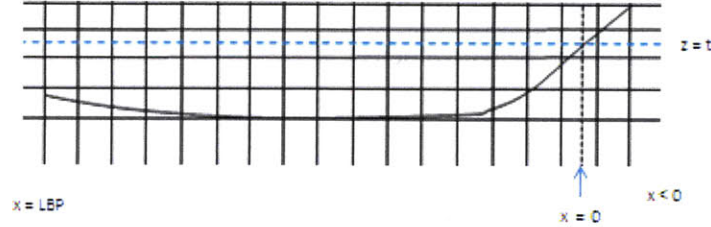
Figure 3-6 Adjusted Profile

3. The final possibility is there is no longer adequate free board. If this occurs, the variant generates an error code and no further calculations will be performed on that variant.

The calculations for balancing are performed in *PCAT_adjustoffsets* and *PCAT_execute*.

3.12 Seakeeping

Calculating the response of ship in seas is no small task. Traditionally, seakeeping is analyzed at the end of the design cycle after most design decisions have been made. In general if the ship meets its minimum seakeeping requirements, little thought is put into improving seakeeping.

The most widely used method for calculating seakeeping in initial ship design is strip theory. Ships motions of heave pitch, and roll are oscillatory in nature, due to a restoring force created by changes in buoyancy. In strip theory, ship's motions are modeled as a forced damped mass-spring system (15). For instance, uncoupled heave can be modeled as

$$(M + A_{33})\ddot{\eta}_3 + B_{33}\dot{\eta}_3 + C_{33}\eta_3 = F_3 e^{i\omega_e t}$$

Where:

M is the mass of the vessel

A_{33} is the added mass coefficient for heave due to heave

B_{33} is the damping coefficient for heave due to heave

C_{33} is the hydrostatic restoring coefficient for heave due to heave

F_3 is the heave exciting force

η_3 is the instantaneous heave displacement

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$\dot{\eta}_3$ is the instantaneous heave velocity

$\ddot{\eta}_3$ is the instantaneous heave velocity

This method works very well for ships in the displacement region. However, as a ship speeds up above Fn = 0.4, the ship enters the semidisplacement region where the hydrostatic effect buoyancy is no longer the sole exciting force. In the semidisplacement region, the hydrodynamic force of the water causes additional forces that are difficult to account for using strip theory alone. In fact strip theory has been shown to hold good value only in speeds up to Fn = 0.57 (2).

3.12.1 SWAN2 Inputs

Therefore for PCAT, SWAN2 was chosen to analyze performance in seas. SWAN2 uses the three dimensional Rankine Panel Method to determine fluid flow around high speed bodies. The flows are used to calculate pressures, which in turn are integrated to find the exciting forces on the ship. The inputs into SWAN2 for sea response are very similar to the steady case where resistance was calculated. The only additional required information is the period and direction of the seas and the seas and the wave height.

The seakeeping output used in SWAN2 is a response amplitude operator (RAO). An RAO is a transfer function that when combined with a sea spectrum can give the user information about vessel motion in waves. Because all that is used is the RAO, all wave heights are assumed to be 1 m.

RAO's can be used to generate many useful statistics: occurrences of slamming, occurrence of green water on deck, RMS values for heave, pitch, and roll, etc. These can be calculated for any sea state, and at any heading. A typical analysis might produce an output like that shown in Figure 3-7 Typical Seakeeping Analysis. This figure shows vertical acceleration for a patrol craft in sea state 5 at all sea headings (circumferentially), and at speed from 0 to 22 knots (radially).

60
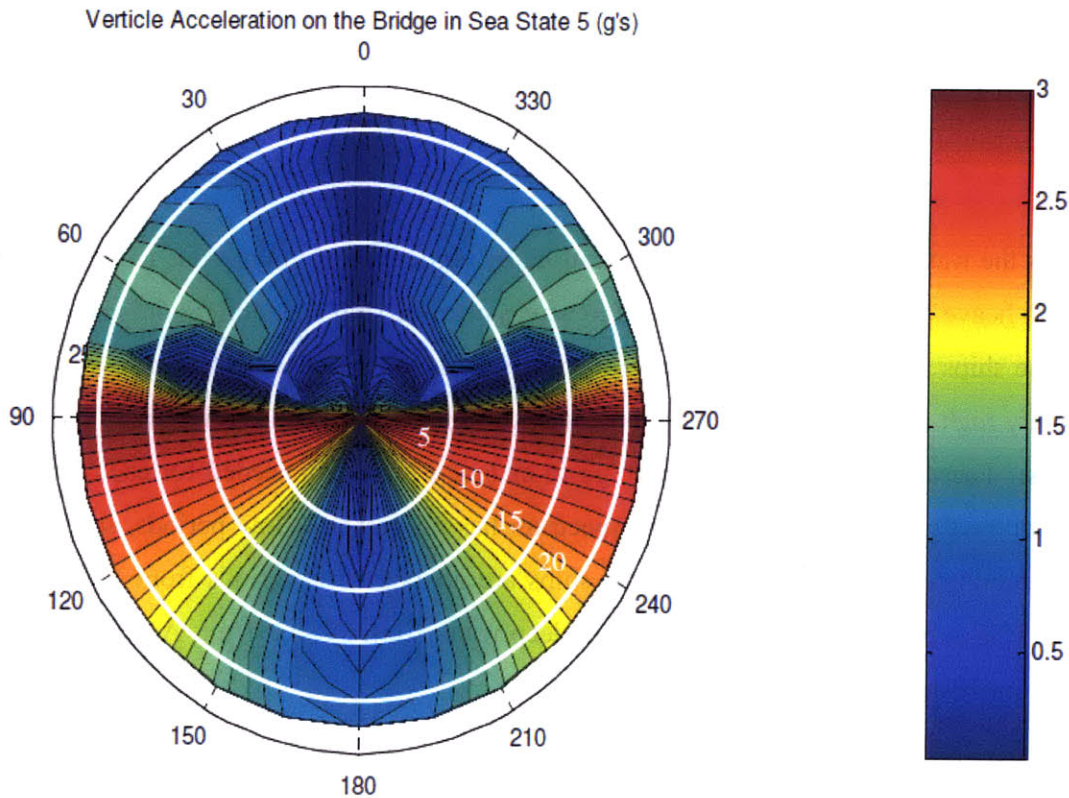
Figure 3-7 Typical Seakeeping Analysis

This type of graph is time consuming to generate, and produces results that are difficult to tabulate especially when the desired response is not yet known.

In general the limiting case for seakeeping is not the strength of the ship, rather it is the health of the personnel and their ability to continue to execute the ship's mission. Therefore the seakeeping analysis is simplified to determining the ability of the crew to continue working (or the ability to remain free from sea sickness) in the user specified sea state, at head seas, at 5 knots. So the SWAN2 input for sea heading is head seas (180°).

The final input needed for SWAN is the period of the waves to analyze. Assuming deepwater waves, the dispersion relationship is

$$\omega^2 = gk$$

where g is the gravitational constant and k is the wave number ($2\pi/\lambda$). Solving for wave period.

$$T = \sqrt{\frac{2\pi\lambda}{g}}$$

where T is the wave period. Sea sickness is caused by vertical accelerations due to heave. Ships resonate in heave at periods that correspond to waves near the ship's length. So it is necessary to analyze the ships motions to ensure the resonance is captured. Analyzing for wave at very low period (very high frequencies) requires more data points to be analyzed and increases the time to get results. Therefore it is desired to only go to as low a period as needed for each individual ship. Additionally, in large seas, the sea spectrum has no power at low periods, so analyzing below a certain point is not necessary. So ships are analyzed for periods from 5 through 15 seconds. This corresponds to wave lengths in deep water from 39 – 351 m. An example RAO from a PC-14 is shown below.
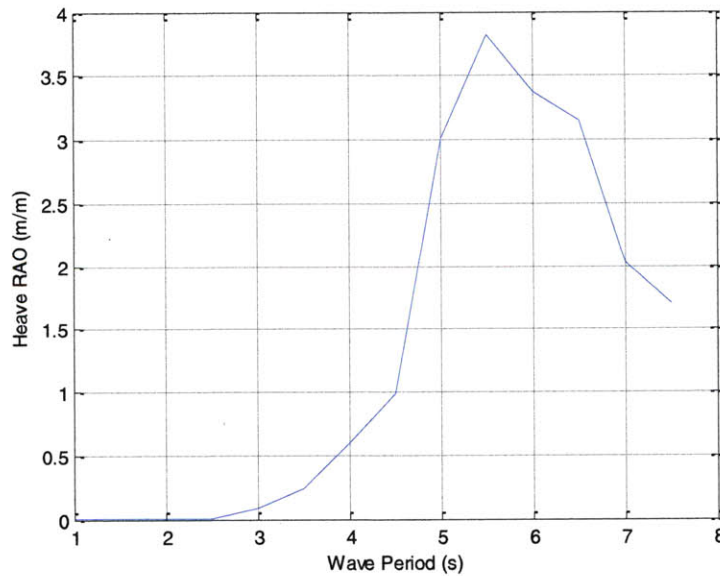
Figure 3-8 Heave RAO for a PC-14

The SWAN input file for seakeeping is generated by *PCAT_writeinpsk*.

3.12.2 Sea Spectrum

To use the RAO generated by SWAN2, a sea spectrum is required. The Brett Schneider sea spectrum was chosen as a standard spectrum to use because it is the ITTC standard sea spectrum for fully developed seas. This spectrum is a two parameter spectrum

$$S^+(\omega) = \frac{1.25}{4} \frac{\omega_m^4}{\omega^5} \zeta^2 e^{-1.25(\omega_m/\omega)^4}$$

where ζ is the significant wave height ($H_{1/3}$), and ω_m is the modal frequency of the spectrum. The modal frequency can be defined as

$$\omega_m = 0.4\sqrt{g/\zeta}$$

where g is the gravitational constant.

When the user inputs a sea state into PCAT, that sea state needs to correspond to a specific sea spectrum. To do this, the Beaufort scale (26) is used to correlate sea state to a wave height. The wave height is then used to calculate the modal frequency.

Beaufort Number (Sea State)	Mean Wave height (m)	Maximum Wave height (m)	Description
1	0.1	0.1	Calm
2	0.2	0.3	Light Breeze
3	0.6	1	Gentle Breeze
4	1	1.5	Moderate Breeze
5	2	2.5	Fresh Breeze
6	3	4	Strong Breeze
7	4	5.5	Near Gale
8	5.5	7.5	Gale

Table 3-8 Beaufort Scale
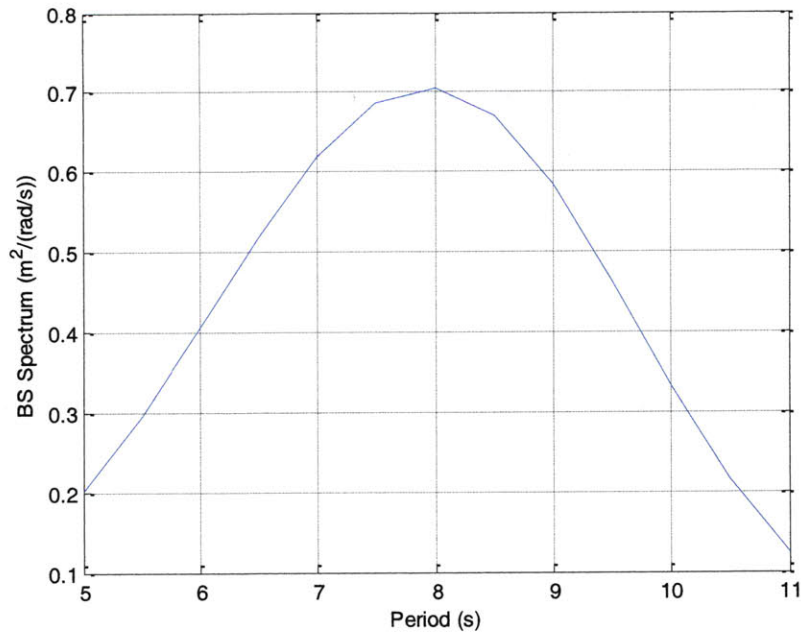
Figure 3-9 Brett Schneider Spectrum for Sea State 5

This sea state however, is the sea state the vessel seas at zero speed. If the ship is at speed the wave encounter frequency (ω_e) is different and therefore the spectrum has changed. To account for this the spectrum is adjusted as shown below.

$$S(\omega_e) = \frac{S(\omega)}{\left|1 - \frac{2\omega U}{g}\cos\beta\right|}$$

Because seas are only analyzed at $\beta = 180°$, there is no singularity.

3.12.3 Motion Sickness Incidence

The motion sickness incidence is defined as the percentage of subjects who vomit in the specified time that the subjects are exposed to the motions. It derives from tests on healthy young males subjected to vertical motions for a period of up to 2 hours. MSI is a function of vertical acceleration and is calculated for a two hour period as follows (15).

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$$MSI\% = 100 * \Phi \left[\frac{log\left(\frac{|\ddot{s}_3|}{g}\right) - \mu_{MSI}}{0.4} \right]$$

$$\mu_{MSI} = -0.819 + 2.32(log\overline{\omega}_e)^2$$

$$|\ddot{s}| = 0.798\sqrt{m_4}$$

where $\Phi(x)$ is the cumulative normal distribution function up to (x) for a normal distribution with zero mean and a standard deviation of 1, $\ddot{s}$ is the ventricle acceleration of the vessel, and m_4 is the 4th moment of the heave the heave response spectrum. The 4th moment of the heave response spectrum is calculated as follows

$$m_4 = \int_{-\infty}^{\infty} \omega_e^4 S_3(\omega_e) d\omega_e = a_{3RMS}^2$$

where S_3 is the heave response spectrum calculated below.

$$S_3(\omega_e) = |RAO(\omega_e)|^2 S(\omega_e)$$

The MSI response and all seakeeping information is calculated in *PCAT_seakeeping*.

3.13 Cost

PCAT calculates two different costs, the acquisition cost and the lifecycle cost. The acquisition cost simply uses cost estimating ratios (CER) to calculate the cost based on each weight group. It is important to have CERs that are relevant to the ship you are building. CERs for a high tech trimaran built of composites will be significantly different that the CERs for a patrol craft designed in PCAT.

The CERs used in PCAT are derived from recent US Coast Guard (USCG) ships (27) and are shown in the table below.

SWBS Group	CER (1000$/mton)
100	26.3
200	86.9
300	189.3
400	100.2
500	132.5
600	102.9
700	5.4

Table 3-9 CERs for PCAT

However, the user inputs actual costs for groups 400 and 700 (with the exception of fuel), so those CERs are not used. These CERs incorporate direct labor, overhead, material, and material overhead cost.

The life cycle cost is the acquisition cost plus the manning cost and the fuel cost. The manning cost is simply a product of the hull life of the variant, the manning level, and the cost per man-year. A default value of $80,000 per man year is used. The fuel cost is calculated by multiplying the SFC of an engine at a given kW times the BHP, time the percent of time the ship is operating at that speed. This result (kg/hr) is then converted into (kg/yr) and multiplied by the percent of time the ship is operational, the life of the hull in years, and the cost of fuel in ($/kg).

$$Fuel\ Cost = \sum_n (SFC_n BHP_n Percent_n) \frac{24hrs}{day} \frac{365days}{yr} (\%\ time\ operational)$$
$$* (Life\ of\ Hull) * (Cost\ of\ Fuel)$$

Where the index represents the number of elements in the speed profile array, and $Percent_n$ is the percentage of time the ship spends at speed n. Table 3-10 shows the default cost values used in PCAT. All default values can be adjusted by the user in the input GUIs. The cost calculations are performed in *PCAT_cost_lc* (lifecycle cost) and *PCAT_cost_aq* (acquisition cost).

Item	Default Cost
Fuel ($/kg)	3.82
Manning ($/man-year)	80000

Table 3-10 Default Costs

3.14 Performance

The performance of each variant is calculated using the overall measure of effectiveness (OMOE) input by the user. The OMOE is broken down into three primary MOEs: operations, mobility, and weapons. Each of the primary levels is assigned a weight of importance, with the sum of the primary weights equaling unity.

Mobility and operations MOEs are then broken down into secondary measures. Mobility is a function of maximum speed, endurance, range, and draft. Each of these secondary MOEs is also assigned a weight by the user and the sum of the mobility weights is also unity. Operations is a function of main deck area, in-hull area, manning and seakeeping. The operations weights are assigned in the same manner as the mobility weights. The weapons MOE is assigned by the user and is not broken down to a second level.

Each secondary MOE is given a value based on the user inputs and PCAT calculations. The user either specifies the threshold and goal values, or the threshold is set at the worst value of a particular parameter and goal is set at the best. The threshold value for a given parameter is given a MOE of zero. The goal is given a value of one. All values in between are linearly interpolated between 0 and 1 as shown in Figure 3-10.
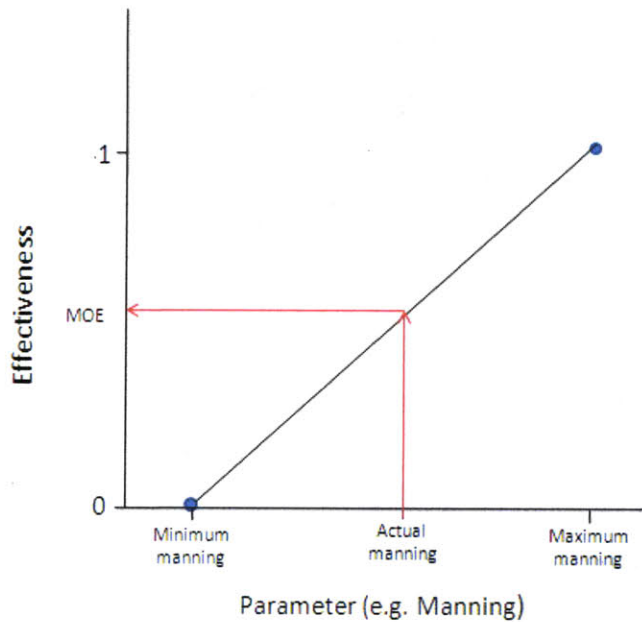
Figure 3-10 Example MOE

The total operation MOE is then:

$$MOE_{OPS} = W_{IHAREA} MOE_{IHAREA} + W_{MDAREA} MOE_{MDAREA} + W_{MAN} MOE_{MAN} + W_{SEA} MOE_{SEA}$$

Where W represents the user assigned weighting value. The mobility MOE is calculated in the same way. The overall MOE is then

$$OMOE = W_{OPS} MOE_{OPS} + W_{MOBILITY} MOE_{MOBILITY} + W_{WEPS} MOE_{WEPS}$$

3.15 Rejection Criteria

Ships can be rejected for many different reasons. In each case the rejection will generate an error code so the user will know why the rejection occurred. The list below is all of the reasons a ship may be rejected

- Froude number mismatch – One of the major limitations of PCAT is the range over which resistance can be calculated. If the Froude number of the maximum speed, the

endurance speed (if not set to default) or any of the speeds in the speed profile are less than 0.1 or greater than 0.6, the program will not converge on a final design for that variant, and an error code will be generated.

- Inadequate area – If the main deck area is less than the area required for the weapons, or the internal area is less than the area required for the weapons and the prime movers, the program will not converge on a final design for that variant, and an error code will be generated.

- Inadequate GM – If the GM for a particular variant less than 0.5 m, the program will not converge on a final design for that variant, and an error code will be generated.

- Unable to converge – If there is a significant mismatch between the weight and the displacement of the ship and the freeboard at midships is reduced to less than 4% of the overall length, the program will not converge on a final design for that variant, and an error code will be generated.

4.0 Optimization for PCAT

Each individual ship run or experiment on PCAT takes nominally 1 hour to accomplish. While that may not seem like an incredibly long time, to do a full factorial search on 13 variables at only 4 levels each, would require 13^4 or 28,561 hours or about 3 years. 3 years is clearly not an acceptable time frame for results on an early stage design program, so some optimization must be done to minimize the number of experiments and still allow for useful results that can lead a designer to either perform additional experiments or to make design decisions.

4.1 Response Surface Methodology

Response surface methodology (RSM) is a collection of statistical and mathematical techniques useful for developing, improving, and optimizing a process. Additionally, it can be used to design, develop, and formulate new products, or improve existing designs. RSM was originally created by G. E. Box and K. B. Wilson in 1951. It uses a sequence of specific experiments designed to capture a snap shot of the entire design space and then uses regression techniques to derive the relationship between several independent input variables (x_i) and one or more response variables (y) (28).

Because of the regression techniques used, RSM can only be used with continuous variables. For the case of PCAT, that limits the variables to:

- L
- L/B
- L/D
- Deck height
- Frame spacing,
- LCG/L
- KG/D
- Manning
- Range

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- Number of Shafts

These will be the 10 independent variables for RSM. The remaining design variables that can assume different levels are:

- Parent hull

- Hull Material

- Weapon group

- Choice of Waterjets or Propellers

These variables will be considered discrete and will be addressed later in the chapter. The discrete variables will all be fixed at one level (the first level entered is chosen if the user input multiple levels) for the entire RSM analysis. There are many other design variables in PCAT such as the speed profile and the percentage of the manning that is officer, enlisted, or senior enlisted, however these design variables are held fixed for all ships in the run. Therefore it is not necessary to include these variables in the RSM.

PCAT produces three different responses.

- Acquisition cost

- Lifecycle Cost

- Performance (OMOE)

These variables are the response variables for RSM in PCAT.

In general the user wants to know what the effect changing an input (x_i) has on the response (y). A single response can be characterized by

$$y = f(x_1, x_2, x_3, \dots, x_n)$$

If the system was assumed to be linear and first order, then the response could be characterized by

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_n x_n$$

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This first order model is called a main effects model because it only includes the effects of the variables themselves. If there is an interaction between these variables, it is not captured by a main effects model. Often the first order model is inadequate to capture the response. Therefore a higher order model is used in PCAT.

If first order effects are considered as well as interaction and quadratic effects, the model would be represented by

$$y(x) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 x_2 \ldots$$

Or more generally, for n variables

$$y(x) = \beta_0 + \sum_{i=0}^{n} \beta_i x_i + \sum_{i<j}^{n} \beta_{ij} x_i x_j + \sum_{i=0}^{n} \beta_{ii} x_i^2$$

This model is called a second order, or quadratic model. This is the model that will be used in PCAT.

