Final Project Report

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Automated Multidisciplinary Design Optimization Method for Multi-Hull Vessels

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Automated Multidisciplinary Design Optimization Method for Multi-Hull Vessels

Task 4.8 Final Project Report

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Executive Summary

This report presents the formulation of a multidisciplinary design and optimization (MDO) method, based on a Systems Engineering approach, for use in the preliminary design stage of multihull ships. Using the quadratic programming algorithm (NPLQL) for a single criterion and the Neighborhood Cultivation Genetic Algorithm – (NCGA) for multicriteria optimization, the method integrates into a single design tool the hydrodynamic performance, evaluated by Neural Networks, with structures, stability, powering, payload and ship cost. This tool is applied to a baseline trimaran design for demonstration.

The primary outcome of this project, which is described in this report, and the accompanying user manual, is an MDO design tool based on a single criterion or multicriteria design optimization methodology, suitable for the preliminary (synthesis) design stage of a trimaran.

The application of the method to a trimaran configuration produces reasonable results for a demonstration. Three single objective optimizations are presented to minimize Required Freight Rate, Maximize Annual Cargo, and Minimize Ship Building Cost. A multi objective case, to minimize Ship Building Cost and Maximize Annual Cargo, is also presented. The results indicate that the method is robust and efficient. For the purpose of demonstration, the range of design space and the constraints for these cases are chosen to be broad. For applications to specific missions, various optimization parameters need to be carefully defined. More detailed parametric studies and application to specific mission requirements will be conducted in the next phase of the program.

During the next phases of this program, the MDO tool developed will also be expanded to include a higher fidelity model for the prediction of powering and the inclusion of seakeeping, as well as subsystem optimization models for hull shape and structures. Descriptions of the processes for these additions, and their integration for future extension of the method, are described in this report. When completed in the future phase of the program, the outcome will be a comprehensive MDO tool for multihull ships, encompassing hull form optimization, powering, stability, seakeeping, structures, general/cargo arrangement, and ship cost models.

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Nomenclature

α = (Separation): Ratio of clearance between the center and side hulls

β = (Stagger) Ratio of longitudinal position of side hull

λ_{sh} = Ratio of Length of side hull to Length of center hull

v = viscosity (m^2/s)

Λ = Ratio of Displacement of Trimaran side hull to Displacement of the Trimaran.

ρ = density of salt water (kg/m^3)

a = Clearance between aft perpendiculars of center hulls and side hulls

b = Clearance between center hull and side hull

$AA1$ = Shape coefficient for center hull

AAC_{crew} = Average annual cost of 1 member of the crew ($/year)

AC_{Pilot} = Cost of pilotage ($)

AC_{CH} = Annual cost of cargo handling ($)

ACC = Annual capital cost ($)

ACF = Annual cost of fuel ($)

$ACFLEET$ = Annual cost of fleet ($)

$ACLO$ = Annual cost of lube oil ($)

AF_{volume} = Annual freight volume per 1 vessel fleet

$Area\_C_{deck}$ = Deck cargo area (m^2)

B_{ch} = Beam of center hull, (meters)

B_d = Deck Breadth,(meters)

B_{sh} = Beam of side hull, (meters)

BM = Metacentric radius of trimaran (meters)

BOL = Beam Overall of the trimaran, (meters)

BOL_{MAX} = Maximum beam overall length of trimaran, (meters)

C_b^{ch} = Block coefficient of center hull.

C_b^{sh} = Block coefficient of side hull.

C_{crew} = Annual payroll costs ($/year)

$C_{C\&S}$ = Annual consumables and supplies ($)

C_{ch}^d = Block coefficient of depth volume of center hull

C_{sh}^d = Block coefficient of depth volume of side hull

C_m^{ch} = Midship coefficient of center hull

C_m^{sh} = Midship coefficient of side hull

C_{wl}^{ch} = Waterline coefficient of center hull

C_{wl}^{sh} = Waterline coefficient of side hull

$CARGO_{area}$ = Cargo area for containers / trailer

$CDAU$ = Deck area utilization coefficient

CF = Coefficient of friction resistance

C_HULL = Cost of hull (\$)

$C\_MACHINERY$ = Total cost of machinery (\$)

$C\_MACHINERY_{GT}$ = Cost of Machinery for gas turbines (\$)

$C\_MACHINERY_{diesel}$ = Cost of Machinery for diesel engines (\$)

C_OUTFIT = Cost of outfit (\$)

C_M_M = Annual cost of machinery maintenance (\$)

C_MISC = Miscellaneous costs (\$)

CK = Correlation Coefficient

CO = Coefficient of residual resistance

$COST_{LUBE}$ = Cost of lube oil (\$/kg)

$COST\_FUEL$ = Fuel Cost (\$/ton)