4.2 Designing the Experiments

As previously discussed, it is important to choose the experiments in such a way that the entire design space is covered in a minimum number of experiments. Central Composite Designs (CCDs) are appropriate for calibrating quadratic models(28) (29). There are three types of CCDs: circumscribed, inscribed, and faced. Examples are shown below.
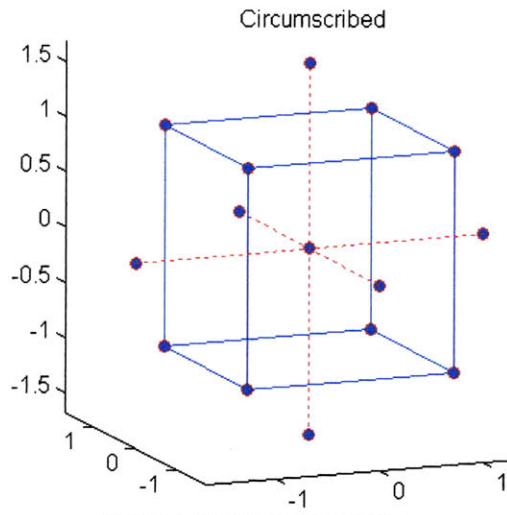
Circumscribed

Figure 4-1 Circumscribed CCD
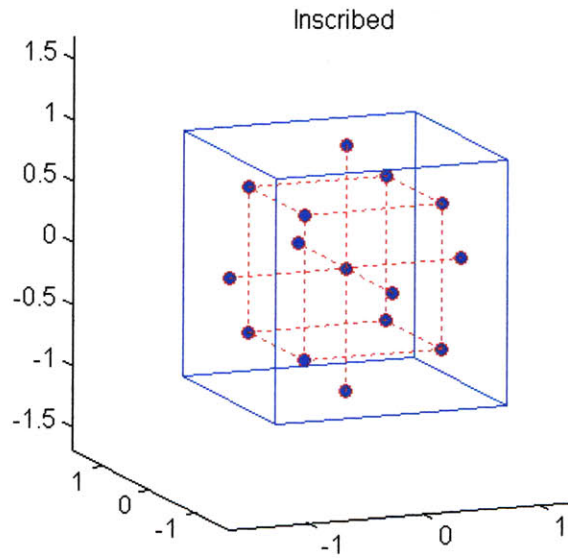
Inscribed

Figure 4-2 Inscribed CCD

73
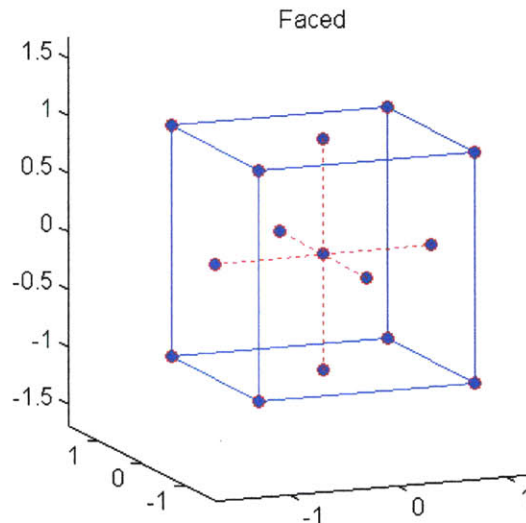
Figure 4-3 Faced CCD

Each CCD consists of a factorial design (the corners of a cube) together with center and star points that allow for estimation of second-order effects. For a full quadratic model with n factors, CCDs have enough design points to estimate the coefficients in a full quadratic model with n factors (29).

The type of CCD is determined by the number or levels a variable can take and by the desired properties of the design. The following table below summarizes properties of the three CCD designs (29).

Design	Factor Levels	Uses Outside Points	Accuracy
Circumscribed	5	Yes	Good over the entire design space
Inscribed	5	No	Good over the central subset of the design space
Faced	3	No	Fair over the entire design space, though poor for pure quadratic coefficients

Table 4-1 Properties of CCDs

For the bounds of the experiments, the limits of the user inputs are selected. Therefore, it is not desired to use any points outside the user inputted range. This eliminates the circumscribed CCD. Additionally is not desired to diminish the effects of the quadratic coefficients, therefore the Inscribed CCD was chosen to design all experiments. It is important to note the inscribed

CCD is not as accurate around the edges of the design space as the other methods. For this reason, when using RSM in PCAT, the user should be aware that the results near the edges of the design space may not be as accurate and should be fully modeled.

For 10 variables the inscribed CCD requires a minimum of 149 experiments. This is much more reasonable, and should take on the order of 6 days. If the user can fix only two factors, such as frame spacing and LCG/L, then the number of experiments is down to 81 which should take on the order of 3.5 days. The variable levels are assigned only for variables that have a different maximum and minimum, thereby ensuring that no experiments are unnecessarily repeated. The experiments are designed in *PCAT_rsm*. Once the experiments are designed, the ship building and analysis is performed in the same method as shown in chapter 3.

4.3 Analysis and Optimization

After the analysis is complete with all three response variables calculated for each ship, linear regression is used to determine the coefficients for the quadratic model. In general at this point in RSM, the user would use graphical tools to look at the effects of specific variable input on a response using the model created, allowing the user to find an optimal or near optimal solution with little additional calculation from the program. However, for this design there are two issues that make this difficult.

First, there are multiple responses that will not optimize at the same point. Performance and cost are inherently opposed. The highest performing ship will likely be the most expensive. This makes it difficult to define THE optimal ship, much less find it. The simplest way to alleviate this concern is to allow users to look at this trade off, use good engineering judgment, and choose ships they would like to optimize around. To do this, a chart that shows ships cost and performance of ships over a wide range of variable inputs is given to the user. The ships will form a pareto frontier and the user then is allowed to choose what ships to use a basis for further study.

The range of ships used to create the pareto frontier takes every variable analyzed for in the RSM and does a full factorial search at 5 levels using the quadratic model to determine the responses instead of the original program. This is done in *PCAT_rsmfinal*. A sample chart is shown below.
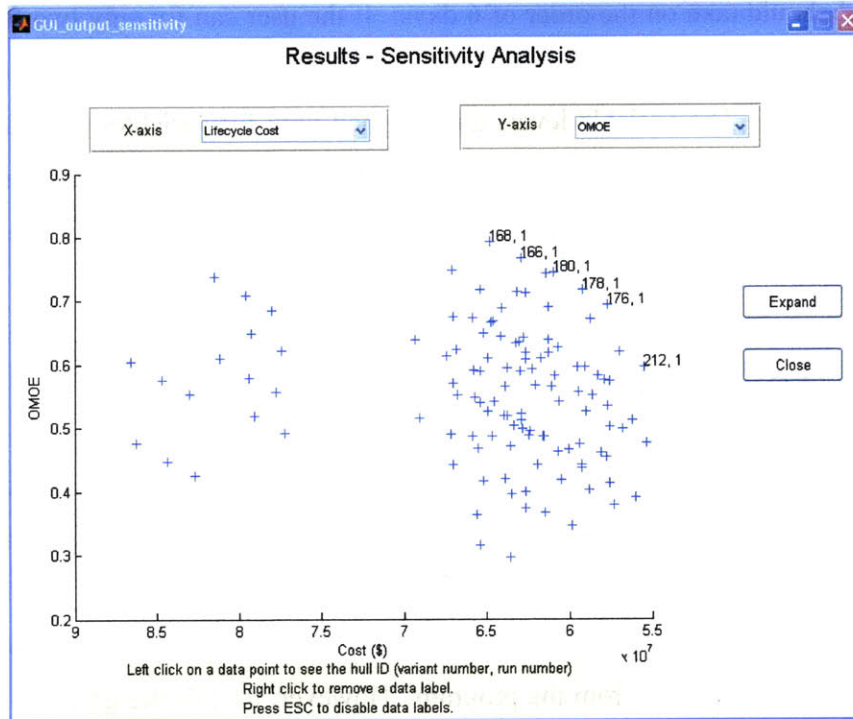
Figure 4-4 Sample Cost/Performance chart

The user can then drill down to find information about high performing, low cost ships. In general the ships analyzed will be in the top right portion of this chart. With a narrower range of variables, the user now needs to run a second set of analysis at a full factorial level that will allow for the optimization of discrete variables. This is just like running PCAT originally with a full factorial set of experiments. However, the design space has been narrowed to now limit the number of experiments. Chapter 5 gives an example of this process.

5.0 Using PCAT

This chapter describes the process for one particular example of PCAT using RSM on the first run, and a full factorial analysis on the second.

5.1 Inputs

User inputs for the first run are shown below. These variables were chosen so RSM could be used.

Geometry
- Length was given a range of 27.4 m to 33.5 m.
- L/B was given a range of 4.5 to 5.206.
- L/D was given a range of 7.0 to 8.148.
- The PC-14 was chosen for the parent hull.
- Deck height was set to be 2.75 m.

Loading
- KG/D was set a 0.6.
- The LCG was set to default.
- The material was set to ordinary strength steel.
- The frame spacing was set to 1.5 m.

Machinery
- Only 1 engine per shaft was allowed.
- Each ship had 2 shafts.
- Only propellers were allowed.

Speed

- The maximum speed was set to 20 kts.

- The endurance speed was set to default.

- The range was set from 700 to 800 nm.

- The speed profile is [5 kts-20% 10 kts-35% 12.5 kts-25% 15 kts-15% 20kts-5%]

Weapons – The weapons profiles was set as shown in Table 5-1.

ID	Weight (mton)	DH area (m^2)	IH area (m^2)	Power (kW)	KG/D	WMOE	Cost (k$)
Med	8	14	27.9	120	1	0.6	2000

Table 5-1 Input Parameters for Weapons

Manning – 15 men on board with 13.3% officer, 13.3% CPO, and 73.3% enlisted.

Seakeeping – The Sea State was set to Sea State 5.

Cost – All the cost values were left at their default values.

OMOE – All the secondary MOEs goal and threshold values were left to default. The weights for all the MOEs are:

- Maximum speed - 0.25

- Endurance - 0.25

- range - 0.25

- Draft - 0.25

- Main deck area - 0.30

- In-hull area - 0.30

- Manning - 0.20

- Seakeeping - 0.20

- Operations - 0.40

- Mobility - 0.40

- Weapons - 0.20

5.2 First Run Outputs

PCAT first designed the experiments using an inscribed CCD. Then each variant was built and analyzed. RSM was then used to make a model of the surface. PCAT then showed the main output screen, shown in Figure 5-1. The create Rhino function is not yet functional, but the capability can be added without much difficulty. The first place a user needs to click is on the sensitivity analysis. This allows the user to see all of the designs in many different formats.
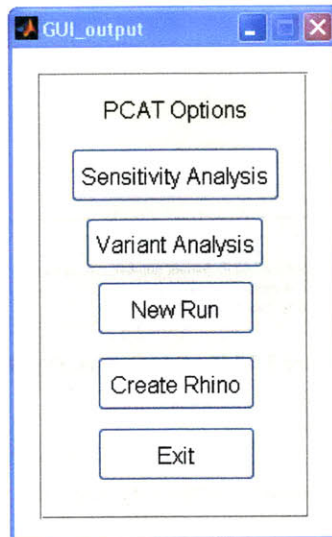
Figure 5-1 Main Output Screen

At the sensitivity analysis screen, the user can place lifecycle cost, acquisition cost, or any input parameter on the x axis. The y axis can be populated with any output parameter such as BHP required, maximum speed, deck area, GM, or MSI. Figure 5-2 and Figure 5-3 show sample sensitivity graphs.
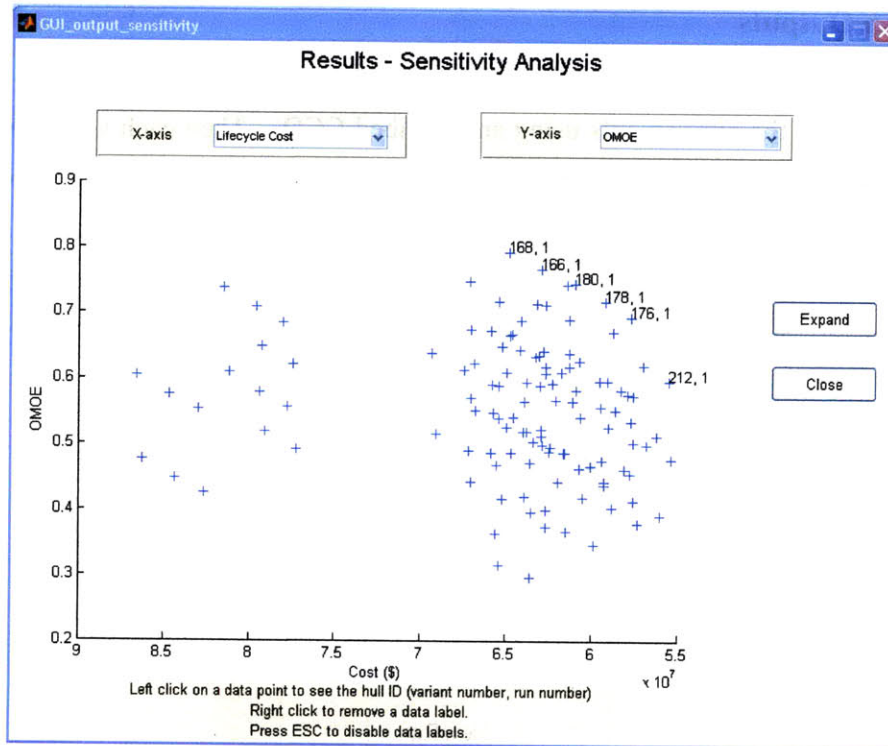
Figure 5-2 Lifecycle Cost vs. OMOE
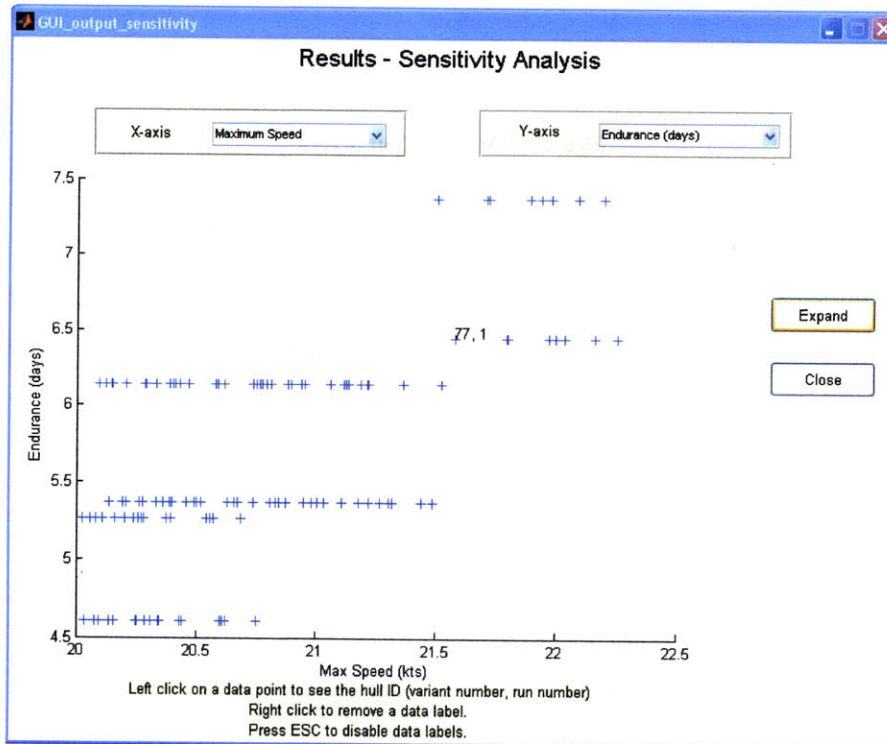
Figure 5-3 Maximum Speed vs. Endurance

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On each sensitivity graph the user can click on a data point to get the identification of the particular variant. This information is then taken to the next output screen, variant analysis. On variant analysis, the user can get data on a particular variant. Reports include:

- Summary: Geometry
- Summary: Machinery
- Summary: Speed, Range, and Manning
- Summary: Loading, Weapons, and Cost
- Body Plan
- Weight Report
- Operating Profile
- Powering Curves
- Structures Graphical
- Structures Summary
- OMOE

**** GEOMETRY SUMMARY FOR VARIANT 164, RUN 1 *****

Length overall - 35.72 m
Maximum beam - 7.44 m
Maximum depth - 4.48 m
Full load draft - 2.50 m
Length between perpendiculars (LBP)- 33.77 m
Displacement - 281.1 mton
Parent hull - PC-14
Block coefficent (Cb) - 0.440
Prismatic coefficent (Cp) - 0.688
Deck height - 2.75 m
Main deck area - 233.4 m^2
In hull area - 174.24 m^2
Wetted surface area - 258.08 m^2
Metacentric height (GM) - 1.55 m
Height of the metacenter (KM) - 4.24 m

Figure 5-4 Geometry Summary

***** SPEED, RANGE, and MANNING SUMMARY FOR VARIANT 164, RUN 1 *****

Maximum speed 21.2 kts
Endurance speed 6.0 kts
Enduance time 6.1 days
Range - 800.0 nm
Fuel load required to meet range (with 50% margin) - 8.84 mton

Total manning 15
Officer manning 2
CPO manning 2
Enlisted manning 11

Figure 5-5 Speed, Range, and Manning Summary

***** MACHINERY SUMMARY FOR VARIANT 164, RUN 1 *****

There are 2 Caterpillar 3516C-3386 engines on this hull
Number of engines per shaft - 1
Number of shafts - 2
Maximum speed - 21.2 kts

*** ENGINE SPECIFICS ***
Length - 3.22 m
Width - 2.23 m
Height - 2.07 m
Weight - 8.28 mton
BHP - 2525 kW
Maximum RPM - 1800 RPM
Full load fuel usage - 605.0 LPH
Full load s.f.c. - 0.20 kg/(kW-hr)
Full load torque - 13395 N-m

Figure 5-6 Machinery Summary

***** LOADING, WEAPONS AND COST SUMMARY FOR VARIANT 164, RUN 1 *****

The material used for this hull was Ordinary Strength Steel
Frame Spacing = 1.5 m
Longitudinal center of gravity = -0.06 (% LBP fwf of misdhips)
Height of center of gravity (KG) = 2.7 m

The ID of the weapons group was Med

Cost of manning = 80000 $/man-yr
Percent time operational = 33%
Life of the ship = 22.0 years
Total Acquisition cost of the ship = $ 18.9 M
Total lifecycle cost of the ship = $ 77.9 M

Figure 5-7 Loading Weapons, and Cost Summary
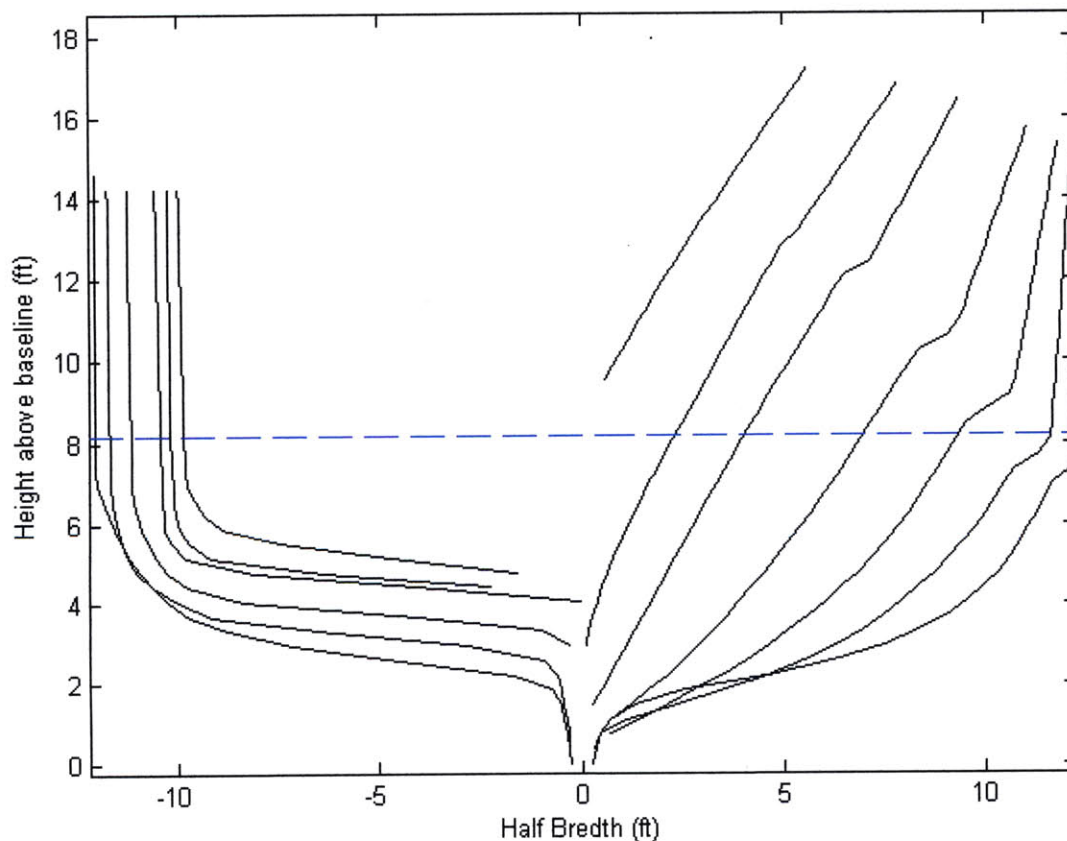
Figure 5-8 Body Plan

Weights are in mton

W100 149.1 HULL STRUCTURES
W200 31.2 PROPULSION PLANT
W300 27.3 ELECTRIC PLANT, GENERAL
W400 5.1 COMMAND+SURVEILLANCE
W500 30.3 AUXILIARY SYSTEMS, GENERAL
W600 18.4 OUTFIT+FURNISHING, GENERAL
WF41 22.6 DIESEL FUEL MARINE

TOTAL FULL LOAD WEIGHT 284.0 mton

Note that SWBS W400 is input by the user and incorporates W400 and W700 and other variable loads