$COST\_M_{maint}$ = Cost of machinery maintenance (\$)

$COST\_M_{maint}diesel$ = Cost of machinery maintenance for diesel engine (\$)

$COST\_M_{maint}GT$ = Cost of machinery maintenance for gas turbine (\$)

$COST_{ins}$ = Annual insurance cost (\$)

$COST_{maint}$ = General annual cost of ship maintenance (\$)

$COST_{pilot}$ = Pilotage cost per port (\$)

$COST_{supply}$ = Provision & hotel supply (\$)

$COST_{TEUTRAI}$ = Cargo handling cost as port for TEU or trailer (\$)

CR = Total Resistance Coefficient

$Displ$ = Displacement – trimaran (tons)

$Displ_{ch}$ = Displacement – center hull (tons)

$Displ_{sh}$ = Displacement – side hull (tons)

$Deck_{cl}$ = Cargo deck clearance (m)

$E2$ = Squared error

F_{ch} = Proportionality factor for center hull

F_{sh} = Proportionality factor for side hull

F_n = Froude Number

F_{n_vol} = Volumetric Froude number

g = Gravitational acceleration (m/s^2)

GM = Metacentric height of trimaran (meters)

H_H = Productivity rate for hull manufacturing and assembly (hrs/ton)

H_M = Productivity rate for machinery assembly and installation (hrs/ton)

H_{misc} = Productivity rate for other systems (hrs/ton)

H_o = Productivity rate for outfit systems (hrs/ton)

H_{ship} = Height of ship (m)

HWC_{ch} = Depth of center hull (m)

HWC_{sh} = Depth of side hull (m)

h_{wc} = Relative height of water clearance (m)

K_{bd} = Deck weight dimensional coefficient (tons/m^2)

K_{ch} = Center hull weight dimensional coefficient (tons/m^3)

$K_{hull-misc}$ = Miscellaneous weight dimensional coefficient of hulls (tons/m^3)

$K_{LWT-misc}$ = Miscellaneous weight dimensional coefficient of light ship (tons/m^3)

K_{m_GT} = Statistical dimensional coefficient for gas turbines (tons/m^3)

K_{m_diesel} = Statistical dimensional coefficient for diesel engine (tons/m^3)

K_o = Dimensional statistic coefficient (tons/m^3)

K_{sh_conv} = Side Hull Weight dimensional coefficient for conventional type side hull (tons/m^3)

K_{sh_swa} = Side Hull Weight dimensional coefficient for SWA type side hull (tons/m^3)

K_{ss} = Superstructure weight dimensional coefficient (tons/m^3)

KB = Vertical center of buoyancy for trimaran (meters)

KB_{ch} = Vertical center of buoyancy for center hull (meters)

KB_{sh} = Vertical center of buoyancy for side hull (meters)

KG = Vertical center of gravity of trimaran (meters)

KG_{ch} = Vertical center of gravity of center hull (meters)

KG_{sh} = Vertical center of gravity of side hull (meters)

$KOEF_{cap\_cost}$ = Capital cost coefficient

L_{ch} = Length of center hull, (meters)

L_d = Length of deck (meters)

L_{sh} = Length of side hull, (meters)

LWT = Light ship weight (tons)

M_H = Relative material cost for hull ($/ton)

$M_{LWT-misc}$ = Relative material cost for electric, electronics, navig. ($/ton)

M_M = Relative material cost for machinery ($/ton)

M_o = Relative material cost for outfit ($/ton)

N_{crew} = Number of crewmembers

N_{diesel} = Number of diesel engines

N_d = Number of decks

N_{d_MAX} = Maximum number of decks

N_{GT} = Number of gas turbines

N_{pas} = Number of passengers

$N_{TEUTRAI}$ = Number of equivalent 20` containers (TEU) or trailers per trip

$NTEUTRAI_{rows}$ = Number of container or trailers rows at upper deck

$NNet$ = Neural Network

$NTRIP$ = Number of trips

P_{aux} = Auxiliary power (MW)

$P_{effective}$ = Effective Power (MW)

$P_{full-speed}$ = Shaft power / Power at full speed (MW)

P_{max} = Number of points in training or validation set

P_{pilot} = Required power for low speed – for pilotage (MW)

PEC = Propulsion Efficiency Coefficient

R = Range / Length of shipping line of operation (nm)

R_H = Labor rate for hull construction ($/hr)

R_M = Labor rate for machinery installation ($/hr)

R_{misc} = Labor rate for engineering and shipyard support ($/hr)

R_o = Labor rate for outfit works ($/hr)

R_{pilot} = Range at pilotage (nm)

RE = Reynolds number – trimaran

RE_{ch} = Reynolds number – center hull

RE_{sh} = Reynolds number – side hull

RES = Resistance of trimaran (N)

RFR = Required freight rate

Sl = Slenderness - trimaran

Sl_{ch} = Slenderness – center hull

Sl_{sh} = Slenderness – side hull

$SCOST$ = Ship cost ($)

SFC_{GT} = Specific fuel consumption for gas turbines (kg/hr/kW)

SFC_{diesel} = Specific fuel consumption for diesel engines (kg/hr/kW)

SFC_{aux} = Auxiliary specific fuel consumption (kg/hr/kW)

SFC_{pilot} = Specific fuel consumption at pilotage (kg/hr/kW)

$SLOC$ = Specific lube oil consumption (kg/hr)

$STOW_{TEUTRAI}$ = Cargo stowage factor TEU or Trailer

T_{aux} = Engine time (Auxiliary engines for generators) (hrs)

T_{ch} = Draft of center hull, (meters)

$T_{full-speed}$ = Time at full speed (hrs)

T_{pilot} = Time at pilotage (hrs)

T_{sh} = Draft of side hull, (meters)

T_{trip} = Total time for trip (hrs)

TOP = Annual operational period (days)

V = Total volume displacement (m^3)

V_{ch} = Volume displacement of center hull (m^3)

V_{sh} = Volume displacement of side hull (m^3)

V_{pilot} = Speed at pilotage (m/s)

V_s = Speed, (m/s)

V_k = Design Speed, (knots)

Vd = Total volume of depth displacement (m^3)

Vd_{ch} = Volume of depth displacement of center hull (m^3)

Vd_{sh} = Volume of depth displacement of side hull (m^3)

W_{ch} = Weight of center hull (tons)

W_{deck} = Weight of Bridge deck (tons)

W_{hull} = Weight of the hulls (tons)

$W_{hull-misc}$ = Miscellaneous hull weight (tons)

$W_{LWT-misc}$ = Miscellaneous light ship weight (tons)

W_{m_GT} = Machinery & Propulsion Weight for gas turbines (tons)

W_{m_diesel} = Machinery & Propulsion Weight for diesel engines (tons)

W_o = Outfit Weight of trimaran (tons)

W_{sh} = Weight of side hulls (tons)

W_{ss} = Weight of superstructure (tons)

$W_{TEUTRAI}$ = Weight of TEU or Trailer (tons)

$WFUEL$ = Total weight of fuel (tons)

$WFUEL_{aux}$ = Weight of fuel for auxiliary engines (tons)

$WFUEL_{full-speed}$ = Weight of fuel at full speed (tons)

$WFUEL_{pilot}$ = Weight of fuel at pilotage (tons)

WS = Wetted Surface – trimaran (m^2)

WS_{ch} = Wetted Surface – center hull (m^2)

WS_{sh} = Wetted Surface – side hull (m^2)

y_p = Output of Neural network for p^{th} pattern

t_p = Neural network target for p^{th} pattern

TS = Training Set

VS = Validation set

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1. Introduction

The vast majority of current U.S. naval ships are relatively large monohulls with limited speed capabilities. The desire for high-speed transit capabilities has resulted in increased interest in the application of multi-hull platforms for naval missions. Multi-hull ships have many potential advantages over monohull ships, however, their design procedures are not as mature. Further, multi-hull ships also offer avenues of hydrodynamic design optimization that are not found for mono-hull ships – such as the optimization of hull spacing or relative hull proportions.

Synthesis tools that are used to explore the ship design trade space in the concept design phase (ASSET, PASS, SDSM, and SEP) have been around for many years and are used widely by industry for monohull ships [Reference 1]. While some synthesis tools have been developed for multi-hulls, they are not nearly comparable in depth or level of fidelity to the monohull tools. Typically, they are used to develop point solutions of ship designs to populate and study the trade space; the difference in the point designs as determined by the design team. This process could be extensively enhanced by the application of optimization tools to the design problem, and by further development of multi-hull synthesis tools.

Optimization will allow for a more complete analysis of the trade space in two ways. First, the automation of the synthesis tool required for optimization will allow for more ship designs within the trade space to be examined, or a greater population of data in the trade space in a shorter period. Secondly, advanced optimization procedures will be able to better define the 'hot spots' or areas of the trade space worth examining in detail. The development of multi-hull design optimization and analysis tools will allow alternative hull forms and their corresponding designs to be explored to the same level of fidelity that monohulls can currently be examined, thus allowing for better comparisons between various hulls for a given ship capability, and faster generation of concept multi-hull designs.

Some recent investigators have worked on different aspects of ship design optimization. Reference 2, for example, integrates the design optimization software DARWIN with the U.S. Navy's ship design evaluation software ASSET for optimization of an amphibious assault ship and a destroyer class vessel. Another ongoing project at the University of Michigan [Reference 3] also uses ASSET (for determining design feasibility) along with a multi criteria optimization method for the optimization of the hydrodynamic design of high-speed multi-hull craft. Another ongoing project entitled Project Endeavour [Reference 4] plans to leverage Science Applications International Corporation (SAIC)'s work in software architecture for linking

optimization to advanced analysis codes and collaborative design of undersea weapons supported by ONR.