Figure 5-9 Weight Report
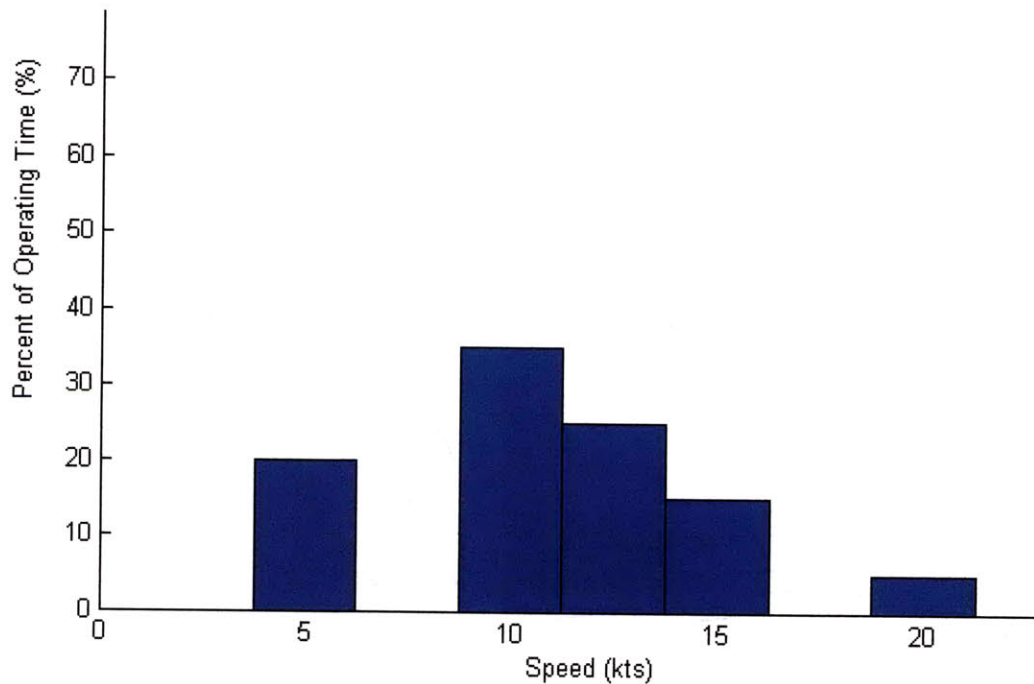
Figure 5-10 Speed Profile

← break between bottom and side shell
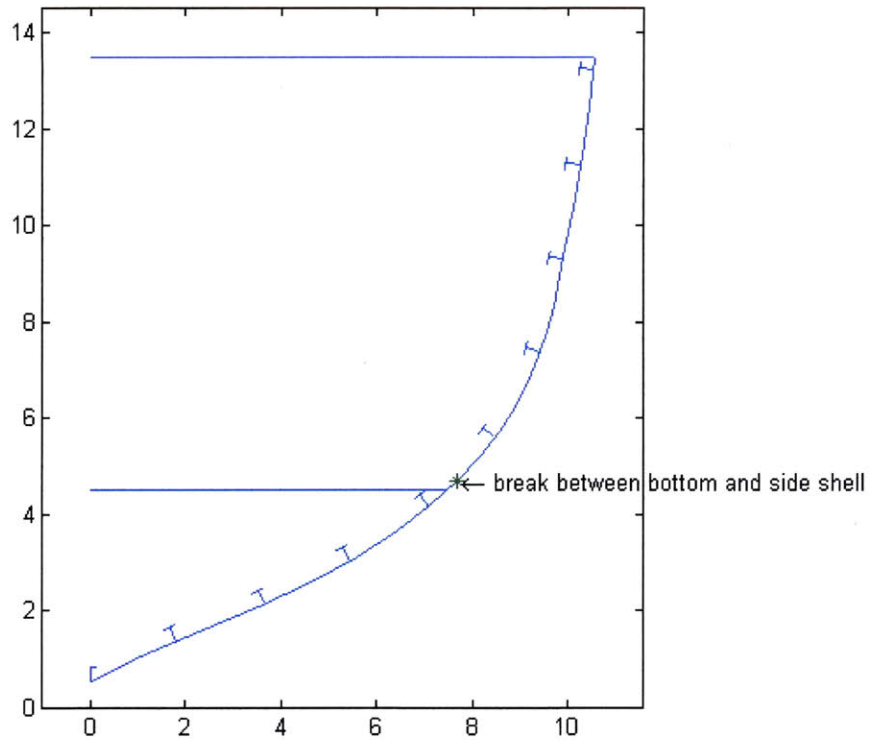
Figure 5-11 Structures Graphical

**** STRUCTURES SUMMARY FOR VARIANT 205, RUN 1 *****

Minimum section modulus -   2252 m-cm^2

Bottom shell plating thickness - 1.47 cm
Side shell plating thickness near midships - 1.76 cm
Side shell plating thickness near ends - 1.53 cm
Bottom girder critical thinkness - 0.445 cm
Bottom frame critical thinkness - 0.864 cm
Side stringer critical thinkness - 0.457 cm
Side frame critical thinkness - 1.60 cm
Main Deck thickness - 0.711 cm
Internal deck thickness - 0.673 cm
The midships neutral axis is located 2.2 m above baseline

Figure 5-12 Structures Summary

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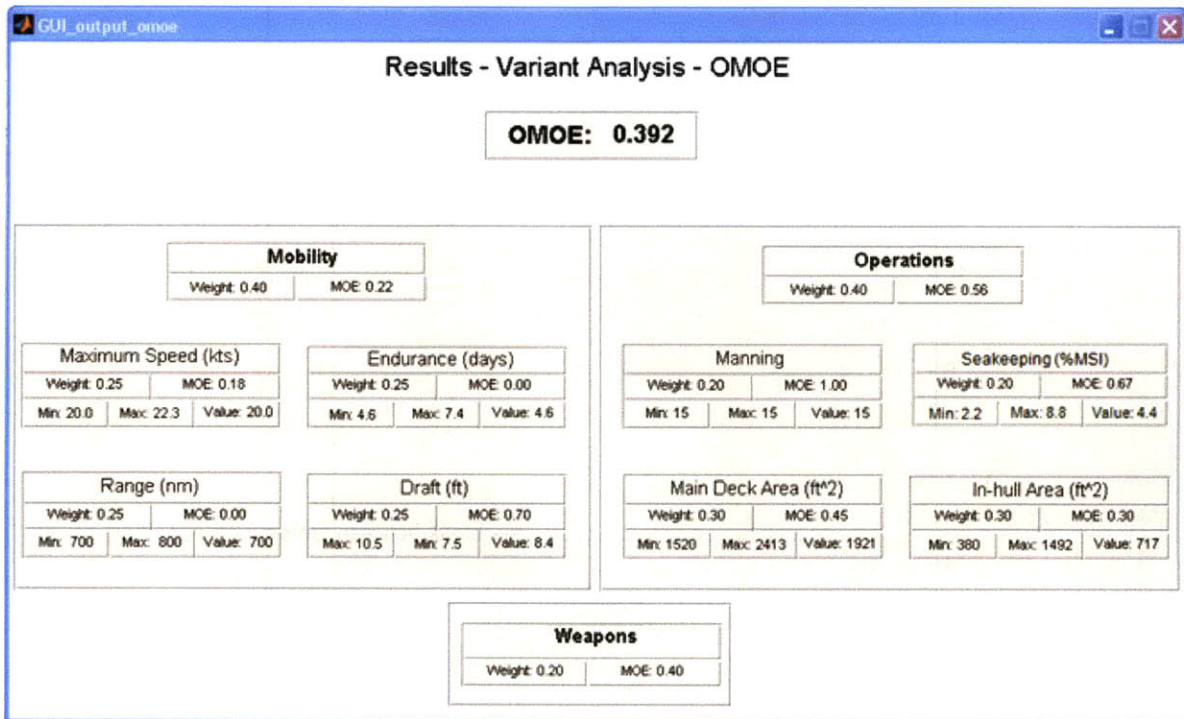
Figure 5-13 OMOE

In the variant analysis section, the user gathers data on the high performing variants, and looks for trends that might show the user how better to refine the inputs. Ten variants were analyzed from the first run (150, 164, 166, 168, 176, 178, 180, 205, 211, 212).

Several facts were noted.

- All had a high range of 800 nm

- 80% of the variants were 33.5 m in length.

- No variant had the smallest L/D value.

- 70% of variants had an L/B of 4.5.

- 80% of variants were from the longer ship

5.3 Second Run Results

With the design space better understood, the input parameters were reassigned to try and optimize the design, along with assigning the discrete variables. It is clear that the longer ship performs better, so the possible length values were increased. L/D was set at the highest level and L/B at the lowest. Additionally, the range value was set to 800nm. The discrete variables were assigned as shown below. Table 5-2 shows the parameters that were changed or added

	Original Values	New Values
Length (m)	27.4 – 33.5	33.5, 36.6, 39.6
L/B	4.5 - 5.206	4.5
L/D	7.0 - 8.148	7.5, 8.148
Range (nm)	700 - 800	800
Hull Type	PC-14	PC-14, NPL
Weapon Groups	Med	Low, Med, Hi

Table 5-2 Changes for Second Run Inputs

The new weapon groups are shown in the table below.

ID	Weight (mton)	DH area (m^2)	IH area (m^2)	Power (kW)	KG/D	WMOE	Cost (k$)
Lo	5	9.3	27.9	100	1	0.4	1000
Med	8	14	27.9	120	1	0.6	2000
High	12	18.7	37.2	170	1	0.9	3000

Table 5-3 Second Run Weapon Groups

With the new variant runs, two objectives are being met simultaneously. The discrete variables are added and the continuous variables are further refined. For instance, the length array is extended to experiment with longer ships. Other variables that showed clear dominance in one area were set to that value. It is important to note, that in the second full factorial run, it is also possible to just explore the discrete variables with the continuous variables optimized. It is at the user's discretion.

With the new variables set, PCAT was run again, this time with a full factorial run. Through a careful selection of variables, the second run was limited to 36 ships.

The second run results are shown in Figure 5-14 with the second run results in green and the first run results in blue. The second run results show moderate improvement in the design. The user can perform up to eight runs on one set of design parameters, each time refining the design in an attempt to optimize the ship. Each run can either be a full factorial run or a RSM run.
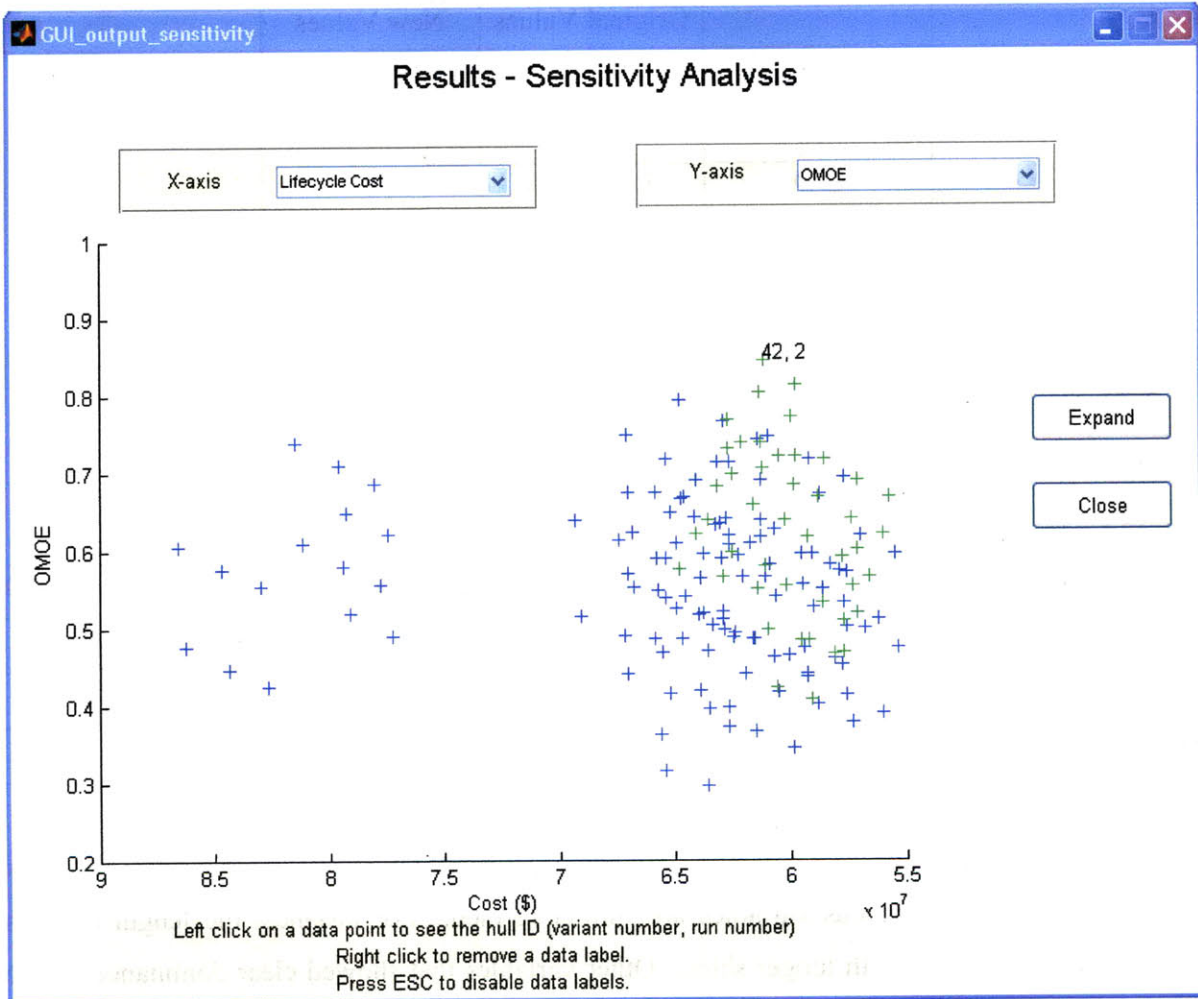
Figure 5-14 Second Run Results

6.0 Whole Ship Validation

To validate the entire model, PCAT was used to create a Cyclone class patrol craft. The PC-14 is a member of this class of ships and that specific ship was used for validation.

The first step in validation is defining the PCAT inputs for the PC-14. Most inputs were taken from the U.S. Navy's ASSET model of the PC-14 (10). Items marked with an asterisk (*) were assumed values. OMOE values are irrelevant for this experiment and therefore are not listed.

Variable	Value
Length	50.7 m
L/B	6.95
L/D	10.35
Parent Hull	PC-14
Deck Height*	2.6 m
LCG/L	Default
KG/D	0.6
Frame Spacing*	1.5 m
Material[6]	AH36
Engines per shaft	1
Shafts	4
Waterjets	No
Manning	28 men
Manning Breakdown	14.3% Officer 14.3% CPO 71.4% Enlisted
Maximum Speed	25.1 kts
Endurance Speed	12 kts
Range	2649nm
Speed Profile*	5 kts - 20% 10 kts - 40% 15 kts - 25% 20 kts - 10% 25 kts - 5%
Seastate	5
Cost	Default Values

Table 6-1 PCAT Values for Validation

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[6] There was no exact match for the material used in the PC-14. AH-36 was chosen because of the similarity in σ_y and σ_{UTS}. For PC-14 HSS, $\sigma_y = 352$ N/mm^2, $\sigma_{UTS} = 496$ N/mm^2. For AH-36, $\sigma_y = 355$ N/mm^2, $\sigma_{UTS} = 555$ N/mm^2.

The weapons onboard the PC-14 are listed below (30). The PC-14 is fit with the following weapons systems:

- 1 sextuple SAM stinger
- 1 Bushmaster 25mm mk-38 25mm gun
- 4 - 12.7 mm machine guns
- 4 – 7.62 mm maching guns
- 2 – 40 mm Mk 19 grenade launchers
- 2 – Mk 52 sextuple and Wallop Super Barricade Mk 3 chaff launchers

The PC-14 also has the following command and control systems (30):

- Privateer APR-39 radar electronic surveillance measures (ESM) system
- Marconi VISTAR IM 405 IR weapons control system
- 2 – Sperry RASCAR; E/F/I/J-band surface search radars
- 1 – Wesmar; hull mounted active high frequency hull mounted active sonar

To calculate the weight of this equipment, the ASSET PC-14 model was used. The area requirement came from the ASSET model as well. To calculate the cost of the SWBS groups 400 and 700, the USCG CERs for SWBS groups 400 and 700 were used. This generated the weapons input below.

ID	Weight (mton)	DH area (m²)	IH area (m²)	Power (kW)	KG/D	WMOE	Cost (k$)
PC-14	20.0	564	21.2	25*	1*	1*	468.7

Table 6-2 PCAT Weapons Input for Whole Ship Validation

6.1 Validation Results

The validation results shown below are grouped by PCAT report. For those response values with no comparable value, the response is just list for informational purposes.

Response	PCAT Output	ASSET Value	% Difference
Block Coefficient (C_b)	0.379	N/A	N/A
Prismatic Coefficient (C_p)	0.661	0.650	1.7%
Main Deck Area (m^2)	345.0	N/A	N/A
In Hull Deck Area (m^2)	275.8	281	-2.1%
Wetted Surface Area (m^2)	424.5	446.1	-4.8%
GM (m)	1.55	1.31	18.3%
KM (m)	4.45	4.22	5.5%

Table 6-3 Geometric Validation

Response	PCAT Output	ASSET Value	% Difference
Main Engine Power (kW)	1864	2498	-25.4%
Final Maximum Speed	27.1 kts	28.4 kts	-4.8%

Table 6-4 Power and Speed Validation

The large difference in the main engine power is troubling at first glance. However, both PCAT and ASSET met the stated speed goal of 25.1 knots. The difference in power is due to excess power supplied by the main engines over the required speed. If a cubic relationship between power and speed is assumed ($power^3$ α speed), the expected difference in speed due to an increase in supplied power can be calculated and the values in the above table more accurately compared.

$$2490 kW - 1864 kW = 634 kW$$

$$\left(\frac{634 kW}{1864 kW} \right)^3 = 0.0393$$

$$27.1 kts + 0.0393 * 27.1 kts = 28.2$$

So if the PCAT model was supplied with the same engine catalog as the model ASSET, and PCAT converged to the same engine, PCAT's speed output would be 28.2 knots, or within a 1% error.

Response	PCAT Output	ASSET Value	% Difference
SWBS 100 (mton)	222.8	224.9	-0.95%
SWBS 200 (mton)	32.9	75.8	-56.5%
SWBS 300 (mton)	27.3	20.5	24.9%
SWBS 400 and 700 (mton)	20.1	20.1	0%
SWBS 500 (mton)	54.8	66.2	-17.2%
SWBS 600 (mton)	31.2	32.6	-4.3%
SWBS WF41 (mton)	44.2	40.8	8.3%
Total Displacement (mton)	469.7	480.8	-2.3%

Table 6-5 Weight Validation

These results are, in total, very pleasing. The largest weight errors occur in two SWBS groups, the propulsion (SWBS 200) group and the electric (SWBS 300) group. The electric group is very roughly modeled in PCAT and it is understandable that the weight would be more than 25% off. It is surprising though that the propulsion group so far off. After significant investigation, there was no known cause for this disparity.

Because the Navy did not use ABS guide lines for the designing of the structures, it would be erroneous to compare the individual pieces in the structures module from PCAT and ASSET. However, by comparing the section modulus and the location of the neutral axis, it can be shown that the structures are quite similar.

Response	PCAT Output	ASSET Value	% Difference
Neural Axis to Keel Distance (m)	2.47	2.39	3.3%
Section Modulus to Keel (m-cm^2)	3467	3093	12.1%

Table 6-6 Structural Validation

The PC-14 was ordered in 1997 for $23.19 million (31). Accounting for inflation to 2008 (32) (CERs are in 2008 dollars) gives a cost of the actual PC-14 in 2008 dollars of $31.84 million

Response	PCAT Output	Actual cost	% Difference
Acquisition Cost	$24.83M	$31.84M	-22.0%
Lifecycle Cost	$107.43	N/A	N/A

Table 6-7 Cost Validation

The acquisition cost results are quite good. The most important aspect of cost in PCAT is for comparison purposes, so to be within 25% on a rough model is excellent. Calculating the actual lifecycle cost for an actual decommissioned ship is difficult at best. For a ship during its service life, it is near impossible, and the PC-14 is still in service. Additionally, the lifecycle cost calculated in PCAT only includes manning and fuel considerations, and not many of the other important lifecycle cost factors such as maintenance and repair. Even if an actual lifecycle cost was available, it would not be worthwhile to compare the actual value to PCAT's value. Therefore no comparison for lifecycle cost is given.

In total, PCAT's results seem reasonable and comparable with an actual ship.

7.0 Conclusion

The goal of PCAT was:

> *Using a systems approach, a Patrol Craft Assessment Tool (PCAT) will be created and tested to aide designers in the initial design and assessment of patrol craft of < 90 m operating in the semi-displacement or displacement regions. PCAT will be an open source MATLAB code that incorporates resistance, engine selection, structures, mission profiles, seakeeping, cost, and performance into one design program to aide a designer in optimizing a patrol craft.*

For the most part this goal was met, though there are several areas in which PCAT could be improved.

7.1 Areas for Future Work

In a model such as the one created in PCAT, there are always areas to improve. The first area for improvement is an interface problem between Matlab and SWAN2. As SWAN2 solves for flow around the hull it goes through a three step process. First a spline sheet geometry file is generated. Next the boundary integral equation is setup and a solution is determined for the base flow is solved. Finally, the boundary integral equation is solved for the problem. Between each of these steps SWAN requires a carriage return to be hit. SWAN2 and hence PCAT will wait for a carriage return before moving on to the next step. This means that the user must continually hit enter on their keyboard for PCAT to advance. While this is just a technical "glitch" it is a very inconvenient one and should be fixed if at all possible in future work with PCAT.

Another area to help improve the speed of the program would be the creation of a function to parse the design information before the ships are analyzed and recombine the results at a later point in time. This would allow the user to take the information to multiple computers to dramatically lower the analysis time.

When designing the experiments for RSM an inscribed CCD was used to chose what experiments to run. The stated disadvantage to that method was poor accuracy on the borders of the design space. Another method for choosing the experiments is using Latin hypercubes. Latin hypercubes were first described by McKay in 1979. To explain Latin hypercubes, it is best to first look at a Latin square. A Latin square is a square grid containing sample positions where there is only one sample in each row and each column.
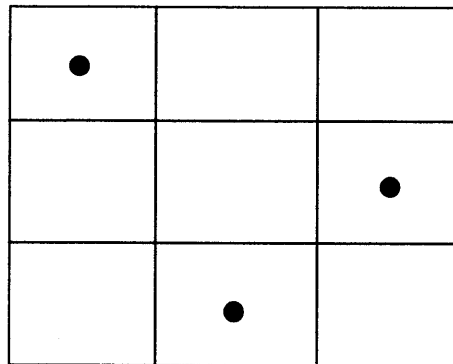
Figure 7-1 Example of a Latin Hypercube

A Latin hybercube is an extension of that idea to an arbitrary number of dimensions. Latin Hypercubes have two significant advantages over CCDs. First, Latin hypercubes can better sample the entire design space and will not give poor performance in a particular sector. Second, with Latin hypercubes the intervals for sample can be chosen in such a way as to ensure the number of experiments does not exceed a certain value, thereby ensuring timely results from the program even if more variables were used (33). This is definitely an area worth investigation in the future.

Another area worth investigating is the use of graphical tools with RSM. Due to the sheer number of variables, graphical tools were not used to the extent that they could have been during the analysis stage. It would be interesting to see if there is value added through the use of 3-D displays where the user can see graphically the effect of change length and L/B on the OMOE of the ship.