The objective of the present work is to develop a multidisciplinary design and optimization (MDO) method, based on a Systems Engineering approach, for use in the preliminary design stage of multihull ships. Using advanced multicriteria optimization, the method will integrate hydrodynamic performance evaluated by neural networks, with structures, stability, powering, payload and ship cost into a single design tool. This tool is applied to a baseline trimaran design for demonstration purposes.

The primary outcome of this project, which is described in this report and the accompanying user manual, is an MDO design tool based on single criterion or multicriteria design optimization methodology, suitable for the preliminary (synthesis) design stage of a trimaran. During the next phases of this program, the MDO tool developed can be expanded to subsystem optimization levels. The description of some of the processes for subsystems optimizations and their integration for future extension of the method are also described in this report. When completed in the future phases of the program, the outcome will be a comprehensive MDO tool for multihull ships, encompassing hull form optimization, powering, stability, seakeeping, structures, payload capacity and ship cost subsystem models.

In the following sections of this report, the first synthesis level optimization problem including objective(s) and constraints, are defined. Synthesis level approximation models for powering, stability, weight, payload and cost are then described. The implementation of single criterion and multi criteria optimization using iSIGHT software and results are presented, and some descriptions of processes for extension of the method to subsystem optimization models are give. The accompanying user manual describes details of the operation of the MDO synthesis level tool.

2. Problem description:

The required capability of a ship depends on the types of missions, and can be different for commercial or naval vessels. In commercial shipping, Required Freight Rate is the primary indicator of shipping efficiency. Required Freight Rate – RFR is the combination of Cost and Efficiency. However, the shipper is also interested in seeing the relative influences of the Cost of the ship and the Transport Efficiency on ship design characteristics. Therefore, both single

criterion and multi criteria optimizations for commercial ships have practical sense. For military naval vessels, the multiple criteria option is often required or desirable.

This chapter describes the Objectives functions, the design variables and Input Model Parameters and Constraints for both single criterion and multi criteria, and the synthesis level optimization of a simple Trimaran Configuration.

2.1.   Objectives:

2.1.1 Multiple Criteria:-

The goal of the optimization (objective functions) is to maximize the annual cargo shipped, and minimize the building cost.

Minimize Building Cost

Building cost is the cost incurred in the construction of the ship, which includes the hull cost, machinery cost, outfit cost and miscellaneous cost.

$$SCOST = C\_HULL + C\_MACHINERY + C\_OUTFIT + C\_MISC \qquad\qquad \text{EQUATION 1}$$

Maximize Annual Cargo

Annual cargo is the product of Number of 20 ft equivalent Container or Trailer and Number of trips. The objective function is to be maximized so that more cargo can be transported across.

$$AnnualCARGO = N_{TEUTRAI} \times NTRIP \qquad\qquad \text{EQUATION 2}$$

2.1.2 Single Criterion:-

Minimize Required Freight Rate (RFR)

Required freight rate depends on Annual cost per one vessel fleet ($ACFLEET$), Annual freight volume per one vessel fleet (AF_{volume}) and the Range / Length of shipping line of operation (R). RFR is to be minimized in order to reduce the cost incurred per TEU or trailer.

$$RFR = ACFLEET / AF_{volume} / R \qquad\qquad \text{EQUATION 3}$$

2.2 Constraints

A feasible design needs to satisfy the following requirements, which are interpreted as the constraints on the ship dimensions, displacement, powering and stability.

The ratio between draft for center hull (T_{ch}) and side hull (T_{sh}) varies from zero to 1.5. '1' means the desired waterline is the same for center hull and side hull of the trimaran.

$$0 \leq T_{sh}/T_{ch} \leq 1.5 \qquad \text{EQUATION 4}$$

The ratio between beam of center hull (B_{ch}) and draft of center hull (T_{ch}) varies from 1.5. to four.

$$1.5 \leq \frac{B_{ch}}{T_{ch}} \leq 4 \qquad \text{EQUATION 5}$$

The ratio between beam of side hull (B_{sh}) and draft of side hull (T_{sh}) varies from one to three.

$$1 \leq \frac{B_{sh}}{T_{sh}} \leq 3 \qquad \text{EQUATION 6}$$

The stability constraint is that the Metacentric Height must be greater than 1% of the Beam Overall Length:

$$GM_T/BOL \geq 0.01 \qquad \text{EQUATION 7}$$

Froude number (F_n) varies from 0.2 to one.

$$0.2 \leq F_n \leq 1 \qquad \text{EQUATION 8}$$

A volumetric Froude number value is less than 1.5.

$$F_{n\_vol} \leq 1.5 \qquad \text{EQUATION 9}$$

The volumetric Froude Number is formulated as,

$$F_{n\_vol} = \frac{V_s}{\sqrt{g \times \sqrt[3]{V}}} \qquad \text{EQUATION 10}$$

where,

V is the total volume displacement of the trimaran,

$$V = V_{ch} + 2 \times V_{sh} \qquad \text{EQUATION 11}$$

and,

$$V_{ch} = C_b^{ch} \times L_{ch} \times B_{ch} \times T_{ch} \qquad \text{EQUATION 12}$$

$$V_{sh} = C_b^{sh} \times L_{sh} \times B_{sh} \times T_{sh}$$

The total power generated by gas turbines and diesel engines is power at full speed, which is less than 200MW.

$$P_{full-speed} < 200MW$$

The ratio of beam overall length to maximum beam overall length is less than one.

$$(BOL / BOL_{max}) < 1$$

The ratio of minimum payload to payload is less than one.

$$\frac{Payload_{MIN}}{Payload} < 1$$

2.3   Design Variables

2.3.1 Coordinate System

The schematic of a generic trimaran configuration considered, is given in Figure 1. For synthesis level models, the specifics of the hull forms are not important, since all models (stability, powering, weight, etc) are independent of hull forms. Configuration (spacing and stagger) however are considered as design variables.
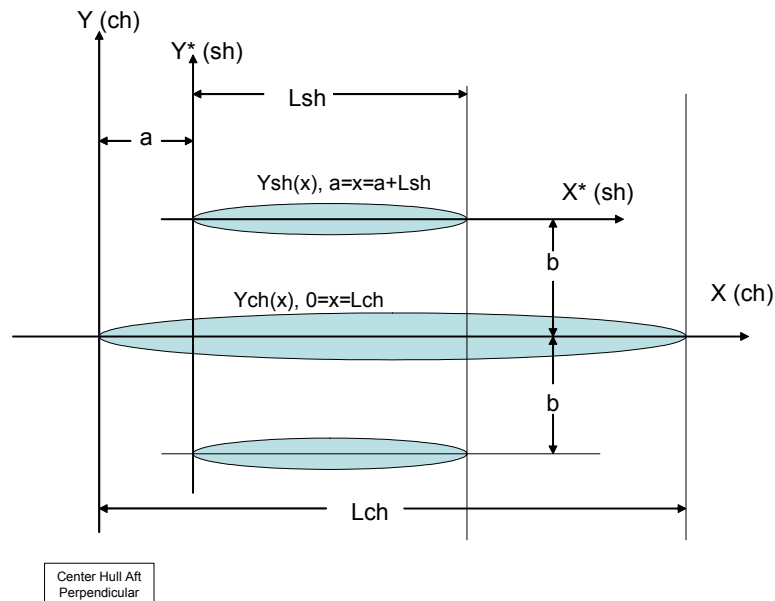
FIGURE 1: TRIMARAN CONFIGURATION (TOP VIEW)

Here, the center hull waterline is:

$$Y_{ch}(x) = \pm y_{ch}(x) \quad 0 \leq x \leq L_{ch}$$
<div align="right">*EQUATION 17*</div>

The side hull waterline is:

$$Y_{sh}(x) = \pm y_{sh}(x) \quad a \leq x \leq a + L_{sh}$$
<div align="right">*EQUATION 18*</div>

2.3.2 *List of Design Variables*

The Design Variables entirely define the Trimaran geometry and speed. Table 1 shows the list of design variables and their bounds. Below the table is a brief description of the variables.

<div align="center">*TABLE 1: LIST OF DESIGN VARIABLES AND THEIR BOUNDS*</div>

SR.NO	DESIGN VARIABLE	LOWER BOUND	UPPER BOUND	DESCRIPTION
1.	L_{ch}	100	250	Length of Center Hull
2.	B_{ch}	12	24	Beam of Center Hull
3.	B_{sh}	3	8	Beam of Side Hull
4.	T_{ch}	4	12	Draft of Center Hull
5.	C_b^{ch}	0.45	0.60	Block Coefficient of Center Hull
6.	C_b^{sh}	0.45	0.60	Block Coefficient of Side Hull
7.	V_k	25	45	Speed (knots)
8.	α	0.5	1.5	Separation
9.	β	0	1.0	Stagger
10.	Λ	0.03	0.15	Displacement ratio
11.	λ_{sh}	0.1	0.75	Length ratio

α : Separation: Ratio of clearance between the center hull and side hulls, meters to Beam of the center hull, B_{ch}, α can vary from 0.5 to two. The most common is 0.75-1. SAIC's concepts have about 1.0.