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Additionally, there is an opportunity to refine the propeller design. Using lifting line theory, a propeller could be designed to fit the specific needs of each ship. With this information, a more accurate propulsive coefficient could be determined at all speeds. This would allow PCAT to more accurately determine lifecycle fuel usage and hence lifecycle fuel cost. Typically the propeller is design with regard to a specific speed. With a whole ship model, the propeller design could be iteratively designed with the ship to minimize lifecycle cost instead. The same iterative method could be used to select the optimum waterjet for the entire speed range vice the optimum waterjet for maximum speed.

A final area of future work is in the robustness of the design. In the US Navy today, ship requirements are developed more than 10 years before a ship enters production. If multiple ships are produced the construction phase could continue for 20 or more years. Add this to a 20-30 year lifecycle of the ship and the time from requirements generation until the last ship in a class is decommissioned can very reasonably be place at 60 years if not higher. With that much time between requirements generation and decommissioning, it is virtually guaranteed that during the course of the life of a ship class, the mission of the ship and the requirements will change. It would be valuable to know if a ship's performance (OMOE) would still be at a high level throughout a wide range of performance criteria. Stated another way, given various OMOEs, which ship performs best under all different performance criteria? And what are the costs of choosing such a ship? This knowledge would help to ensure some degree of robustness in the design of a ship and ensure the ship provides value to the owner throughout its lifecycle and would be a valuable addition to PCAT.

7.2 Final Thoughts

It would be naive to say that PCAT could produce "the" optimum hull. PCAT is not robust enough to perform the detailed analysis necessary for truly optimizing an object as complex as a ship. However PCAT can aide a designer in quickly narrowing the design space, determining which variables are meaningful and require more study, and which variable can be reasonably selected at a certain level.

It is not intended that a designer use PCAT as currently coded. Rather a designer should consider the requirements of their ship and ensure that PCAT adequately addresses the design challenges. Are there additional performance factors that should be included in OMOE? Is the model detailed enough in the areas that are important for each specific design? Questions like these must be asked and answered to ensure that the results or meaningful. This thesis was written and PCAT was coded in such a way as to facilitate change and improvement to the program and to allow a designer analyze the tradeoffs involved in ship design..

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APPENDIX A – ABS Standards for vessels < 90m in length

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CHAPTER 1 General

SECTION 1 Definitions

1 Application

The following definitions apply throughout these Rules.

3 Length

3.1 Scantling Length (L)

L is the distance in meters (feet) on the summer load line from the fore side of the stem to the centerline of the rudder stock. For use with the Rules, L is not to be less than 96% and need not be greater than 97% of the length on the summer load line. The forward end of L is to coincide with the fore side of the stem on the waterline on which L is measured.

3.3 Freeboard Length (L_f)

L_f is the distance in meters (feet) on a waterline at 85% of the least molded depth measured from the top of the keel from the fore side of the stem to the centerline of the rudder stock or 96% of the length on that waterline, whichever is greater. Where the stem is a fair concave curve above the waterline at

85% of the least molded depth and where the aftmost point of the stem is above the waterline, the forward end of the length, L_f, is to be taken at the aftmost point of the stem above that waterline. See 3-1-1/Figure 1.

FIGURE 1
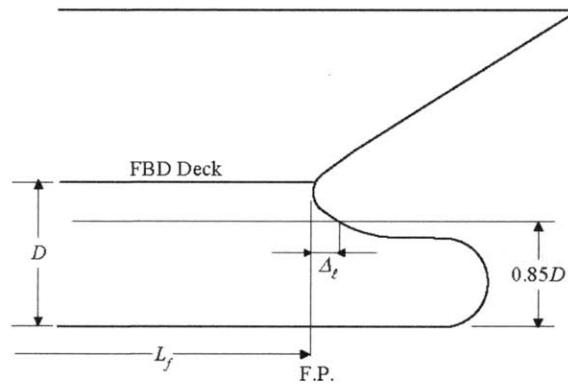
5 Breadth (B)

B is the greatest molded breadth in meters (feet).

7 Depth

7.1 Molded Depth (D)

D is the molded depth at side in meters (feet) measured at the middle of L from the molded base line to the top of the freeboard-deck beams. In vessels having rounded gunwales, D is to be measured to the point of intersection of the molded lines of the deck and side shell plating. In cases where watertight bulkheads extend to a deck above the freeboard deck and are to be recorded in the Record as effective to that deck, D is to be measured to the bulkhead deck.

7.3 Scantling Depth (D_s)

The depth, D_s, for use with scantling requirements is measured to the strength deck, as defined in 3-1-1/13.5.

9 Draft for Scantlings (d)

d is the draft in meters (feet) measured at the middle of the length, L, from the molded keel or the rabbet line at its lowest point to the estimated summer load waterline, the design load waterline or 0.66D, whichever is greater.

11 Molded Displacement and Block Coefficient

11.1 Molded Displacement (Δ)

Δ is the molded displacement of the vessel in metric tons (long tons), excluding appendages, taken at the summer load line.

11.3 Block Coefficient (C_b)

C_b is the block coefficient obtained from the following equation:

$$C_b = \Delta/1.025LB_{wl}d \text{ (SI \& MKS units)}$$

$$C_b = 35\Delta/LB_{wl}d \text{ (US units)}$$

where

Δ = molded displacement, as defined in 3-1-1/11.1

L = scantling length, as defined in 3-1-1/3.1

d = draft, as defined in 3-1-1/9

B_{wl} = the greatest molded breadth at summer load line

Part 3 Hull Construction and Equipment Chapter 1 General Section 1 Definitions 3-1-1

13 Decks

13.1 Freeboard Deck

The freeboard deck is normally the uppermost continuous deck having permanent means for closing all openings in its weather portions, and below which all openings in the vessel's side are equipped with permanent means for watertight closure. In cases where a vessel is designed for a

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special draft considerably less than that corresponding to the least freeboard obtainable under the International Load Line Regulations, the freeboard deck for the purpose of the Rules may be taken as the lowest actual deck from which the draft can be obtained under those regulations.

13.3 Bulkhead Deck

The bulkhead deck is the highest deck to which watertight bulkheads extend and are made effective.

13.5 Strength Deck

The strength deck is the deck which forms the top of the effective hull girder at any part of its length. See Section 3-2-1.

13.7 Superstructure Deck

A superstructure deck is a deck above the freeboard deck to which the side shell plating extends. Except where otherwise specified, the term superstructure deck, where used in the Rules, refers to the first such deck above the freeboard deck.

13.9 Deckhouses

A deckhouse is an enclosed structure above the freeboard deck having side plating set inboard of the hull's side-shell plating more than 4% of the breadth, B, of the vessel.

15 Deadweight and Lightship Weight

For the purpose of these Rules, the deadweight, DWT, is the difference in metric tons (long tons) between the displacement of the vessel in water having a specific gravity of 1.025 at the summer load line and the lightship weight. For the purpose of these Rules, lightship weight is the displacement of a vessel in metric tons (long tons) without cargo, fuel, lubricating oil, ballast water, fresh water and feed water in tanks, consumable stores, and passengers and crews and their effects.

17 Gross Tonnage

17.1 International Tonnage

For the purpose of application of these Rules to vessels intended for unrestricted service (see 1-1-3/1), the referenced gross tonnage throughout the Rules is the measure of the internal volume of spaces within the vessel as determined in accordance with the provisions of the "International Convention on Tonnage Measurement of Ships, 1969".

17.3 National Tonnage

As an alternative to 3-1-1/17.1 above, requirements applicable on the basis of National Tonnage measurement and National Regulations will be considered for vessels whose operation is intended to be restricted exclusively to domestic service. (See 1-1-3/7).

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CHAPTER 2 Hull Structures and Arrangements

SECTION 1 Longitudinal Strength

1 General

Vessels are to have longitudinal hull girder section modulus in accordance with the requirements of this section. The equation in this section is, in general, valid for all vessels having breadths, B, which do not exceed two times their depths, D, as defined in Section 3-1-1. Vessels whose proportions exceed these limits will be subject to special consideration.

3 Longitudinal Hull Girder Strength

3.1 Minimum Section Modulus

The minimum required hull girder section modulus, SM, at amidships, is to be determined in accordance with the following equation:

$$SM = C_1 C_2 L^2 B (C_b + 0.7) \text{ m-cm}^2 \text{ (ft-in}^2)$$

where

C_1 $= 30.67 - 0.98L$ $12 \leq L < 18$ m

   $= 22.40 - 0.52L$ $18 \leq L < 24$ m

   $= 15.20 - 0.22L$ $24 \leq L < 35$ m

   $= 11.35 - 0.11L$ $35 \leq L < 45$ m

   $= 6.40$ $45 \leq L < 61$ m

   $= 0.0451L + 3.65$ $61 \leq L < 90$ m

C_1 $= 30.67 - 0.299L$ $40 \leq L < 59$ ft

   $= 22.40 - 0.158L$ $59 \leq L < 79$ ft

   $= 15.20 - 0.067L$ $79 \leq L < 115$ ft

   $= 11.35 - 0.033L$ $115 \leq L < 150$ ft

   $= 6.40$ $150 \leq L < 200$ ft

   $= 0.0137L + 3.65$ $200 \leq L < 295$ ft

$C_2 = 0.01$ (0.01, 0.000144)

L = length of vessel, as defined in 3-1-1/3, in m (ft) B = breadth of vessel, as defined in 3-1-1/5, in m (ft)

C_b = block coefficient at design draft, based on the length, L, measured on the design

load waterline. C_b is not to be taken as less than 0.60.

5 Decks

5.1 Strength Decks

The uppermost deck to which the side shell plating extends for any part of the length of the vessel is to be considered the strength deck for that portion of the length, except in way of comparatively short superstructures. In such a case, the deck on which the superstructures are located is to be considered the strength deck in way of the superstructure. In general, the effective sectional area of the deck for use in calculating the section modulus is to exclude hatchways and other large openings through the deck but may include seam overlaps.

The deck sectional areas used in the section modulus calculations are to be maintained throughout the midship 0.4L in vessels. They may be reduced to one-half the normal requirement at 0.15L from the ends. In way of a superstructure beyond the midship 0.4L, the strength deck area may be reduced to approximately 70% of the normal requirement at that location.

5.3 Effective Lower Decks

To be considered effective for use in calculating the hull girder section modulus, the thickness of the deck plating is to comply with the requirements of Section 3-2-3. The sectional areas of lower decks used in calculating the section modulus are to be obtained as described in 3-2-1/5.1. These areas are to be maintained throughout the midship 0.4L and may be gradually reduced to one-half their midship value at 0.15L from the ends.

7 Longitudinal Strength with Higher-Strength Materials

7.1 General

Vessels in which the effective longitudinal material of either the upper or lower flanges of the main hull girder, or both, are constructed of materials having mechanical properties greater than those of ordinary strength hull structural steel [see Section 2-1-2 of the ABS Rules for Materials and Welding (Part 2)], are to have longitudinal strength generally in accordance with the preceding paragraphs of this section, but the value of the hull girder section modulus may be modified as permitted by the following paragraphs. Applications of higher-strength material are to be continuous over the length of the vessel to locations where the stress levels will be suitable for the adjacent mild steel structure. Higher strength steel is to be

extended to suitable locations below the strength deck and above the bottom, so that the stress levels will be satisfactory for the remaining ordinary strength steel structure. The strength deck and bottom structure are to be longitudinally framed. The longitudinal framing members are to be essentially of the same material as the plating they support and are to be continuous throughout the required extent of higher strength steel. Calculations showing that adequate strength has been provided against buckling are to be submitted for review and care is to be exercised against the adoption of reduced thicknesses of materials which may be subject to damage during normal operations.

7.3 Hull Girder Moment of Inertia

The hull-girder moment of inertia is to be not less than required by 3-2-1/3.5.

7.5 Hull Girder Section Modulus

When either the top or the bottom flange of the hull girder, or both, is constructed of higher-strength material, the section modulus, as obtained from 3-2-1/3.1 or 3-2-1/3.3.4, may be reduced by the factor Q.

$$SM_{hts} = Q(SM)$$

where

      $Q = 0.78$ for Grade H32

      $Q = 0.72$ for Grade H36

      H32, H36 are as specified in Section 2-1-3 of the ABS Rules for Materials and Welding (Part 2).

      Q factor for steels having other yield point or yield strength will be specially considered.

9 Loading Guidance (1 July 1998)

9.1 Loading Manual and Loading Instrument

All vessels that are contracted for construction on or after July 1998 are to be provided with a loading manual and, where required, a loading instrument, in accordance with Appendix 3-2-A1.

9.3 Allowable Stresses

9.3.1 At Sea

See 3-2-1/3.3.4 for bending stress and 3-2-1/3.3.5 for shear stress for vessels with ordinary strength steel

material. For higher strength steel, the allowable stress may be increased by a factor of 1/Q where Q is as defined in 3-2-1/7.5.

9.3.2 In Port

The allowable in-port stress is 13.13 kN/cm^2 (1.34 tf/cm^2, 8.5 Ltf/in^2) for bending and 10 kN/cm^2 (1.025 tf/cm^2, 6.5 Ltf/in^2) for shear. For higher strength steel, the allowable stress may be increased by a factor of 1/Q where Q is as defined in 3-2-1/7.5.

11 Section Modulus Calculation

11.1 Items Included in the Calculation

In general, the following items may be included in the calculation of the section modulus, provided they are continuous or effectively developed within midship, 0.4L, and gradually tapered beyond the midship, 0.4L. Where the scantlings are based on the still-water bending moment envelope curves, items included in the hull girder section modulus amidships are to be extended as necessary to meet the hull girder section modulus required at the location being considered.

> Deck plating (strength deck and other effective decks)
> Shell and inner bottom plating
> Deck and bottom girders
> Plating and longitudinal stiffeners of longitudinal bulkheads
> All longitudinals of deck, sides, bottom and inner bottom
> Continuous longitudinal hatch coamings. See 3-2-1/13.

11.3   Effective Areas Included in the Calculation

In general, the net sectional areas of longitudinal strength members are to be used in the hull girder section modulus calculations, except that small isolated openings need not be deducted, provided the openings and the shadow area breadths of the other openings in any one transverse section do not reduce the section modulus by more than 3%. The breadth or depth of such openings is not to be greater than 1200 mm (47 in.) or 25% of the breadth or depth of the member in which it is located, whichever is less, with a maximum of 75 mm (3 in.) for scallops. The length of small isolated openings not required to be deducted is generally not to be greater than 2500 mm (100 in.) The shadow area of an opening is the area forward and aft of the opening enclosed by the lines tangential to the corners of the opening intersecting

each other to form an included angle of 30 degrees.

11.5 Section Modulus to the Deck or Bottom

The section modulus to the deck or bottom is obtained by dividing the moment of inertia by the distance from the neutral axis to the molded deck at side amidships or baseline, respectively.

11.7 Section Modulus to the Top of Hatch Coamings

For continuous longitudinal hatch coamings, in accordance with 3-2-1/13, the section modulus to the top of the coaming is to be obtained by dividing the moment of inertia by the distance from the neutral axis to the deck at side plus the coaming height. This distance need not exceed y_t as given by the following equation, provided y_t is not less than the distance to the molded deck line at side.

$$y_t = y \ (0.9 + 0.2x/B) \text{ m (ft)}$$

where

y = distance, in m (ft), from the neutral axis to the top of the continuous coaming

x = distance, in m (ft), from the top of the continuous coaming to the centerline of the vessel

B = breadth of the vessel, as defined in 3-1-1/5, in m (ft). x and y are to be measured to the point giving the largest value of y_t.

Section modulus to the top of longitudinal hatch coamings between multi-hatchways will be subject to special consideration.

13 Continuous Longitudinal Hatch Coamings and Above-Deck Girders

Where strength deck longitudinal coamings of length greater than 0.14L are effectively supported by longitudinal bulkheads or deep girders, the coamings are to be longitudinally stiffened, in accordance with 3-2-12/7.7. The section modulus amidships to the top of the coaming is to be as required by 3-2-1/3.1, 3-2-1/3.3, and 3-2-1/11.7, but the section modulus to the deck at side, excluding the coaming, need not be determined in way of such coaming.

Continuous longitudinal girders on top of the strength deck are to be similarly considered. Their scantlings are also to be in accordance with Section 3-2-6.

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CHAPTER 2 Hull Structures and Arrangements

SECTION 2 Shell Plating

1 General

Shell plating is to be of not less thickness than is required by the equations for thickness of side and bottom plating as required by this section, nor less than required by Section 3-2-1 for longitudinal strength and Section 3-2-8 for deep tank plating with h not less than the vertical distance to the freeboard deck at side.

3 Bottom Shell Plating

3.1 Extent of Bottom Plating

The term "bottom plating" refers to the plating from the keel to the upper turn of the bilge or upper chine.

3.3 Bottom Shell Plating

The thickness of the bottom shell plating throughout is not to be less than that obtained from the following equations:

3.3.1

$t = s\sqrt{h}/254 + 2.5$ mm

$t = s\sqrt{h}/460 + 0.10$ in.

where

t = thickness of bottom shell plating, in mm (in.)

s = frame spacing, in mm (in.)

h = depth, D, in m (ft), as defined in 3-1-1/7.1, but not less than 0.1L or 1.18d, whichever is greater

d = draft for scantlings, as defined in 3-1-1/9, or 0.066L, whichever is greater

L = length of vessel, in m (ft), as defined in 3-1-1/3

3.3.2

$$t = \frac{s}{R}\sqrt{\frac{SM_R}{SM_A}} \cdot \frac{1}{\sqrt{Q}} \quad \text{mm (in.)}$$

where t and s are as defined above.

R = 45 with transverse framing = 55 with longitudinal framing

SM_R = hull girder section modulus required by 3-2-1/3, in $\text{cm}^2\text{-m}$ ($\text{in}^2\text{-ft}$)

SM_A = bottom hull girder section modulus, in $\text{cm}^2\text{-m}$ ($\text{in}^2\text{-ft}$)

Q = as defined in 3-2-1/7.5

3.5 Bottom Forward

For vessels of 61 m (200 ft) in length and above, where the heavy weather ballast draft or operating draft forward is less than 0.04L, the plating on the flat of bottom forward, forward of the location given in 3-2-4/Table 1 is to be not less than required by the following equation:

$$t = 0.0046s\sqrt{(0.005L^2 - 1.3d_f^2)/d_f} \quad \text{mm}$$

$$t = 0.0026s\sqrt{(0.005L^2 - 1.3d_f^2)/d_f} \quad \text{in.}$$

where

s = frame spacing, in mm (in.)

L = length of vessel, as defined in 3-1-1/3

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d_f = heavy weather ballast draft at the forward perpendicular, in m (ft)

5 Side Shell Plating

5.1 General (1998)

The side shell plating is not to be less in thickness than that obtained from the following equation:

$$t = \frac{s\sqrt{h}}{268} + 2.5 \ \text{mm}$$

$$t = \frac{s\sqrt{h}}{485} + 0.10 \ \text{in.}$$

where

t = thickness, in mm (in.)

s = spacing of transverse frames or longitudinals, in mm (in.)

h = depth, in m (ft), as defined in 3-1-1/7, but not less than 0.1L or 1.18d, whichever

is greater d = draft for scantlings, as defined in 3-1-1/9, or 0.066L, whichever is greater L = length of the vessel, as defined in 3-1-1/3

t is not to be taken less than 8.5 mm (0.33 in.) for offshore support vessels.

The side shell plating in way of hold frames of dry cargo vessels with typical bulk carrier configuration (sloping upper and lower wing tanks with a transversely framed side shell in way of the hold) is also not to be less than that obtained from the following equation:

$$t = \sqrt{L} \ \text{mm}$$

$$t = 0.0218\sqrt{L} \ \text{in.}$$

5.3 Recommendation for Vessels Subject to Impact

For vessels subject to impact loadings during routine operations, it is recommended that a side shell 25% greater in thickness than that obtained from the equation in 3-2-2/5.1 be provided.

5.5 Side Shell Plating at Ends

The minimum side shell plating thickness, t, at ends is to be obtained from the following equations and is

not to extend for more than 0.1L from the ends. Between the midship 0.4L and the end 0.1L, the thickness of the plating may be gradually tapered.

t = 0.0455L + 0.009s mm   t = 0.000545L + 0.009s in.

where

> s = frame spacing, in mm (in.)

> L = length of vessel, as defined in 3-1-1/3, in m (ft)

Where the strength deck at the ends is above the freeboard deck, the thickness of the side plating above the freeboard deck may be reduced to the thickness given for forecastle and poop sides at the forward and after ends, respectively.

5.7 Forecastle and Poop Side Plating

5.7.1 Forecastle Side Plating

The thickness, t, of the plating is to be not less than that obtained from the following equation:

> t = 0.038(L + 30.8) + 0.006s mm

> t = 0.00045(L + 103.3) + 0.006s in.

5.7.2 Poop Side Plating

The thickness, t, of the plating is to be not less than that obtained from the following equation:

> t = 0.0296(L + 39.5) + 0.006s mm

> t = 0.00035(L + 132.9) + 0.006s in.

where

> s = spacing of frames, in mm (in.)

> L = length of vessel, as defined in 3-1-1/3, in m (ft)

17 Higher-strength Materials

17.1 General

In general, applications of higher-strength materials are to take into consideration the suitable extension of the higher-strength material above and below the bottom and deck, respectively, as required by 3-2-1/7.1. Care is to be taken against the adoption of reduced thickness of material that might be subject to damage during normal operation. The thickness of bottom and side-shell plating, where constructed of higher-strength materials, are to be not less than required for purposes of longitudinal hull girder strength;

nor are they to be less than required by the foregoing paragraphs of this section when modified as indicated by the following paragraphs.

17.3 Bottom Plating of Higher-strength Material

Bottom shell plating, where constructed of higher-strength material and where longitudinally framed, is to be not less in thickness than that obtained from the following equation:

$$t_{hts} = (t_{ms} - C)\sqrt{Q} + C$$

where

t_{hts} = thickness of higher-strength material, in mm (in.)

t_{ms} = thickness, in mm (in.), of ordinary-strength steel, as required by preceding paragraphs of this section, or from the requirements of other sections of the Rules, appropriate to the vessel type.

C = 4.3 mm (0.17 in.)

Q = as defined in 3-2-1/7.5

17.5 Side Plating of Higher-strength Material

Side-shell plating, where constructed of higher-strength material, is to be not less in thickness than that obtained from the following equation:

$$t_{hts} = [t_{ms} - C][(Q + 2\sqrt{Q})/3] + C$$

where t_{hts}, t_{ms}, C and Q are as defined in 3-2-2/17.3 for bottom plating.

17.7 End Plating

End-plating thickness, including plating on the flat of bottom forward, where constructed of higher-strength materials, will be subject to special consideration.

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CHAPTER **2 Hull Structures and Arrangements**

SECTION **3 Deck Plating**

1 General

The thickness of the deck plating is not to be less than that required to obtain the hull-girder section modulus given in Section 3-2-1, nor less than required by this section.

3 Deck Plating

The thickness of plating on each deck is to be not less than the greater of those obtained from the following equations. The required thickness is not to be less than 5.0 mm (0.20 in.), except for platform decks in enclosed passenger spaces where the thickness is not to be less than 4.5 mm (0.18 in.). Thickness of strength deck inside line of openings may be reduced by 1.0 mm (0.04 in.) from t obtained by 3-2-3/3.3 below.

3.1 All Decks

$$t = \frac{s\sqrt{h}}{254} + 2.5 \ \text{mm}$$

$$t = \frac{s\sqrt{h}}{460} + 0.10 \ \text{in.}$$

where

t   = thickness, in mm (in.)

s   = beam or longitudinal spacing, in mm (in.)

h   = height, in m (ft), as follows:

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=for a deck or portion of deck forming a tank top, the greater of the following distances:

- two-thirds of the distance from the tank top to the top of the overflow, or

- two-thirds of the distance from the tank top to the bulkhead deck or freeboard deck.

=for a lower deck on which cargo or stores are carried, the tween-deck height at side; where the cargo weights are greater than normal [7010 N/m^3 (715 kgf/m^3, 45 lbf/ft^3)], h is to be suitably adjusted.

=for an exposed deck on which cargo is carried, 3.66 m (12 ft). Where it is intended to carry deck cargoes in excess of 25850 N/m^2 (2636 kgf/m^2, 540 lbf/ft^2), this head is to be increased in proportion to the added loads which will be imposed on the structure

Elsewhere, the value of h is to be not less than that obtained from the appropriate equation below, where L is the length of vessel in m (ft), as defined in 3-1-1/3.

3.1.1   Exposed Freeboard Deck Having No Deck Below

h = 0.028L + 1.08 m

h = 0.028L + 3.57 ft

3.1.2   Exposed Freeboard Deck Having a Deck Below, Forecastle Deck, Superstructure Deck Forward of Amidships 0.5L

h = 0.028L + 0.66 m

h = 0.028L + 2.14 ft

3.1.3   Freeboard Deck within Superstructure, Any Deck Below Freeboard Deck, Superstructure Deck Between 0.25L Forward of and 0.20L Aft of Amidships

h = 0.014L + 0.87 m

h = 0.014L + 2.86 ft

3.1.4   All Other Locations

h = 0.014L + 0.43 m

h = 0.014L + 1.43 ft

3.3   Strength Decks within the Midship 0.8L (2002)

For vessels of length equal to or greater than 61 meters, the strength deck plating within the midship 0.8L

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shall meet the following requirement: t = 0.009s + 2.4 mm t = 0.009s + 0.095 in. where s = beam or longitudinal spacing, in mm (in.)

3.5 All Strength Deck Plating Outside the Line of Openings and Other Effective Deck Plating (2002)

For vessels of length equal to or greater than 61 meters, the strength deck plating within the midship 0.8L shall meet the following requirement:

$$ t = \frac{s}{R} \sqrt{\frac{SM_R}{SM_A}} \cdot \frac{1}{\sqrt{Q}} \quad \text{mm (in.)} $$

where

t = thickness, in mm (in.)

s = beam or longitudinal spacing, in mm (in.), not to be taken less than 610 mm (24 in.)

R = 60 for longitudinal framing, 45 for transverse framing

SM_R = hull girder section modulus required in 3-2-1/3, in cm^2-m (in^2-ft)

SM_A = hull girder section modulus, in cm^2-m (in^2-ft), measured to the deck in question

Q = material factor for the material used in determining SM_R, as defined in 3-2-1/7.5

5 Compensation

Compensation is to be provided for openings in the strength deck and other effective decks to maintain the longitudinal and transverse strength. Openings in the strength deck are to have a minimum corner radius of 0.125 times the width of the opening, but need not exceed a radius of 600 mm (24 in.). In other decks, the radius is to be 0.09375 times the width of the opening, but need not exceed radius of 450 mm (18 in.). Openings are to be a suitable distance from the deck edge, from cargo hatch covers, from superstructure breaks and from other areas of structural discontinuity.

9 Higher-strength Material

9.1 Thickness

In general, applications of higher strength materials are to take into consideration the suitable extension of

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the higher strength material below the deck, forward and aft. Care is to be taken to avoid the adoption of reduced thickness of material such as might be subject to damage during normal operation. The thickness of deck plating for longitudinally framed decks, where constructed of higher-strength material, is to be not less than required for longitudinal strength, nor is it to be less than that obtained from the following equation:

$$t_{hts} = (t_{ms} - C)\sqrt{Q} + C$$

where

t_{hts} = thickness of higher-strength material, in mm (in.)

t_{ms} = thickness of ordinary-strength steel, in mm (in.), as required 3-2-3/3.1 and 3-2-3/3.3

C = 4.3 mm (0.17 in.)

Q = is as defined in 3-2-1/7.5

Where the deck plating is transversely framed, or where the Rules do not provide a specific thickness for the deck plating, the thickness of the higher-strength material will be specially considered, taking into consideration the size of the vessel, intended service and the foregoing Rule requirements.

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3

CHAPTER **2 Hull Structures and Arrangements**

SECTION **4 Bottom Structure**

1 Double Bottoms

1.1 General

Inner bottoms are to be fitted fore and aft between the peaks or as near thereto as practicable in vessels of ordinary design of 500 GT or over. Where, for special reasons, it may be desired to omit the inner bottom, the arrangements are to be clearly indicated on the plans when first submitted for approval. A double bottom need not be fitted in way of deep tanks, provided the safety of the vessel in the event of bottom damage is not thereby impaired. It is recommended that the inner bottom be arranged to protect the bilges as much as possible and that it be extended to the sides of the vessel.

Shell longitudinals and frames in way of deep tanks are to have not less strength than is required for stiffeners on deep tank bulkheads.

1.3 Center Girder

A center girder is to be fitted extending as far forward and aft as practicable. The plates are to be continuous within the midship three-quarters length; elsewhere, they may be intercostal between floors. Where double bottoms are to be used for fuel oil or fresh water, the girders are to be intact, but need not be tested under pressure. This requirement may be modified in narrow tanks at the ends of the vessel or where other intact longitudinal divisions are provided at about 0.25B from centerline. Where the girders are not required to be intact, manholes may be cut in every frame space outside the midships three-quarters length; they may be cut in alternate frames spaces within the midships three-quarters length. For

vessels which have a length more than 61 m (200 ft) and the length of the cargo hold is greater than 1.2B, the thickness and depth of center girder plates are to be specially considered based on the results of a direct structural calculation.

1.3.1 Thickness Amidships

The thickness of the center girder within the midship one-half length is not to be less than that obtained from the following equation.

t = 0.056L + 5.5 mm

t = 0.00067L + 0.22 in.

where

t = thickness, in mm (in.)

L = length of vessel, in m (ft), as defined 3-1-1/3

1.3.2 Thickness at Ends

The thickness of the center girder forward and aft of the midship one-half length may be reduced to 85% of the girder thickness amidships.

1.3.3 Depth

The depth of the center girder is not to be less than that obtained from the following equation:

$$h_g = 32B - 190\sqrt{d} \quad \text{mm}$$
$$h_g = 0.384B + 4.13\sqrt{d} \quad \text{in.}$$

where

h_g = depth, in mm (in.)

B = breadth of vessel, in m (ft), as defined in 3-1-1/5

d = draft for scantlings, in m (ft), as defined in 3-1-1/9

1.5 Side Girders

Where the distance between the center girder and the side shell exceeds 4.57 m (15 ft), intercostal side girders are to be fitted approximately midway between the center girder and the side shell. The minimum thickness of the intercostal side girders is not to be less than obtained from the following equation.

$t = 0.036L + c$ mm

$t = 0.00043L + c$ in.

where

t = thickness, in mm (in.)

L = length of vessel, in m (ft), as defined in 3-1-1/3

c = 4.7 mm (0.18 in.)

1.7 Floors

Solid floors are to be fitted at every frame under the engine room, at every frame in the peaks and under transverse bulkheads. Elsewhere, the solid floors are to have a maximum spacing of 3.66 m (12 ft) in association with intermediate open floors or longitudinal framing. The thickness of solid floors is to be equal to the thickness of side girders obtained in 3-2-4/1.5, except that for widely spaced floors in association with longitudinal framing, c is to be taken as 6.2 mm (0.24 in.).

1.9 Frames

In transversely framed vessels, open floors consisting of frames and reverse frames are to be fitted at all frames where solid floors are not fitted. Center and side brackets are to overlap the frames and reverse frames for a distance equal to 0.05B. They are to be of the thickness required for side girders in the same location and are to be flanged on their outer edges. Alternatively, longitudinal framing is to be fitted in association with widely spaced floors. The section modulus, SM, of each frame, reverse frame or bottom, or inner bottom longitudinal in association with the plating to which it is attached is not to be less than that obtained from the following equation.

$$SM = 7.8chs\ell^2 \text{ cm}^3$$

$$SM = 0.0041chs\ell^2 \text{ in}^3$$

where

      s = frame spacing, in m (ft)

      ℓ = unsupported span between supporting members, in m (ft).

Where brackets are fitted in accordance with 3-1-2/5.5 and are supported by bulkheads, inner bottom, or side shell, the length, ℓ, may be measured as permitted therein.

h = vertical distance, in m (ft), from the middle of ℓ to the deck at side. In way of a deep tank, h is the greatest distance from the middle of ℓ to a point located at two-thirds of the distance from the top of the tank to the top of the overflow; a point located above the top of the tank not less than 0.01L + 0.15 m or 0.46 m (0.01L + 0.5 ft or 1.5 ft), whichever is greatest. c for transverse frames and reverse frames: = 0.8 clear of tanks = 1.0 in way of tanks = 0.5 with struts c for longitudinal frames: = 1.0 without struts = 0.55 with struts c for inner bottom longitudinals: = 0.85 without struts = 0.45 with struts Frames and reverse frames in way of tanks are not to be less than that required clear of tanks if that be greater.

1.11 Struts

Struts are to be angle bar sections fitted midway between floors. In general, they are not to be used where cargo is discharged by grabs, where heavy cargoes are carried or in the bottom forward slamming area. The permissible load, W_a, for struts is to be determined in accordance with 3-2-6/3.5.3. The calculated load, W, is to be determined by:

W = nphs kN (tf, Ltf)

where n = 10.5 (1.07, 0.03)

p = the sum of the half lengths, in m (ft), on each side of the strut, of the frames supported

h = as defined in 3-2-4/1.9

s = frame spacing, in m (ft)

Struts are to be positioned so as to divide the span into approximately equal intervals.

1.13 Inner-bottom Plating

The thickness of the inner-bottom plating throughout the length of the vessel is to be not less than that obtained from the following equation. Where applicable, the plating is to meet deep tank requirements.

$$t = 0.037L + 0.009s + c \text{ mm}$$
$$t = 0.000445L + 0.009s + c \text{ in.}$$

where

t = thickness, in mm (in.)

L = length of vessel, in m (ft), as defined in 3-1-1/3

s = frame spacing, in mm (in.)

c = 1.5 mm (0.06 in.) in engine space

= −0.5 mm (−0.02 in.) elsewhere

Where no ceiling is fitted under cargo hatchways, except for vessels intended for the exclusive carriage of containers on the inner bottom, the thickness of the inner-bottom plating is to be increased 2.0 mm (0.08 in.). For vessels with longitudinally-framed inner bottoms, the minimum thickness of inner-bottom plating may be reduced by 1 mm (0.04 in.).

For vessels regularly engaged in trades where the cargo is handled by grabs or similar mechanical appliances, it is recommended that flush inner-bottom plating be adopted throughout the cargo space, and that the plating be suitably increased, but the increase need not exceed 5 mm (0.20 in.). It is also recommended that the minimum thickness be not less than 12.5 mm with 610 mm (0.50 in. with 24 in.) frame spacing and 19 mm with 915 mm (0.74 in. with 36 in.) frame spacing. Intermediate thicknesses may be obtained by interpolation.

Where provision is to be made for the operation or stowage of vehicles having rubber tires, and after all other requirements are met, the thickness of the inner bottom plating is to be not less than that obtained from 3-2-3/7.

Margin plates which are approximately horizontal are to have thicknesses not less than the adjacent inner bottom plating. Where they are nearly vertical, they are to be not less than the required inner bottom plating in the engine space and are to extend the full depth of the inner bottom.

3 Single Bottoms with Floors and Keelsons

3.1 General

Where double bottom construction is not required by 3-2-4/1.1 or is not applied, single bottom construction is to be in accordance with 3-2-4/3 or 3-2-4/5, as may be applicable.

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3.3 Center Keelsons

Single-bottom vessels are to have center keelsons formed of continuous or intercostal center girder plates with horizontal top plates. The thickness of the keelson and the area of the horizontal top plate are to be not less than that obtained from the following equations. Vessels less than 30.5 m (100 ft) in length will be subject to special consideration. Tapering of the horizontal top plate area at the ends is not normally considered for vessels less than 30.5 m (100 ft) in length. The keelsons are to extend as far forward and aft as practicable.

3.3.1 Center-girder Plate Thickness Amidships

t = 0.063L + 5 mm

t = 0.00075L + 0.2 in.

3.3.2 Center-girder Plates Thickness at Ends

t = 85% of center keelson thickness amidships

3.3.3 Horizontal Top-plate Area Amidships

$A = 0.168L^{3/2} - 8 \text{ cm}^2$

$A = 0.0044L^{3/2} - 1.25 \text{ in}^2$

3.3.4 Horizontal Top-Plate Area at Ends [L ≥ 30.5 m (100 ft)]

$A = 0.127L^{3/2} - 1 \text{ cm}^2$

$A = 0.0033L^{3/2} - 0.15 \text{ in}^2$

where

t = thickness of center-girder plate, in mm (in.)

L = length of vessel, as defined in 3-1-1/3, in m (ft)

A = area of horizontal top plate, in cm^2 (in^2)

3.5 Side Keelsons

Side keelsons are to be arranged so that there are not more than 2.13 m (7 ft) from the center keelson to the inner side keelson, from keelson to keelson and from the outer keelson to the lower turn of bilge. Forward of the midship one-half length, the spacing of keelsons on the flat of floor is not to exceed 915 mm (36 in.). Side keelsons are to be formed of continuous rider plates on top of the floors. They are to be connected to the shell plating by intercostal plates. The intercostal plates are to be attached to the floor plates. In the engine space, the intercostal plates are to be of not less thickness than the center girder plates. The scantlings of the side keelsons are to be obtained from the following equations but need not exceed 3-2-4/3.3, if that be less.

3.5.1 Side Keelson and Intercostal Thickness Amidships

t = 0.063L + 4 mm

$t = 0.00075L + 0.16$ in.

3.5.2 Side Keelson and Intercostal Thickness at Ends

$t = 85\%$ of center thickness amidships

3.5.3 Side Keelson and Intercostal, Horizontal Top Plate Area Amidships

$A = 0.038L^{3/2} + 17$ cm^2

$A = 0.001L^{3/2} + 2.6$ in^2

3.5.4 Side Keelson and Intercostal, Horizontal Top Plate Area at Ends

$A = 0.025L^{3/2} + 20$ cm^2

$A = 0.00065L^{3/2} + 3.1$ in^2

t, L and A are as defined in 3-2-4/3.3.

3.7 Floors

3.7.1 Section Modulus

With transverse framing, a floor as shown in 3-2-4/Figure 1 is to be fitted on every frame and is to be of the scantlings necessary to obtain a section modulus, SM, not less than that obtained from the following equation:

$SM = 7.8chs\ell^2$ cm^3

$SM = 0.0041chs\ell^2$ in^3

where

c = 0.55

h = draft, d, in m (ft), as defined in section 3-1-1/9, but not to be less than 0.66D or 0.066L, whichever is greater.

s = floor spacing, in m (ft)

ℓ = span, in m (ft). Where brackets are fitted in accordance with 3-1-2/5.5 and are supported by bulkheads, inner bottom or side shell, the length, ℓ, may be measured as permitted therein.

The section modulus may be calculated at the centerline of the vessel, provided the rise of floor is such that the depth at the toe of brackets is not less than one-half of the depth at the centerline. The above requirements are limited to cargo holds where cargoes of specific gravity 0.715 or less are uniformly loaded. In way of engine room and in the forward 0.2L, the floor face bar area is to be doubled.

3.7.2 Depth

The minimum depth of floors at centerline is not be less than that obtained from the following equation:

$$h_f = 62.5\ell \qquad \text{mm}$$

$$h_f = 0.75\ell \qquad \text{in.}$$

where

$h_f =$ floor depth, in mm (in.)

$\ell =$ unsupported span of floors, in m (ft). Where brackets are fitted in accordance with 3-1-2/5.5, the length, ℓ, may be measured as permitted therein.

3.7.3 Thickness

The minimum thickness of floors is not to be less than that obtained from the following equation:

$$t = 0.01h_f + 3 \text{ mm}$$

$$t = 0.01h_f + 0.12 \text{ in.}$$

where

$t =$ floor thickness, in mm (in.)

$h_f =$ floor depth, in mm (in.)

Floors under engine girders are to be not less in thickness than the thickness required for keelsons.

FIGURE 1 Plate Floors

ℓ/2 for floors

side keelson

keelson
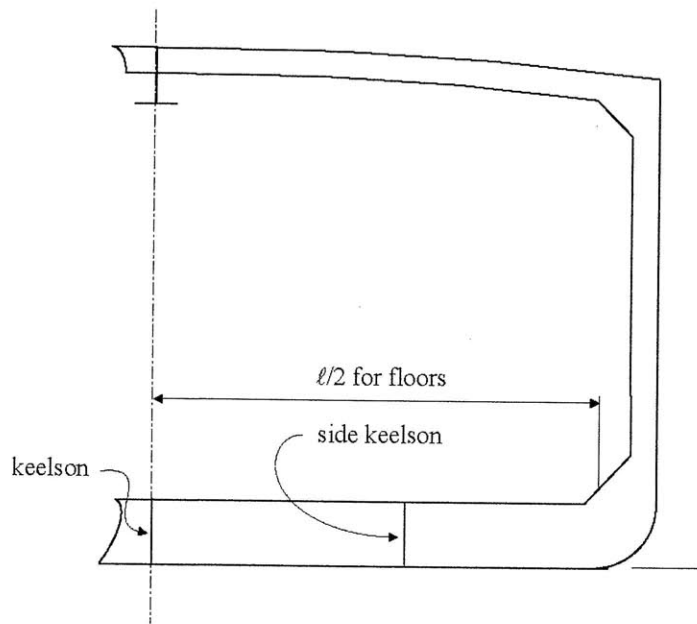
5 Single Bottoms with Longitudinal or Transverse Frames

5.1 General

Where longitudinal frames supported by bottom transverses or transverse frames supported by longitudinal girders and bottom transverses are proposed in lieu of keelsons referred to in 3-2-4/3, the construction is to be in accordance with this subsection. Frames are not to have less strength than is required for watertight bulkhead stiffeners or girders in the same location in association with head to the bulkhead deck. In way of deep tanks, frames are not to have less strength than is required for stiffeners or girders on deep tank bulkheads. See 3-2-4/Figure 2, 3-2-4/Figure 3 and 3-2-4/Figure 4.

FIGURE 2 Round Bottom Floors with Deadrise
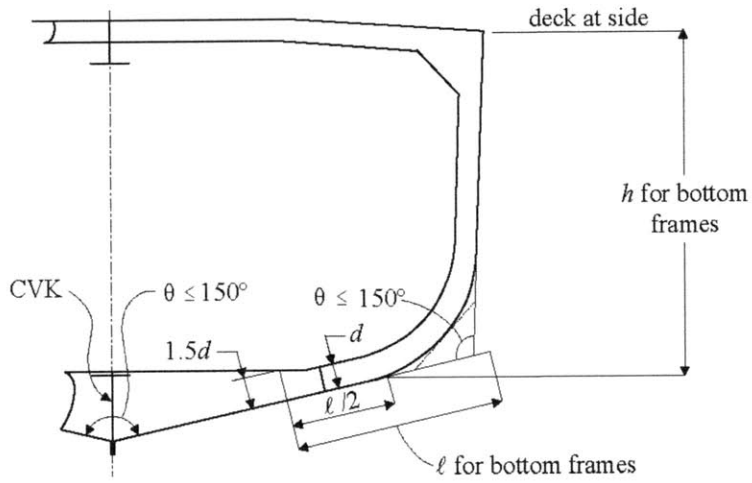
FIGURE 3 Transverse Bottom Frames with Longitudinal Side Girders
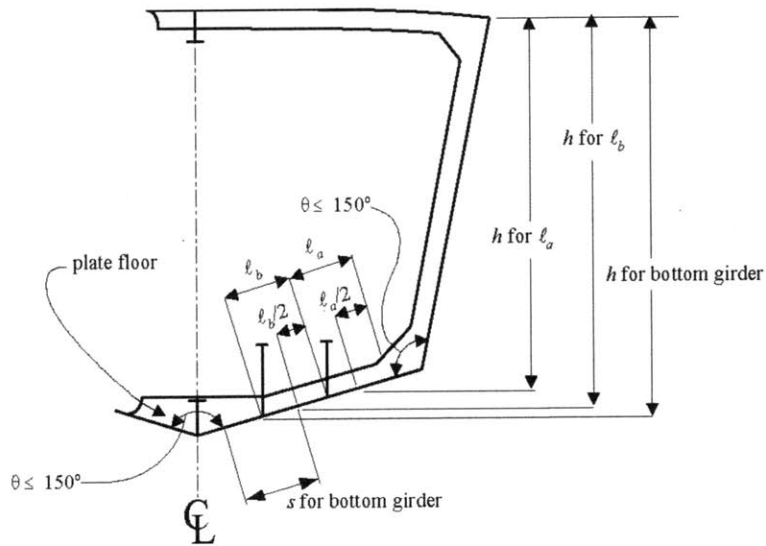
FIGURE 4 Longitudinal Frames with Transverse Webs
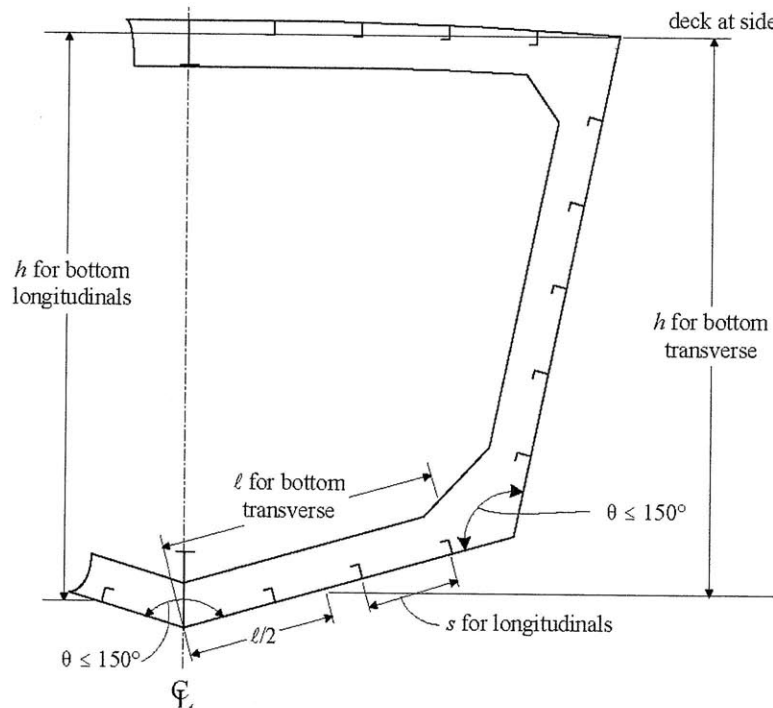
5.3 Bottom Girders and Transverses

5.3.1 Section Modulus

The section modulus, SM, of each bottom girder and transverse, where intended as a primary supporting member, in association with the plating to which it is attached, is not to be less than that obtained from the following equation:

$$SM = 7.8chs\ell^2 \ cm^3$$

$$SM = 0.0041chs\ell^2 \ in^3$$

where

c = 0.915

h = vertical distance, in m (ft), from the center of area supported to the deck at side

s = spacing, in m (ft)

ℓ = unsupported span, in m (ft). Where brackets are fitted in accordance with 3-1-2/5.5 and are supported by bulkheads, inner bottom or side shell, the length, ℓ, may be measured as permitted therein.