$$b = \frac{(1+\alpha) \times B_{ch}}{2} + \frac{B_{sh}}{2}$$
<div align="right">*EQUATION 19*</div>

β : Stagger: Ratio of longitudinal position of the side hull. β =Zero, if the transoms (aft perpendiculars) of the center and side hulls are at the same line; β =one, if the bows (bow

perpendiculars) of the center and side hulls are the same line. Common practice is to have β to be zero or 0.5. SAIC's trimaran concepts have zero.

$$a = \beta \times \left(L_{ch}\right) = \beta \times \left(1 - \lambda_{sh}\right)$$
<div align="right">EQUATION 20</div>

Λ : Ratio of displacement of trimaran side hull to displacement of the trimaran ($\Lambda = Displ_{sh} / Displ$). Λ can vary from 0.03 to 0.15. "0" means no displacement side hulls; "0.15" – is the maximum reasonable figure. The most common world practice is 0.03 – 0.05. SAIC's trimaran concepts have about 0.1.

λ_{sh} : Ratio of length of side hull (L_{sh}) to length of center hull (L_{ch}), ($\lambda_{sh} = L_{sh} / L_{ch}$) can vary from 0.1 to 0.75. Most common in the world practice is 0.2 - 0.3. SAIC's trimaran concepts have about 0.5

C_b : Block coefficient ranges from 0.45 to 0.60. C_b is not constrained by the cross sectional shape of the hull so it measures the fullness of the entire displaced volume. If the hull filled the entire block defined by length beam and draft, the C_b would be 1. For C_b^{sh} & C_b^{ch} it is the same.

2.4   Input Model Parameters

Besides the Design Variables, the model definition requires many auxiliary inputs, called Input Model Parameters (IMP), which are constant during optimization. The complete list of IMP parameters for various models is given in Appendix A.

Some IMP's are problem dependent and can be changed by the user according to the type of ship (conventional side hull or small waterplane area (SWA) type), the shipping line, type of cargo that will be handled, and shipyard chosen to build the ship. Those are called Optimization Problem Parameters or OPP's.

2.5   Optimization Problem Parameters

The Optimization Problem Parameters (OPP) are the parameters that can be input by the user/customer, depending on the Optimization Problem. All of these parameters can be changed in the Parameters list in iSIGHT Process Integration module.

Type of Cargo

The model has been programmed to handle two basic types of freight: 20 ft equivalent containers (TEU) or trailers (TRAI). The customer must define the Stowage Factor (STOWteutrai), Weight of trailer/container (Wteutrai) and Number of rows of Trailer per deck (Nteutrairows), as well of the Cost of cargo handling (COSTteutrai), which can also depend on the ports of shipping line (see section 4.3.2).

Recommended values for TEU or 20ft equivalent containers:

$STOW_{TEUTRAI}$ =1.4865 m^2/ton
$W_{TEUTRAI}$ =10 tons
$NTEUTRAI_{rows}$ = 2 or more
$COST_{TEUTRAI}$ = $ 125/TEU

Recommended values for Trailers:

$STOW_{TEUTRAI}$ = 1.6723 m^2/ton
$W_{TEUTRAI}$ = 10 tons
$NTEUTRAI_{rows}$ = 2
$COST_{TEUTRAI}$ = $ 30/TEU

Minimum Payload, Maximum Beam Overall Length, Maximum Number of Decks
The current values are:

$Payload_{MIN}$ = 1000 tons
BOL_{MAX} = 57m
N_{d_MAX} = 4
Shipping Line information

Range of Shipping Line
Range (R) must be changed according to shipping line length in nautical miles. Currently R is set to 800nm.

Port information

a.   Length of restricted speed (low speed & pilotage) and speed of pilotage (low speed) can be chosen. For the current application, the speed of pilotage (Vpilot) is assumed 10 knots and the Length of restricted speed (Rpilot) is set to 50 nm.

b.   Cost of port pilot services – COSTpilot currently set to 650 $/port

c.   Cost of cargo handling operations in the ports of shipping line COSTteutrai. (Also depends on the type of cargo used (see subsection above)

Cost of Fuel – COSTFUEL [$/ton]

COSTFUEL is assumed to be 400 $/ton in this application

Type of Trimaran configuration – TYPEsh

TYPEsh=1, if Side hulls are conventional high speed ship hull forms (of Serial 64 type);
TYPEsh=0 if Side hulls are of Small Waterplane Area (SWA) type.

Type of building facility (where the ship is supposed to be built)

TYPEbuild_yard=1, if the ship would be built in international commercial ship yard;
TYPEbuild_yard=2, if the ship would be built in a U.S. commercial ship yard;
TYPEbuild_yard=3, if the ship would be built in a U.S. Navy yard.