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Tripping brackets are to be fitted at intervals of about 3 m (10 ft) and stiffeners are to be fitted as may be required.

5.3.2 Depth

The minimum depth of the girder or transverse is to be not less than 2.5 times the depth of the cutouts for bottom frames, unless effective compensation for cutouts is provided, nor less than that obtained from the following equation:

$h_w = 145l$ mm

$h_w = 1.75l$ in.

where

h_w = girder or transverse depth, in mm (in.)

l is defined in 3-2-4/5.3.1.

5.3.3 Thickness

The minimum thickness of the web is to be not less than that obtained from the following equation:

$t = 0.01h_w + 3$ mm

$t = 0.01h_w + 0.12$ in.

where

t = floor thickness, in mm (in.)

h_w is as given in 3-2-4/5.3.2.

5.3.4 Non-prismatic Members

Where the cross sectional properties of the member is not constant throughout the length of the girders or transverses, the above requirements will be specially considered with particular attention being paid to the shearing forces at the ends.

5.5 Center Girder

In general, a center girder is to be fitted, complying with 3-2-4/5.3; however, alternative arrangements that provide suitable support for docking will be considered.

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5.7 Frames

The section modulus, SM, of each bottom frame to the chine or upper turn of bilge, in association with the plating to which it is attached, is not to be less than that obtained from the following equation:

$$SM = 7.8chs\ell^2 \text{ cm}^3$$

$$SM = 0.0041chs\ell^2 \text{ in}^3$$

where

c   = 0.80 for transverse frames clear of tanks

       = 1.00 for longitudinal frames clear of tanks, and in way of tanks

       = 1.00 for transverse frames in way of tanks

s = frame spacing in, m (ft)

ℓ = unsupported span, in m (ft), Where brackets are fitted in accordance with 3-1-2/5.5 and are supported by bulkheads, inner bottom or side shell, the length, ℓ, may be measured as permitted therein.

h = vertical distance, in m (ft), from the middle of ℓ to the deck at side. In way of a deep tank, h is the greatest of the distances, in m (ft), from the middle of ℓ to a point located at two-thirds of the distance from the top of the tank to the top of the overflow, a point located above the top of the tank not less than 0.01L + 0.15 m (0.01L + 0.5 ft) or 0.46 m (1.5 ft), whichever is greatest.

L is as defined in 3-1-1/3.

9 Higher-strength Materials

9.1 General

In general, applications of higher-strength materials for bottom structures are to meet the requirements of this section, but may be modified as permitted by the following paragraphs. Care is to be exercised to avoid the adoption of reduced thickness of material such as might be subject to damage during normal operation, and calculations are to be submitted to show adequate provision against buckling. Longitudinal framing members are to be of essentially the same material as the plating they support.

9.3 Inner-bottom Plating

Inner-bottom plating, where constructed of higher-strength material and where longitudinally framed, is to be not less in thickness than required by 3-2-4/1.13 or for tank top plating as modified by the following

equation:

$$t_{hts} = [t_{ms} - C][(Q + 2\sqrt{Q}\,Q)/3] + C$$

where

t_{hts} = thickness of higher-strength material, in mm (in.)

t_{ms} = thickness of mild steel, as required by 3-2-4/1.13, in mm (in.), increased where required for no ceiling

C = 3 mm (0.12 in.) or 5 mm (0.20 in.) where the plating is required by 3-2-4/1.13 to be increased for no ceiling

Q = as defined in 3-2-1/7.5

The thickness of inner-bottom plating, where transversely framed, will be specially considered.

Where cargo is handled by grabs, or similar mechanical appliances, the recommendations of 3-2-4/1.13 are applicable to t_{hts}.

9.5 Bottom and Inner-bottom Longitudinals

The section modulus of bottom and inner-bottom longitudinals, where constructed of higher-strength material and in association with the higher-strength plating to which they are attached, are to be determined as indicated in 3-2-4/1.9, except that the value may be reduced by the factor Q, as defined in 3-2-1/7.5.

9.7 Center Girders, Side Girders and Floors

Center girders, side girders and floors, where constructed of higher-strength materials, are generally to comply with the requirements of 3-2-4/1.3, 3-2-4/1.5 or 3-2-4/1.7, but may be modified as permitted by the following equation:

$$t_{hts} = [t_{ms} - C][(Q + 2\sqrt{Q}\,Q)/3] + C$$

where

t_{hts}, t_{ms} and C are defined in 3-2-4/9.3.

Q is as defined in 3-2-1/7.5.

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CHAPTER **2 Hull Structures and Arrangements**

SECTION **5 Side Frames, Webs and Stringers**

1 General

1.1 Basic Considerations

Frames or webs and stringers are not to have less strength than is required for watertight bulkhead stiffeners, or girders, in the same location in association with heads to the bulkhead deck. In way of deep tanks, frames or webs and stringers are not to have less strength than is required for stiffeners or girders on deep-tank bulkheads. The calculated section modulus is based upon the intact sections being used. Where a hole is cut in the flange of any member or a large opening is made in the web of the member, the net section is to be used in determining the section modulus of the member in association with the plating to which it is attached.

1.3 End Connections

At the ends of unbracketed frames, both the web and the flange are to be welded to the supporting member. At bracketed end connections, continuity of strength is to be maintained at the connection to the bracket and at the connection of the bracket to the supporting member. Welding is to be in accordance with 3-2-16/Table 1. Where longitudinal frames are not continuous at bulkheads, end connections are to effectively develop their sectional area and resistance to bending. Where a structural member is terminated, structural continuity is to be maintained by suitable back-up structure, fitted in way of the end connection of frames, or the end connection is to be effectively extended by a bracket or flat bar to an adjacent beam, stiffener, etc.

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3 Longitudinal Side Frames

3.1 Section Modulus

The section modulus, SM, of each longitudinal side frame above the chine or upper turn of bilge is to be not less than that obtained from the following equation:

$$SM = 7.8chs\ell^2 \text{ cm}^3$$

$$SM = 0.0041chs\ell^2 \text{ in}^3$$

where

c = 0.915

h = vertical distance, in m (ft), from the frame to the freeboard deck at side, but not less than 0.02L + 0.46 m (0.02L + 1.5 ft)

s = frame spacing, in m (ft)

ℓ = straight-line unsupported span, in m (ft). Where brackets are fitted in accordance with 3-1-2/5.5 and are supported by bulkheads, the length, ℓ, may be measured as permitted therein.

5 Transverse Side Frames

5.1 Section Modulus

The section modulus, SM, of each transverse side frame other than tween deck frames above the chine or upper turn of bilge, in association with the plating to which the frame is attached, is not to be less than that obtained from the following equation. See 3-2-5/Figure 1, 3-2-5/Figure 2 and 3-2-5/Figure 3.

$$SM = 7.8chs\ell^2 \text{ cm}^3$$

$$SM = 0.0041chs\ell^2 \text{ in}^3$$

where

c = 0.915 for frames having no tween decks above

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$= 0.90 + 5.8/\ell^3 \, (0.90 + 205/\ell^3)$ for frames having tween decks above

s = frame spacing, in m (ft)

ℓ = straight-line unsupported span, in m (ft). Where brackets are fitted in accordance with 3-1-2/5.5 and are supported by decks or inner bottoms, the length ℓ may be measured as permitted therein. Where tween decks are located above the frame, ℓ is to be taken as the length between the toes of the brackets, except where beam knees are fitted on alternate frames, ℓ is to be increased by one half the depth of the beam knees. ℓ is not to be taken less than 2.1 m (7.0 ft).

h = on frames having no tween decks above, the vertical distance, in m (ft), from the mid length of the frame to the freeboard deck at side, but not less than 0.02L + 0.46 m (0.02L + 1.5 ft).

  = on frames having tween decks above, the vertical distance, in m (ft), from the middle of ℓ to the load line or 0.4ℓ, whichever is greater, plus $bh_1/33$ ($bh_1/100$).

b = horizontal distance, in m (ft), from the outside of the frames to the first row of deck beam supports.

h_1 = vertical distance, in m (ft), from the deck at the top of the frame to the bulkhead or freeboard deck plus the height of all cargo tween deck spaces above the bulkhead or freeboard deck plus one-half the height of all passenger spaces above the bulkhead or freeboard deck, or plus 2.44 m (8 ft), if that is greater. Where the cargo load differs from 715 kgf/m^3 (45 lbf/ft^3), h_1 is to be adjusted accordingly.

FIGURE 1 Transverse Side Frame Transverse Side Frame

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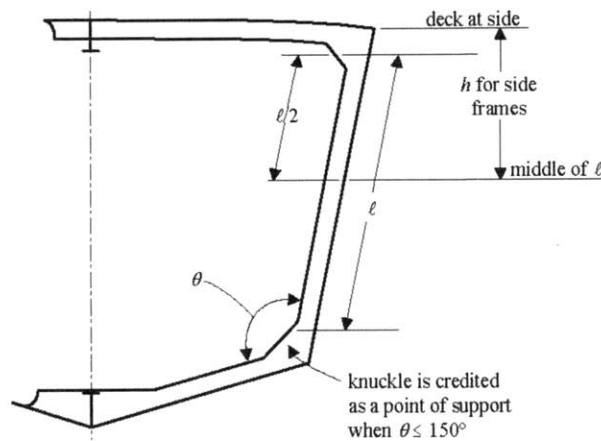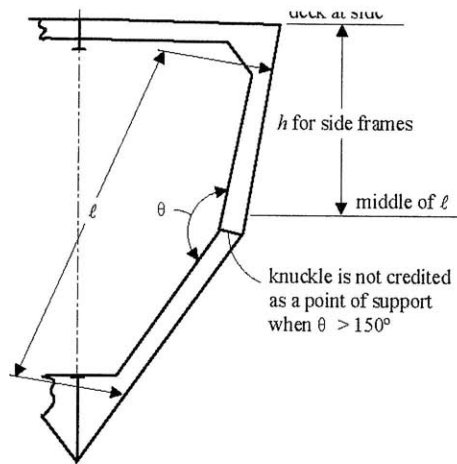
FIGURE 2

FIGURE 3 Hold and Tween Deck Frames
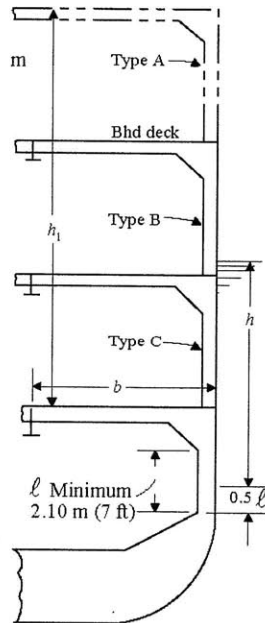
5.3 Tween-deck Frames

- The section modulus, SM, of each transverse side frame above the chine or upper turn of bilge, in association with the plating to which the frame is attached, is not to be less than obtained from the following equation:

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$$SM = 7.8chs\ell^2 \text{ cm}^3$$

$$SM = 0.0041chs\ell^2 \text{ in}^3$$

where

c = 0.90

h = 0.032L − 0.68 m (0.032L − 2.23 ft) type A frame

= 0.049L − 0.81 m (0.049L − 2.66 ft) type B frame

= 0.052L − 0.13 m (0.052L − 0.43 ft) type C frame

= in no case less than the vertical distance, in m (ft), from the mid-length of the frame to the freeboard deck, but not less than 0.02L + 0.46 m (0.02L + 1.5 ft)

s = frame spacing, in m (ft)

ℓ = tween deck height or unsupported length along frame, whichever is greater, in m (ft), not to be taken less than 2.13 m (7.0 ft). For frame types, see 3-2-5/Figure 3. Forward of 0.125L, frames above the bulkhead or freeboard deck are to be type B frames.

Longitudinal tween deck frames are to meet the requirements of 3-2-5/3. The section modulus of each longitudinal tween deck frame forward of 0.125L from the stem is to be not less than required by 3-2-5/5.1 for transverse frames in the same location, taking ℓ as the unsupported span along the frame length.

7 Side Web Frames

7.1 Section Modulus

The section modulus, SM, of each side web frame supporting longitudinal framing or shell stringers above the chine or upper turn of bilge, in association with the plating to which the web frame is attached, is not to be less than that obtained from the following equation:

$$SM = 7.8chs\ell^2 \text{ cm}^3$$

$$SM = 0.0041chs\ell^2 \text{ in}^3$$

where

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c   = 0.915 aft of the forepeak

= 1.13 in the forepeak of vessel 61 m (200 ft) or greater in length.

s = frame spacing, in m (ft)

ℓ = straight-line unsupported span, in m (ft). Where brackets are fitted in accordance with 3-1-2/5.5 and are supported by decks or inner bottoms, the length, ℓ, may be measured as permitted therein

h   = on frames having no tween decks above, the vertical distance, in m (ft), from the mid length of the frame to the freeboard deck at side, but not less than 0.02L + 0.46 m (0.02L + 1.5 ft).

= on frames having tween decks above, the vertical distance, in m (ft), from the middle of ℓ to the load line or 0.5ℓ, whichever is greater, plus $bh_1/45K$ ($bh_1/150K$).

b = horizontal distance, in m (ft), from the outside of the frames to the first row of deck beams supports.

h_1 = vertical distance, in m (ft), from the deck at the top of the web frame to the bulkhead or freeboard deck plus the height of all cargo tween deck spaces above the bulkhead or freeboard deck plus one-half the height of all passenger spaces above the bulkhead or freeboard deck, or plus 2.44 m (8 ft), if that is greater. Where the cargo load differs from 715 kgf/m^3 (45 lbf/ft^3), h_1 is to be adjusted accordingly.

K   = 1.0 where the deck is longitudinally framed and a deck transverse is fitted in way of each web frame.

= the number of transverse frame spaces between web frames where the deck is transversely framed.

7.3 Tween-deck Web Frames

Tween-deck web frames are to be fitted below the bulkhead deck over the hold web frames, as may be required to provide continuity of transverse strength above the main web frames in holds and machinery space.

7.5 Proportions

The depth of each web frame is to be not less than 125ℓ mm (1.5ℓ in.) or, unless effective compensation is provided for cutouts, 2.5 times the cutout for frame or longitudinal if greater. The thickness of the web of web frame or stringer is to be not less than 0.01 times the depth plus 3 mm (0.12 in.), ℓ is as defined in 3-2-5/7.1.

9 Recommendation for Vessels Subject to Impact

For vessels subject to impact loadings during routines, it is recommended that side frames with a section modulus 25% greater than that obtained above be provided.

11 Side Stringers

11.1 Section Modulus

The section modulus, SM, of each side stringer in association with the plating to which the side stringer is attached is not to be less than that obtained from the following equation:

$$SM = 7.8chs\ell^2 \text{ cm}^3$$

$$SM = 0.0041chs\ell^2 \text{ in}^3$$

where

c = 0.915

= 1.13 in the forepeak of vessel 61 m (200 ft) or greater in length.

h = vertical distance, in m (ft), from the middle of s to the freeboard deck at side, but not less than 0.02L + 0.46 m (0.02L + 1.5 ft).

= for stringers above the lowest deck or at a similar height in relation to the design draft, not less than given in 3-2-5/5.3 appropriate to the tween deck location.

= for stringers in the peaks of vessels 61 m (200 ft) or greater in length, not less than given in 3-2-5/5.5.

s = sum of the half lengths, in m (ft), (on each side of the stringer) of the frames supported.

ℓ = span, in m (ft), between web frames, or between web frame and bulkhead. Where brackets are fitted

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in accordance with 3-1-2/5.5 and are supported by transverse bulkheads, the length, ℓ, may be measured as permitted therein.

11.3 Proportions

Side stringers are to have a depth of not less than 0.125ℓ (1.5 in per ft of span ℓ) plus one-quarter of the depth of the slot for the frames, but need not exceed the depth of the web frames to which they are attached. In general, the depth is not to be less than 2.5 times the depth of the slots, or the slots are to be fitted with filler plates. The thickness of each stringer is to be not less than $0.014L + 7.2$ mm ($0.00017L + 0.28$ in.) where L is as defined in 3-1-1/3.

APPENDIX B – Global Variable Description

There are two global variables in PCAT: USER which holds the user inputs, and HULL which holds the details of each specific variant, both are structures. Because there is more than one variant HULL is set up as a matrix, where the first dimension is the variant number, and the second dimension is the run number. Each of the two variables are structures with multiple fields. They are described in detail below.

Matlab is a case sensitive code, and in PCAT, HULL and USER are capitalized to bring attention to these global variables. Most of the rest of the variables and fields are in lowercase. To aide a person in editing the code, all variables discussed in this thesis are capitalized in the same manner as in PCAT.

Name: **USER.geometry**
Data type: structure
Purpose: Stores user information from the geometry screen.

Name: **USER.geometry.length**
Data type: array
Purpose: Stores an array of user specified lengths. Lengths are stored in meters.
Example: [30 35 40]

Name: **USER.geometry.ltob**
Data type: array
Purpose: Stores an array of user specified rations of length to beams. Ratios are non-dimensional.
Example: [4.5 5.2]

Name: **USER.geometry.ltod**
Data type: array

Purpose: Stores an array of user specified rations of length to depths at midships. Ratios are non-dimensional.

Example: [7 7.5 8.15]

Name: **USER.geometry.ph**

Data type: cell holding a string or strings

Purpose: Stores a name of the parent hull.

Example: {'NPL High Speed Round Bilge' 'PC-14'}

Name: **USER.geometry.dh**

Data type: array

Purpose: Stores an array of user specified deck heights. Deck height is stored in meters.

Example: [2.5]

Name: **USER.loading**

Data type: structure

Purpose: Stores user information from the loading screen.

Name: **USER.loading.kgtod**

Data type: array

Purpose: Stores an array of user specified ratios of the center of gravity to depth at midships. Ratios are non-dimensional.

Example: [0.6]

Name: **USER.loading.lcg**

Data type: array or string

Purpose: Stores an array of user specified ratios of the longitudinal center of gravity to the length between perpendiculars. Ratios are non-dimensional. When set to 'd', PCAT will set the LCG to the default value of the longitudinal center of buoyancy (LCB) if the LCG falls between the values of -0.02 and -0.13 If it does not, LCG is set to the nearest valid value

(either -0.02 or -0.13). Note that HULL.loading.lcg will never be reset from 'd', the LCG is set in the variable HULL for the particular variant.

Example: 'd'

Name: **USER.loading.materials**

Data type: cell holding a string or strings

Purpose: Stores the name of the material types to be used.

Example: {'Ordinary Strength Steel' 'AH-32'}

Name: **USER.loading.fs**

Data type: array

Purpose: Stores an array of user specified frame spacing values. Frame spacing is stored in meters.

Example: [1.4 1.5 1.6]

Name: **USER.machinery**

Data type: structure

Purpose: Stores user information from the machinery and manning screen relevant to machinery.

Name: **USER.machinery.eps**

Data type: array

Purpose: Stores an array of user specified number of engines per shaft. All engines on board will be the same type (there are no secondary engines). Only possible values are [1] and [1 2] corresponding to only 1 engine per shaft or either 1 or 2 engines per shaft.

Example: [1]

Name: **USER.machinery.shafts**

Data type: array

Purpose: Stores an array of user specified number of shafts.

Example: [2 4]

Name: **USER.machinery.wj**

Data type: structure

Purpose: Stores user a 1 if water jets are going to be analyzed, a 0 if wj will not be analyzed.

Name: **USER.machinery.prop**

Data type: structure

Purpose: Stores user a 1 if propellers are going to be analyzed, a 0 if propellers will not be analyzed.

Name: **USER.manning**

Data type: structure

Purpose: Stores user information from the machinery and manning screen relevant to manning.

Name: **USER.manning.officer**

Data type: scalar

Purpose: Stores the percentage of total manning that is officers.

Example: [.15]

Name: **USER.manning.cpo**

Data type: scalar

Purpose: Stores the percentage of total manning that is chief petty officers.

Example: [.15]

Name: **USER.manning.enlisted**

Data type: scalar

Purpose: Stores the percentage of total manning that is junior enlisted.

Example: [.70]

Name: **USER.manning.total**

Data type: array

Purpose: Stores an array of user specified manning levels.

Example: [15 20 25]

Name: **USER.speed**

Data type: structure

Purpose: Stores user information from the speed screen relevant to machinery.

Name: **USER.speed.profile_speed**

Data type: array

Purpose: Stores an array the array of containing the speeds entered in the speed profile. The length of this array is the same as the length of the profile_percent array.

Example: [5 10 12.5 15 20]

Name: **USER.speed.profile_percent**

Data type: array

Purpose: Stores an array the array of containing the percentages entered in the speed profile. Element (n) corresponds to the nth element of the profile speed array. This array is the same as the length of the profile_percent array, and the sum of all the elements is 100.

Example: [20 35 25 15 5]

Name: **USER.speed.max**

Data type: scalar

Purpose: Stores the user specified maximum speed in knots.

Example: [20]

Name: **USER.speed.endurance**

Data type: scalar or string

Purpose: Stores the user specified endurance speed in knots. If the user desires the endurance speed to be set to the most fuel efficient speed, this variable is set to 'd'.

Example: 'd' or [9]

Name: **USER.speed.range**

Data type: array

Purpose: Stores an array of user specified ranges.

Example: [700 800]

Name: **USER.weapons**

Data type: structure

Purpose: Stores user information from the weapons screen relevant to C4I, weapons, and navigation equipment. The information in this variable should account for all of the equipment in SWBS 400, SWBS 700, and the variable ammunition loads.

Name: **USER.weapons.id**

Data type: cell holding strings

Purpose: Hold identifiers for each weapon set. The length of this variable is equal to the number of weapon sets.

Example: {'Low' 'Med' 'High'}

Name: **USER.weapons.weight**

Data type: array

Purpose: Stores the weights for each weapons set in LT. The nth element of this array corresponds to the nth weapon set.

Example: [5 8 12]

Name: **USER.weapons.dharea**

Data type: array

Purpose: Stores the required main deck area for each weapons set in m^2. The nth element of this array corresponds to the nth weapon set.

Example: [9 9.5 10]

Name: **USER.weapons.iharea**

Data type: array

Purpose: Stores the required in-hull area for each weapons set in ft^2. The nth element of this array corresponds to the nth weapon set.

Example: [27 27 30]

Name: **USER.weapons.power**

Data type: array

Purpose: Stores the required electrical power for each weapons set in kW. The nth element of this array corresponds to the nth weapon set. This value is not used in this version of the program.

Example: [100 120 170]

Name: **USER.weapons.kgtod**

Data type: array

Purpose: Stores the ratio of the height of the center of gravity of each weapons set above the keel over the midship's depth (KG/D). This number is non dimensional. The nth element of this array corresponds to the nth weapon set. This value is not used in this version of the program.

Example: [1 1.1 0.9]

Name: **USER.weapons.wmoe**

Data type: array

Purpose: Stores the measure of effectiveness of a given weapons system relative to the users own standard. Prior to using PCAT, the user must have developed measure of effectiveness for the weapons systems (wmoe). This can incorporate range of radars or weapons, warhead size, maintainability, ability to penetrate certain armor, interoperability, or any other way of comparing systems. The number stored in this variable should be between 0 and 1.

Example: [0.40 0.60 0.90]

Name: **USER.weapons.cost**

Data type: array

Purpose: Stores the cost of the weapons systems in thousands of dollars. The nth element of this array corresponds to the nth weapon set.

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Example: [1100 2500 3000]

Name: **USER.omoe**

Data type: structure

Purpose: Level one fields (ops, mob, and weps) store the relative importance of the level one measures of effectiveness. The remaining fields are classified are level two.

The level one fields are: ops (operations), weps (weapons), and mob (mobility). They all hold a scalar representing the relative importance if the field. Level 1 fields should sum to 1.

The level two fields are:

USER.omoe.speed - maximum speed in kts

USER.omoe.endurance - days at sea

USER.omoe.range - maximum range in nm

USER.omoe.draft – design draft in ft

USER.omoe.md - available main deck space less the main deck space used by the weapons in ft^2.

USER.omoe.ih - available in-hull deck space less the main deck space used by the weapons and the prime movers (ft^2).

USER.omoe.man - manning of the ship created

USER.omoe.sea – %MSI

The level two fields either have a length of 3, in which case the elements are [threshold goal moe] or a length of one in which case the element is [moe]. If the level two fields have a length of one the threshold value is set to the worst possible output and the goal value is set to the best possible output in the course of the program. The first four fields (speed, endurance, range, and draft) are the mobility parameters. The sum of their moe's should be 1. The last four fields (md, ih, man, and sea) are the operation parameters. The sum of their moe's should also be 1. It is important to note that this variable is reassigned during the execution of PCAT so at the completion of the program, every level two field has a length of three. Therefore if default values are desired in subsequent runs, the user must specify this in each run.

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Name: **USER.cost**

Data type: structure

Purpose: Holds relevant cost information. Each field holds a scalar value of the price of some aspect of the ship or other relevant cost parameters. The fields are:

manning – price of a man-year in $/man-year

life – estimated life of the hull in years

ops – percent of time the variant is operational in percent

fuel – price of fuel in $/L

Name: **USER.sea**

Data type: scalar

Purpose: Holds the value of the seastate for seakeeping analysis.

Name: **USER.rsm**

Data type: binary bscalar

Purpose: Set to 1 if the current run uses response surface modeling.
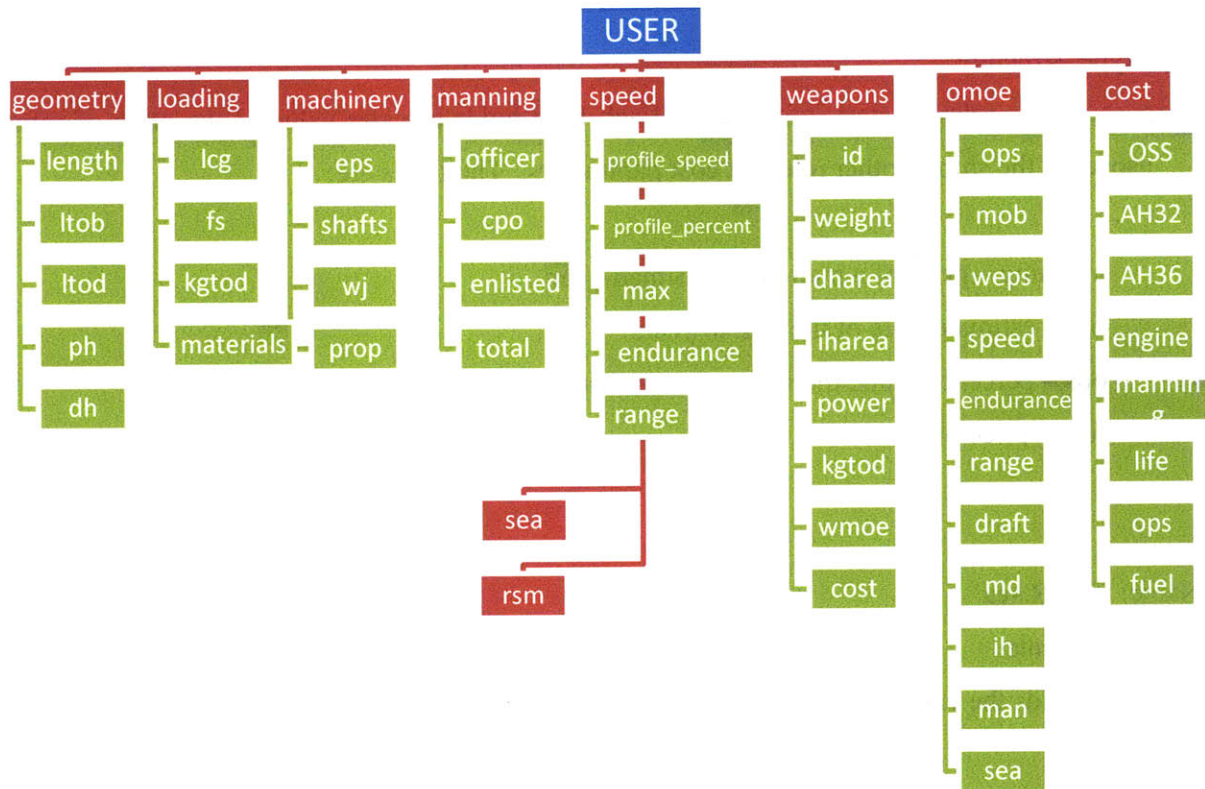
Figure B-0-1 USER variable breakdown

Name: **HULL**

Data type: structure

Purpose: Stores user information for a particular variant. HULL is sized by NxM, where N is the variant number and M is the run number. For the remainder of this appendix, HULL(N,M) will be represented as HULL.

Name: **HULL.geometry**

Data type: structure

Purpose: Holds relevant geometrical parameters for a particular variant. Fields are all scalars unless otherwise noted. Fields are:

lbp – length between perpendiculars (m), initially set by the user, but changes as the design draft of the ship is adjusted.

loa – length overall (m), unlike lbp, this variable is constant for a given hull throughout the design process.

beam_max – maximum ship beam (m)

depth – midships depth (m)

dh – deck height, or separation of internal decks (m)

ph – cell containing a string that names the parent hull

wsa – wetted surface area (m^2), surface area of the wetted portion of the hull at design draft.

main_deckarea – area of the main deck (m^2)

iharea – area of internal decks (m^2)

displacement – displacement of the ship at design draft (mton)

beam_wl – beam of the ship at the waterline (m)

Cb – block coefficient, defined as $\dfrac{Displaced\ Volume}{Design\ Draft * LBP * Beam\ at\ waterline}$

Cp – prismatic coefficient, defined as $\dfrac{Displaced\ Volume}{Maximum\ submerged\ section\ area * LBP}$

gm – metacentric height (m)

km – height of the metacenter above the keel (m)

draft – design draft (m), initially set by the parent hull selection, but changes as ship is balanced.

offsets – structure holding offsets of the ship. This is described in more detail below.

Name: **HULL.geometry.offsets**

Data type: structure

Purpose: Holds the offsets for a ship. The offsets for this program are stored in an unconventional way to allow for easier processing of the data. This requires the user to ensure the data is properly formatted before entering a new hull. The offsets are broken into three coordinates X (longitudinal), Y (transverse), and Z (vertical) with the origin being at the forward perpendicular, centerline, and baseline respectively. Positive X is aft, positive Y is to port, and positive Z is upwards. To represent the offsets a grid is placed on the hull in the X-Z plane.

Then at each point on the grid, the half breadth (Y) is calculated. So X is a 1xn sized array, Z is a 1xm sized array, and Y is a nxm sized matrix. If the there is no offset at a particular point x,z. Then Y(n,m) is set to NaN, or not a number. NaN is a special Matlab value that is used in PCAT to alert the program that there is no hull at a particular point. Figure B-0-2 shows a generic hull form and the associated grid.
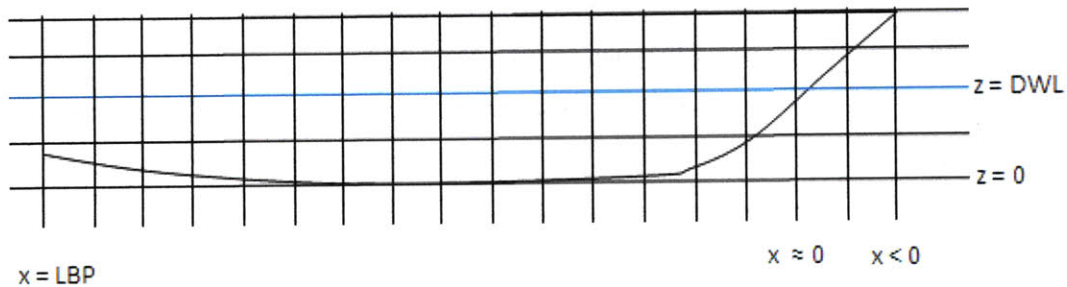
Figure B-0-2 Generic offset grid

The fields of HULL.geometry.offsets are X, Y, Z and t (initial draft). All are in m.

Name: **HULL.loading**

Data type: structure

Purpose: Holds loading information for a specific variant. The fields HULL.loading are all scalar unless otherwise noted. The fields are

kg – estimate of the center of gravity of a hull (m)

lcg – distance from midships to longitudinal center of gravity (lcg) over length where a value > 0 is forward of midships. This variable is non dimensional.

materials – cell holding a string that names the material

fs – frame spacing (m)

Name: **HULL.speed**

Data type: structure

Purpose: Holds speed and range information. All fields are scalar unless otherwise stated. The fields are:

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profile_speed – an array of speeds at which a variant is analyzed for resistance and fuel efficiencies. This array begins as the speeds in knots input by the user in the speed profile but then is "beefed up" to include at speeds in 1 knot increments from a Froude number of 0.1 to the maximum speed (if Froude number of the maximum speed is < 1.0).

profile_percent – an array representing the percent of the time a craft spends at a given speed when operational. This array is initially put in by the user. Zeroes are added for every speed that is added in the "beef up" process so the length of this array is the same at the length of profile_speed.

max – maximum speed (knots) input by the user

endurance – endurance speed (knots) or 'd' for default. Either input by the user or calculated as the most fuel efficient speed.

range – range of the variant in nm. See chapter 3 for more information on range.

new_max – final maximum speed of the hull accounting for the actual engines placed on board. This number will be greater than the value input by the user.

endurance_days – number of days the ship can stay at sea without refueling at endurance speed using 2/3 of the available fuel.

Name: **HULL.machinery**

Data type: structure

Purpose: Holds machinery information relevant to all engineroom machinery. All fields are scalar unless otherwise stated. The fields are:

eps – engines per shaft, can either be 1 or 2

shafts – number of shafts on this variant

wj – binary variable that equals 1 if waterjets are used and 0 if not

prop - binary variable that equals 1 if waterjets are used and 0 if not

endurance_nm_LT – fuel efficiency at endurance speed in nm per LT

nm_LT – an array the same length as the "beefed up" speed profile. Element (n) of this field is the fuel efficiency of the ship in nm per LT at a speed equal to HULL.speed.profile_speed(n).

sfc_profile - an array the same length as the "beefed up" speed profile. Element (n) of this field is the specific fuel consumption of the ship in $lbs/_{hp * hr}$ at a speed equal to HULL.speed.profile_speed(n).

Name: **HULL.weapons**

Data type: structure

Purpose: Holds the information on the weapons systems input by the user for a particular variant. The fields are the same as USER.weapons with the exception that each field of HULL.weapons only holds one value.

Name: **HULL.manning**

Data type: structure

Purpose: Holds the information on the manning of the variant. The fields are all scalar and in units of people. The fields are:

officer – number of officers

cpo – number of chief petty officers

enlisted – number of junior enlisted

total – total number of people

Name: **HULL.resistance**

Data type: structure

Purpose: Holds information or resistance and powering for a particular variant. The fields are all structures also.

bhehp – bare hull effective horsepower (kW), stores the bare hull EHP of the hull.

ehp – EHP with appendages (kW)

bhp – Brake horsepower, or the power required by the engine to move the ship at a given speed (kW).

Each of these fields is a structure and has multiple parts. So for example HULL.resistance.bhp has three fields max, endurance, and profile corresponding to the required power at maximum speed, endurance speed, and along the speed profile.

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max – horsepower at user specified maximum speed. This variable is a scalar.

endurance – horsepower at endurance speed. Note this field will not exist for bhehp and ehp if the user set endurance to default. This variable is a scalar.

profile – power requited along the speed profile. This variable is an array of powers the same length as the profile_speed.

Name: **HULL.good**

Data type: scalar

Purpose: This scalar is initially set to 0 and then is change to 1 if the ship converges.

Name: **HULL.error**

Data type: string

Purpose: This string is the reason for a particular ship not converging.

Name: **HULL.engine**

Data type: structure

Purpose: Holds information on the propulsion engine selected. HULL.engine has the following fields:

Model – a string holding the model name

Specs – an array describing the model. The elements of Specs are:

[ID, length(m), width(m), height(m), weight(mton), maximum BHP(kW), RPM(max)]

SFC – an matrix describing the engine at different rpms. Each row of SFC corresponds to a different RPM. The first five elements are for the engine used in a non-marine environemt. The second five elements are for the engine attached to a propeller. Therefore only the last five elements of each row of SFC were used in PCAT. Each row has the following elements.

[RPM, BHP, Torque(N-m), SFC (kg/kW-hr), GPH (L/hr), RPM, BHP, Torque, SFC, GPH]

SHP – the final shaft power of the ship.

Name: **HULL.temp_weight**

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Data type: structure

Purpose: This structure has fields that hold weights generated outside of the weight module. The fields are:

F41 – Full load fuel loading (mton)

structures – weight of structures generated in the structures section (mton)

Name: **HULL.structures**

Data type: structure

Purpose: Holds information relevant to structures of a variant. All fields hold scalars unless otherwise stated. The fields are:

SM - limiting (minimum) section modulus of the midships section in m-cm^2

bsp – bottom shell plating thickness (cm)

ssp_m – side shell plating thickness near midships (cm)

ssp_e – side shell plating thickness near the ends (cm)

dp – array of deck plating thicknesses (cm), element 1 is the main deck, element 2 is the first deck below the main deck, etc.

x_bg – critical thickness of the bottom girder (cm). See chapter 3 for more information on critical thicknesses.

x_bf – critical thickness of the bottom frame (cm)

x_sf – critical thickness of the side frame (cm)

x_ss – critical thickness of the side stringers frame (cm)

NA – location of the neutral axis above baseline (m)

Name: **HULL.weight**

Data type: array of structures

Purpose: HULL.weight is an array with length 10 where each element is a structure.

Element of HULL.weight	Information stored
HULL.weight(1)	Information on SWBS 100
HULL.weight(2)	Information on SWBS 200
HULL.weight(3)	Information on SWBS 300
HULL.weight(4)	Information on SWBS 400 and 700 and various variable loads
HULL.weight(5)	Information on SWBS 500
HULL.weight(6)	Information on SWBS 600
HULL.weight(7)	Only holds naming information
HULL.weight(8)	Empty
HULL.weight(9)	Information variable loads
HULL.weight(10)	Information on the total weight

Figure B-0-3 HULL.weight description

HULL.weight(4) holds information on the weights for SWBS groups 400, SWBS 700 and the variable ammunition because the user inputs the weights for SWBS 400, SWBS 700 and the variable ammunition as a group and there is no reason to separate them. HULL.weight(9) holds the information on the remainder of the variable loads. The fields of each structure are:

groups – scalar that holds the groups weight in mton

SWBS – string that holds the SWBS number

name – string that holds the name of the SWBS group.

Name: **HULL.seakeeping**

Data type: structure

Purpose: Holds the seakeeping information number for the ship.

Name: **HULL.seakeeping.period**

Data type: array

Purpose: Holds the array of periods at which the seakeeping analysis was performed. This array is in seconds.

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Name: **HULL.seakeeping.freq**

Data type: array

Purpose: Holds the array of frequncies at which the seakeeping analysis was performed. This array is in radians per second.

Name: **HULL.seakeeping.RAO**

Data type: array

Purpose: Holds the array of RAO in Heave of the ship. This array is in m/m.

Name: **HULL.seakeeping.msi**

Data type: scalar

Purpose: Holds the MSI of the variant

Name: **HULL.cost**

Data type: structure

Purpose: Stores the acquisition and lifecycle cost of a variant.

      acquisition – acquisition cost in $

      lifecycle – lifecycle cost in $

Name: **HULL.output**

Data type: structure

Purpose: This variable holds information used in calculating the OMOE that are not explicitly stored elsewhere. Fields are all scalars.

      md_area – main deck area less area used by weapons on the main deck (m^2)

      ih_area – in-hull deck area less area used by weapons and prime movers in-hull (m^2)

Name: **HULL.omoe**

Data type: structure

Purpose: Holds all omoe data. Values in omoe are final measures of effectiveness, not relative importance. Fields are:

      omoe – scalar value for final omoe

moe_1 – array of second tier moe results. First elements are related to mobility. The last
   four elements are related to operations. The elements are: [speed, endurance, range,
   draft, md_area, ih_area, manning, seakeeping]

mob – scalar value for mobility moe

ops – scalar value for operations moe

weps – scalar value for weapons moe

Figure B-0-4 and Figure B-0-5 show the breakdown of HULL to the second level.
HULL.geometry.offsets and all of the HULL.resistance fields are broken down to the third level
as described above.
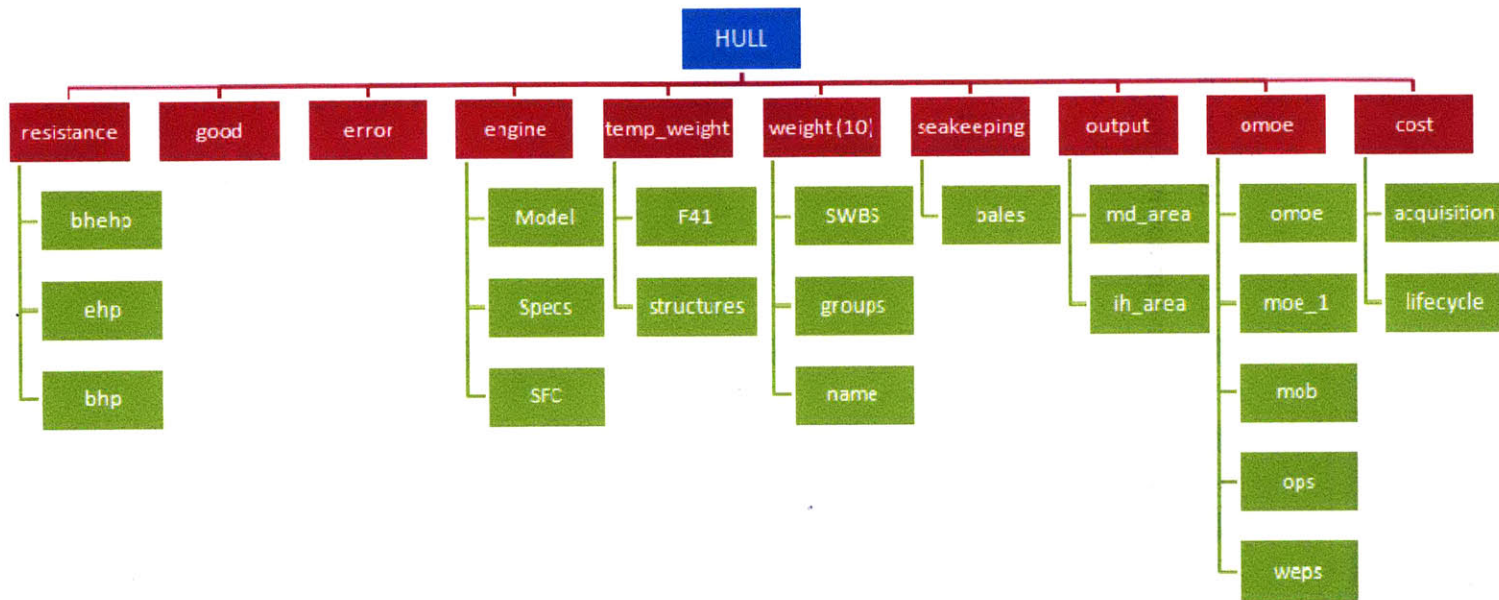
Figure B-0-4 HULL Variable
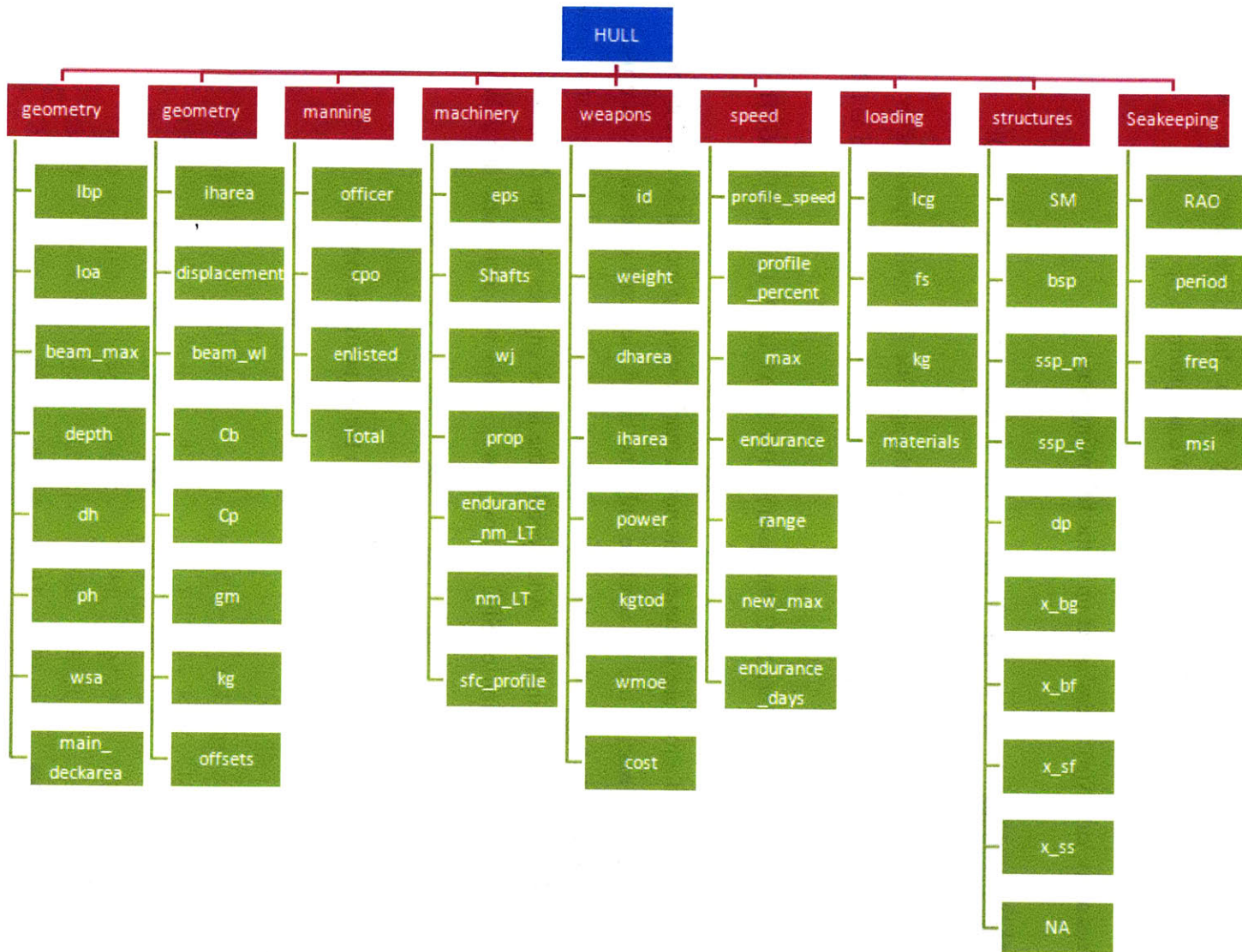
Figure B-0-5 HULL Variable