This parameter indicates the various production rates for hull, machinery and outfit as well as labor rates. They can change and will considerably influence the building cost of a ship. An accurate database, corresponding to this parameter, requires considerable data. It will be included in future models.

3.   Model Description:

This section describes design relationships for multihull (trimaran) ships, based on technical literature sources and the design experience gained in the course of the multi year CCDOTT High Speed Trimaran program development studies. During these studies, the concept designs

were developed for: the Very High Speed Sealift Trimaran; the Dual Short Sea Shipping and Theater Support Vessel; and Large Cruise and Air Capable vessels.

3.1 Powering

3.1.1 *Formulation*

This section provides an explanation of the formulation in the Powering system. The Power required to run at full speed ($P_{full-speed}$) needs to be determined. The Powering section first calculates some geometrical features of the Trimaran-like Displacement, Wetted Surface, Slenderness, and some flow related variables like Froude and Reynolds Numbers. Next, the Total Resistance of the boat can be calculated, and then the Full Speed Power and the number of Diesel and Gas Turbines given as required.

We first calculate the displacement for the center hull, side hull and trimaran. Displacement is the volume under salt water $(tons)$. The Displacement of the center hull ($Displ_{ch}$) is a product of the density of salt water and the volume displacement of the center hull.

$$Displ_{ch} = 1.025 \times V_{ch} \qquad\qquad \text{EQUATION 21}$$

where,

The volume of displacement of the center hull (V_{ch}) is the product of the Block coefficient of the center hull (C_b^{ch}), length of center hull (L_{ch}), Beam of center hull (B_{ch}) and Draft of center hull (T_{ch}). (V_{ch}) is in m3.

$$V_{ch} = C_b^{ch} \times L_{ch} \times B_{ch} \times T_{ch} \qquad\qquad \text{EQUATION 22}$$

Displacement for the center hull can be calculated from Equation 1. Based on which, the displacement of the trimaran is calculated by:

$$Displ = Displ_{ch} / (1 - 2 \times \Lambda), \qquad\qquad \text{EQUATION 23}$$

Where Λ is the ratio of displacement of the side hull ($Displ_{sh}$) to the displacement of the trimaran ($Displ$).

Hence the displacement of the side hull:

$$Displ_{sh} = Displ \times \Lambda \qquad\qquad \text{EQUATION 24}$$

We calculate the Draft for the side hull (T_{sh}), which depends on the displacement of the side hull ($Displ_{sh}$), length of side hull (L_{sh}), beam of side hull (B_{sh}), and the block coefficient of the side hull (C_b^{sh}).

$$T_{sh} = Displ_{sh} / (1.025 \times L_{sh} \times B_{sh} \times C_b^{sh}) \qquad\qquad \text{EQUATION 25}$$

Volume of displacement of side hull (V_{sh}) is the product of the Block coefficient of the side hull (C_b^{sh}), length of side hull (L_{sh}), Beam of side hull (B_{sh}) and Draft of side hull (T_{sh}). (V_{sh}) is in m³.

$$V_{sh} = C_b^{sh} \times L_{sh} \times B_{sh} \times T_{sh} \qquad\qquad \text{EQUATION 26}$$

Total volume displacement of trimaran:

$$V = V_{ch} + 2 \times V_{sh} \qquad\qquad \text{EQUATION 27}$$

Wetted surface (WS) calculated in meters is the sum of the wetted surface for the center hull and twice the wetted surface for the side hull,

$$WS = WS_{ch} + 2 \times WS_{sh} \qquad\qquad \text{EQUATION 28}$$

Now we calculate slenderness for the trimaran and for the center hull.

Slenderness of the center hull (Sl_{ch}) is the ratio of the length of the center hull to the volume of displacement of the center hull:

$$Sl_{ch} = L_{ch} / (V_{ch})^{1/3} \qquad\qquad \text{EQUATION 29}$$

The length of the side hull (L_{sh}) is calculated from:

$$L_{sh} = \lambda_{sh} \times L_{ch}$$

EQUATION 30

Slenderness of side hull (Sl_{sh}) is the ratio of the length of the side hull to the displacement of the side hull,

$$Sl_{sh} = L_{sh} / (V_{sh})^{\frac{1}{3}}$$

EQUATION 31

Since we have determined the slenderness for the center and side hulls, we now calculate the wetted surface for the center and side hulls. Wetted surface for the center hull (WS_{ch}) is a function of Sl_{ch} and V_{ch} .

$$WS_{ch} = AA1 \times Sl_{ch} \times V_{ch}^{\frac{2}{3}} \times (0.3048^2)$$

EQUATION 32

where, AA1 is the statistical shape coefficient and may be variable depending on the hull type used. AA1 is taken as 9.15.

Since we can calculate the wetted surface of the trimaran and for the center hull, we can also get the wetted surface of the side hull.