APPENDIX C – Engine Library

The data for the engines was taken directly from the Caterpillar Inc. web site, http://marinewizard.catmms.com/catwizards/marineWizard/jsp/main.jsp.

The specs array 'catEN(n).Specs' is set up in the following way:

[ID Length(ft) Width(ft) Height(ft) Weight(LT) Maximum BHP(hp) RPM(max)]

The SFC matrix 'catEN(n).SFC' is used to calculate the specific fuel consumption of an engine is setup so each row corresponds to a particular engine power. The columns are set up as follows:

[RPM BHP (hp) Torque (ft-lbf) SFC (lbf/hp-hr) GPH RPM BHP Torque SFC GPH]

The first 5 elements of a row are for an engine not in marine use, the second 5 elements of a row are for the engine in marine use. Therefore only the last 5 elements of each row are used in PCAT. The final three engines did not have complete data available through Caterpillar so some parameters were estimated using(19) Additionally, the lower engines were modeled at very low RPM to allow for interpolation of SFC at low power. This was also done using Woud and Stapersma.

The model array 'catEN(n).Model' holds a string with the name of the model.

```
catEN(1).Model='Caterpillar C7-315';
catEN(1).Specs=[7315    4.01    2.87    3.06    0.79    315     2400];
catEN(1).SFC=[2400 315 689 0.378 17.0   2400    315     690     0.378   17.0
2200    315     752     0.365   16.4    2200    243     580     0.361   12.5
2000    315     827     0.357   16.1    2000    182     479     0.359   9.4
1800    315     919     0.356   16.0    1800    133     388     0.367   7.0
1600    274     900     0.362   14.2    1600    93      307     0.380   5.1
1400    226     848     0.376   12.1    1400    62      235     0.397   3.5
1200    176     770     0.399   10.0    1200    39      173     0.420   2.4
```

```
1000     127      668      0.432    7.8      1000     23       119      0.449    1.5
1         1        1        0.648    0        1        1        1        0.648    0];


catEN(2).Model='Caterpillar C9-503';
catEN(2).Specs=[9503     3.93     3.15     3.22     0.93     503      2500];
catEN(2).SFC=[2500   503 1056     0.362    26.0     2500     503 1056 0.362    26.0
2400     503      1100     0.357    25.6     2400     445      974      0.362    23.0
2300     503      1148     0.349    25.1     2300     392      894      0.358    20.0
2200     509      1216     0.342    24.9     2200     343      818      0.352    17.2
2100     509      1275     0.338    24.6     2100     298      746      0.347    14.8
1900     508      1404     0.336    24.4     1900     221      610      0.350    11.0
1800     495      1443     0.335    23.7     1800     188      548      0.356    9.5
1700     469      1450     0.335    22.4     1700     158      488      0.361    8.2
1600     436      1430     0.337    21.0     1600     132      433      0.367    6.9
1500     378      1324     0.353    19.0     1500     109      381      0.373    5.8
1300     235      948      0.408    13.7     1300     71       285      0.390    3.9
1100     162      774      0.461    10.7     1100     43       204      0.412    2.5
1000     137      718      0.471    9.2      1000     32       169      0.425    2.0
900      113      657      0.469    7.5      900      23       137      0.442    1.5
800      91       599      0.466    6.1      800      16       108      0.473    1.1
600      58       504      0.478    3.9      600      7        61       0.582    0.6
1        1        1        0.655    0        1        1        1        0.655    0];


catEN(3).Model='Caterpillar C12-660';
catEN(3).Specs=[12660    5.16     3.47     3.30     1.16     660      2300];
catEN(3).SFC=[2300   660 1507     0.362    34.1     2300     660 1507 0.362    34.1
2200     664      1584     0.352    33.4     2200     577      1378     0.347    28.6
2000     661      1735     0.342    32.3     2000     434      1140     0.340    21.1
1800     662      1932     0.343    32.5     1800     316      923      0.344    15.5
1600     661      2170     0.350    33.0     1600     222      729      0.346    11.0
1400     545      2044     0.355    27.7     1400     149      558      0.345    7.3
1200     282      1235     0.356    14.3     1200     94       410      0.363    4.9
1000     172      904      0.353    8.7      1000     54       285      0.419    3.2
600      68       597      0.340    3.3      600      12       103      0.770    1.3
1        1        1        0.862    0        1        1        1        0.862    0];


catEN(4).Model='Caterpillar C15-800';
catEN(4).Specs=[15800    5.01     3.09     3.84     1.44     800      2300];
```

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```
catEN(4).SFC=[2300   800 1827      0.355    40.6    2300    800 1828 0.355    40.6

2200    800     1910    0.354    40.4    2200    700    1672    0.340    34.0

2100    800     2000    0.353    40.4    2100    609    1524    0.332    28.9

2000    800     2101    0.353    40.3    2000    526    1382    0.330    24.8

1900    800     2211    0.353    40.3    1900    451    1247    0.332    21.4

1800    800     2334    0.354    40.4    1800    384    1120    0.335    18.4

1700    800     2472    0.356    40.6    1700    323    999     0.341    15.7

1600    800     2624    0.357    40.8    1600    269    884     0.347    13.4

1500    751     2630    0.355    38.1    1500    222    777     0.353    11.2

1400    606     2275    0.351    30.4    1400    181    677     0.358    9.2

1300    470     1897    0.352    23.6    1300    145    584     0.362    7.5

1200    329     1439    0.363    17.0    1200    114    498     0.366    5.9

1100    293     1397    0.380    15.9    1100    88     418     0.374    4.7

1000    255     1340    0.401    14.6    1000    66     345     0.386    3.6

1       1       1       0.599    0       1       1      1       0.599    0];


catEN(5).Model='Caterpillar C18-873';
catEN(5).Specs=[18873    5.11     3.47     3.85     1.56    873     2200];
catEN(5).SFC=[2200   873 2084      0.355    44.2    2200    873    2084 0.355 44.2

2100    873     2183    0.351    43.7    2100    759    1899    0.345    37.4

2000    873     2292    0.347    43.3    2000    656    1722    0.337    31.6

1900    873     2413    0.344    42.9    1900    562    1555    0.332    26.7

1800    873     2548    0.341    42.5    1800    478    1395    0.331    22.6

1700    833     2574    0.335    39.9    1700    403    1244    0.332    19.1

1600    784     2573    0.330    36.9    1600    336    1103    0.335    16.1

1500    662     2319    0.326    30.8    1500    277    969     0.338    13.4

1400    578     2167    0.327    26.9    1400    225    844     0.342    11.0

1300    495     2000    0.331    23.4    1300    180    728     0.345    8.9

1200    431     1888    0.336    20.7    1200    142    620     0.350    7.1

1000    356     1868    0.348    17.6    1000    82     431     0.367    4.3

800     211     1382    0.361    10.9    800     42     276     0.395    2.4

600     138     1212    0.381    7.5     600     18     155     0.437    1.1

1       1       1       0.526    0       1       1      1       0.526    0];


catEN(6).Model='Caterpillar C18-1001';
catEN(6).Specs=[181001   5.11     3.47     3.85     1.56    1001    2300];
catEN(6).SFC=[2300   1001    2286     0.362    51.7 2300 1001 2286 0.362     51.7

2200    1001    2390    0.356    50.9    2200    876    2092    0.346    43.3
```

2100	1001	2504	0.352	50.4	2100	762	1906	0.336	36.6
2000	1001	2629	0.350	50.1	2000	658	1729	0.330	31.0
1900	1001	2767	0.349	50.0	1900	564	1560	0.326	26.3
1800	985	2874	0.348	49.0	1800	480	1400	0.324	22.2
1700	964	2978	0.345	47.4	1700	404	1249	0.323	18.7
1600	925	3035	0.337	44.5	1600	337	1106	0.325	15.6
1500	846	2964	0.330	39.9	1500	278	972	0.329	13.1
1400	755	2834	0.331	35.7	1400	226	847	0.336	10.8
1300	620	2507	0.335	29.7	1300	181	730	0.343	8.8
1200	529	2314	0.336	25.4	1200	142	623	0.360	7.3
1000	342	1797	0.339	16.6	1000	82	432	0.451	5.3
800	229	1502	0.350	11.4	800	42	277	0.515	3.1
600	136	1194	0.371	7.2	600	18	156	0.592	1.1
1	1	1	0.701	0	1	1	1	0.701	0];

catEN(7).Model='Caterpillar 3412E-1200';
catEN(7).Specs=[341200   6.20   4.44   4.50   2.49   1200   2300];
catEN(7).SFC=[2300   1200   2741   0.354   60.6   2300 1200 2741 0.354 60.6

2200	1200	2865	0.353	60.5	2200	1050	2508	0.346	51.9
2100	1200	3001	0.353	60.5	2100	914	2285	0.343	44.7
2000	1200	3151	0.352	60.3	2000	789	2073	0.344	38.8
1900	1200	3316	0.350	60.0	1900	677	1870	0.350	33.8
1800	1200	3500	0.349	59.8	1800	575	1679	0.355	29.2
1700	1199	3705	0.348	59.7	1700	485	1497	0.359	24.9
1600	1199	3935	0.348	59.6	1600	404	1326	0.363	20.9
1500	1102	3857	0.348	54.7	1500	333	1166	0.370	17.6
1400	975	3660	0.350	48.8	1400	271	1016	0.378	14.6
1300	806	3258	0.362	41.7	1300	217	875	0.385	11.9
1200	639	2795	0.382	34.9	1200	170	746	0.391	9.5
1	1	1	0.671	0	1	1	1	0.671	0];

catEN(8).Model='Caterpillar 3412E-1350';
catEN(8).Specs=[341350   6.20   4.50   4.50   2.49   1350   2300];
catEN(8).SFC=[2300   1350   3084   0.359 69.3 2300 1350 3084   0.359   69.3

2200	1350	3223	0.363	70.0	2200	1182	2821	0.350	59.1
2100	1350	3377	0.364	70.2	2100	1028	2571	0.344	50.5
2000	1350	3545	0.364	70.1	2000	888	2332	0.343	43.5
1900	1350	3731	0.362	69.9	1900	761	2104	0.347	37.7

```
1800    1349    3935    0.360   69.3    1800    647     1889    0.351   32.4
1700    1298    4009    0.355   65.9    1700    545     1685    0.354   27.6
1600    1226    4026    0.351   61.4    1600    455     1492    0.358   23.2
1500    1102    3857    0.347   54.6    1500    375     1311    0.365   19.5
1400    975     3660    0.350   48.7    1400    305     1142    0.373   16.2
1300    806     3258    0.362   41.7    1300    244     985     0.380   13.2
1200    639     2795    0.382   34.9    1200    192     839     0.385   10.5
1       1       1       0.660   0       1       1       1       0.660   0];

catEN(9).Model='Caterpillar C30-1500';
catEN(9).Specs=[301500  5.94    4.64    4.52    2.51    1500    2300];
catEN(9).SFC=[2300  1500    3425    0.376   80.5 2300 1500 3525 0.376   80.5
2200    1500    3581    0.368   78.8    2200    1313    3134    0.356   66.7
2100    1500    3751    0.363   77.7    2100    1142    2855    0.345   56.3
2000    1500    3939    0.360   77.2    2000    986     2590    0.342   48.2
1900    1500    4147    0.360   77.1    1900    846     2337    0.344   41.5
1800    1475    4303    0.359   75.7    1800    719     2098    0.346   35.5
1700    1428    4413    0.355   72.4    1700    606     1871    0.349   30.2
1600    1345    4414    0.350   67.2    1600    505     1657    0.351   25.4
1500    1230    4308    0.345   60.6    1500    416     1457    0.354   21.1
1400    1030    3865    0.348   51.2    1400    338     1269    0.357   17.2
1200    745     3261    0.369   39.3    1200    213     932     0.366   11.1
1000    486     2555    0.388   26.9    1000    123     648     0.393   6.9
600     216     1886    0.388   11.9    600     27      233     0.519   2.0
1       1       1       0.621   0       1       1       1       0.621   0];

catEN(10).Model='Caterpillar C32-1652';
catEN(10).Specs=[321652  6.05    4.64    4.52    2.51    1652    2300];
catEN(10).SFC=[2300 1652    3773    0.366   86.4 2300 1652 3773 0.366    86.4
2200    1652    3944    0.361   85.1    2200    1446    3452    0.347   71.6
2100    1652    4132    0.357   84.3    2100    1257    3145    0.337   60.5
2000    1652    4338    0.357   84.3    2000    1086    2853    0.334   51.9
1900    1652    4567    0.359   84.8    1900    931     2575    0.334   44.5
1800    1634    4768    0.361   84.3    ·1800   792     2311    0.336   38.0
1700    1554    4802    0.356   79.1    1700    667     2061    0.338   32.2
1600    1499    4921    0.346   74.0    1600    556     1825    0.340   27.0
1500    1417    4961    0.334   67.6    1500    458     1605    0.343   22.4
1400    1294    4856    0.327   60.5    1400    373     1398    0.345   18.4
```

1300	1127	4552	0.330	53.2	1300	298	1205	0.348	14.8
1200	905	3963	0.340	44.0	1200	235	1027	0.353	11.8
1100	704	3363	0.350	35.2	1100	181	863	0.362	9.3
1000	617	3241	0.358	31.6	1000	136	713	0.375	7.3
700	318	2385	0.370	16.8	700	47	350	0.445	3.0
1	1	1	0.554	0	1	1	1	0.554	0];

catEN(11).Model='Caterpillar C32-1800';
catEN(11).Specs=[321800 6.48   4.62   4.53   2.90   1800   2300];
catEN(11).SFC=[2300 1800   4110   0.366   94.2 2300 1800 4110 0.366   94.2

2200	1800	4296	0.359	92.2	2200	1575	3760	0.360	81.0
2100	1800	4501	0.358	92.0	2100	1370	3426	0.350	68.6
2000	1800	4726	0.361	92.9	2000	1183	3107	0.340	57.4
1900	1800	4975	0.365	93.8	1900	1014	2804	0.331	47.9
1800	1767	5157	0.362	91.3	1800	863	2517	0.330	40.7
1700	1702	5257	0.353	85.7	1700	727	2245	0.333	34.6
1600	1637	5375	0.343	80.3	1600	606	1988	0.337	29.1
1500	1499	5249	0.338	72.3	1500	499	1748	0.341	24.3
1400	1340	5026	0.340	65.0	1400	406	1522	0.346	20.1
1300	1082	4372	0.349	53.9	1300	325	1313	0.351	16.3
1200	837	3663	0.358	42.8	1200	256	1119	0.357	13.0
1100	671	3202	0.366	35.1	1100	197	940	0.362	10.2
1000	586	3078	0.370	31.0	1000	148	777	0.369	7.8
700	287	2153	0.363	14.9	700	51	381	0.433	3.1
600	205	1796	0.355	10.4	600	32	280	0.471	2.1
1	1	1	0.626	0	1	1	1	0.626	0];

catEN(12).Model='Caterpillar 3512B-2250';
catEN(12).Specs=[352250   8.825   6.50   5.96   6.43   2250   1925];
catEN(12).SFC=[1925 2250   6139   0.341 109.6 1925 2250 6139 0.341   109.6

1600	2127	6982	0.327	99.5	1600	1292	4242	0.330	60.9
1400	1486	5574	0.332	70.5	1400	866	3247	0.339	42.0
1100	715	3413	0.359	36.7	1100	420	2005	0.350	21.0
900	496	2896	0.370	26.2	900	230	1342	0.372	12.2
650	300	2427	0.383	16.3	650	87	700	0.469	5.8
1	1	1	0.644	0	1	1	1	0.644	0];

catEN(13).Model='Caterpillar 3512C-2541';

```
catEN(13).Specs=[352541 8.76    7.32     6.35     6.76     2541      1800];
catEN(13).SFC=[1800 2541     7415     0.354    128.4 1800 2541 7415 0.354 128.4
1500      2384     8346     0.336    114.3    1500     1471     5149     0.323    67.8
1300      1986     8024     0.325    92.2     1300     957      3868     0.330    45.1
1100      1008     4815     0.338    48.7     1100     580      2769     0.334    27.7
900       686      4003     0.345    33.8     900      318      1853     0.382    17.3
700       432      3245     0.478    21.4     700      150      1121     0.478    6.9
1         1        1        0.733    0        1        1        1        0.733    0];


catEN(14).Model='Caterpillar 3516B-2800';
catEN(14).Specs=[352800 12.22   7.03     6.30     7.69     2800      1880];
catEN(14).SFC=[1880 2800     78323    0.332    132.7 1880 2800 7823 0.332 132.7
1600      2800     9191     0.321    128.5    1600     1726     5666     0.332    81.8
1400      2654     9956     0.325    123.2    1400     1156     4338     0.337    55.7
1100      825      3938     0.356    41.9     1100     561      2678     0.353    28.3
900       542      3162     0.361    27.9     900      307      1793     0.371    16.3
650       343      2774     0.371    18.2     650      116      935      0.444    7.3
1         1        1        0.576    0        1        1        1        0.576    0];


catEN(15).Model='Caterpillar 3516C-3386';
catEN(15).Specs=[353386 10.57   7.32     6.78     8.15     3386      1800];
catEN(15).SFC=[1800 3386     9880     0.330    159.8 1800 3386 9880 0.330 159.8
1500      2856     10001    0.315    126.6    1500     1959     6861     0.314    88.0
1300      2206     8913     0.312    98.2     1300     1276     5153     0.323    58.9
1100      1325     6326     0.333    63.0     1100     773      3690     0.337    37.2
900       712      4155     0.342    34.8     900      423      2470     0.396    24.0
700       497      3728     0.514    24.5     700      199      1294     0.514    10.2
1         1        1        0.827    0        1        1        1        0.827    0];


%profile data is estimated from Woud and Stampersma and caterpiller data
catEN(16).Model='Caterpillar 3608-3634';
catEN(16).Specs=[363634 18.25   5.67     8.67     18.66    3634      1000];
catEN(16).SFC=[1000 5444     0        0.322    0        0        5444     0    0.329    0
0    0    0    0    0    0    2000     0    0.334    0
0    0    0    0    0    0    1200     0    0.349    0
0    0    0    0    0    0    700      0    0.383    0
0    0    0    0    0    0    400      0    0.443    0
0    0    0    0    0    0    200      0    0.612    0
```

```
 0   0   0   0   0   0   1       0   0.863    0];


catEN(17).Model='Caterpillar 3612-5444';
catEN(17).Specs=[365444 15.92    5.75     11.67    25.57    5444     1000];
catEN(17).SFC=[1000 5444    0   0.322    0    0    5444    0   0.329    0
 0   0   0   0   0   0   3158    0   0.333    0
 0   0   0   0   0   0   1797    0   0.349    0
 0   0   0   0   0   0   980     0   0.389    0
 0   0   0   0   0   0   653     0   0.434    0
 0   0   0   0   0   0   436     0   0.524    0
 0   0   0   0   0   0   1       0   0.883    0];


catEN(18).Model='Caterpillar 3616-7268';
catEN(18).Specs=[367268 18  5.58     10.4     28.05    7268     1000];
catEN(18).SFC=[1000 7268    0   0.322    0    0    7268    0   0.329    0
 0   0   0   0   0   0   4215    0   0.333    0
 0   0   0   0   0   0   2398    0   0.349    0
 0   0   0   0   0   0   1308    0   0.389    0
 0   0   0   0   0   0   872     0   0.434    0
 0   0   0   0   0   0   581     0   0.524    0
 0   0   0   0   0   0   1       0   0.883    0];
```