We have,

$$WS_{sh} = AA1 \times Sl_{sh} \times V_{sh}^{\frac{2}{3}} \times (0.3048^2)$$

EQUATION 33

Now, we can evaluate the slenderness for the trimaran (Sl),

$$Sl = \left(Sl_{ch} \times WS_{ch} + 2 \times Sl_{sh} \times WS_{sh} \right) / WS$$

EQUATION 34

The design speed (V_s), calculated in m/s, is given by:

$$V_s = V_k \times 0.515 \qquad\qquad \textit{EQUATION 35}$$

where, V_k is in knots.

We need to calculate the Coefficient of friction (CF) for the trimaran. In order to calculate the coefficient of friction, we first calculate the Reynolds number (RE) for the center and side hulls.

The coefficient of friction is a function of the Reynolds number (RE) and the Reynolds number is given by,

$$RE_{ch} = V_s \times L_{ch}/v \qquad\qquad \textit{EQUATION 36}$$

Where, viscosity (v) is taken as $1.187 \times 10^{-6} m^2/s$.

Similarly, the Reynolds number for the side hull (RE_{sh}),

$$RE_{sh} = V_s \times L_{sh}/v \qquad\qquad \textit{EQUATION 37}$$

Now, the Reynolds number for the trimaran,

$$RE = \left(RE_{ch} \times WS_{ch} + 2 \times RE_{sh} \times WS_{sh} \right)/\left(WS_{ch} + 2 \times WS_{sh} \right) \qquad\qquad \textit{EQUATION 38}$$

The coefficient of friction (CF) is given by,

$$CF = 0.075/\left(\log_{10}\left(RE \right) - 2 \right)^2 \qquad\qquad \textit{EQUATION 39}$$

The correlation coefficient (CK) reflects the specifics of high speed slender hulls, and is proposed as a scaling factor based on a comparison of the MQLT CFD calculations (used in this synthesis model for resistance prediction), CFD RANS calculations at ship Reynolds numbers

and previous trimaran model test data. A rationale and discussion of this correlation coefficient are given in Reference 5.

$$CK \times 1000 = (-0.003 \times L_{ch} + 0.6)$$ <div align="right">*EQUATION 40*</div>

The Coefficient of Residual Resistance (CO) is delivered from a series of calculations by MQLT (see section 5.2) for various displacements (slenderness) and configuration parameters (stagger and separation between the hulls). A Neural Network is then used as a function approximation to obtain CO values for each point of optimization variables. The Network has been trained using a set of points defined on a Latin Hypercube distribution within the design space called a Training Set (TS). Details of the Neural Network construction are explained in section 0. As mentioned above, the CO is a function of 4 variables: Slenderness (Sl), Separation (α), Stagger (β) and Froude Number (F_n).

The Froude number (F_n) depends on the the speed (V_s), gravitational acceleration (g), and length of the center hull (L_{ch}).

$$Fn = \left(\frac{V_s}{\sqrt{g \times L_{ch}}} \right)$$ <div align="right">*EQUATION 41*</div>

where, g = 9.81m/s^2

$$CO \times 1000 = f(Sl, \alpha, \beta, Fn)$$ <div align="right">*EQUATION 42*</div>

All resistance coefficients i.e., CF, CO, CK add up to the total resistance coefficient (CR).

$$CR = CO + CF + CK$$ <div align="right">*EQUATION 43*</div>

The Resistance (RES) in Newtons can be calculated as:

$$RES = \frac{1}{2} \rho \times V_s^2 \times WS \times CR$$ <div align="right">*EQUATION 44*</div>

Therefore, the Effective Power ($P_{effective}$) in MegaWatts required for the ship is:

$$P_{effective} = V_s \times RES / 10^6$$

EQUATION 45

Now, the shaft power ($P_{full-speed}$) or the Power required to run at full speed is:

$$P_{full-speed} = P_{effective} / PEC$$

EQUATION 46

Where, PEC is the propulsion efficiency coefficient, chosen as equal to .65 for this application. Once Power has been estimated, one needs to choose the type and size of engines required; this is further explained in section 3.1.3.

3.1.2   CO evaluation with Neural Networks

The Coefficient of Residual Resistance is evaluated with a Neural Network trained as a function approximator using a Cascade Correlation Algorithm. [1]
A Neural Network is the development of an optimization procedure based on a form of artificial intelligence. The Neural Network approach encompasses three steps:

1.   Generation of the Training Set (TS) & Validation Set (VS).
2.   Neural Network training to obtain a NN "evaluator(s)".
3.   Optimization with NN evaluator(s).

A training set (TS) corresponds to a set of known data points (design variables and their associated values, such as objective function(s) and constraints) used to train the NN, i.e. the network attempts to achieve an output, which matches the input (training set). A validation set (VS) is a set which, unlike the TS, is not used for training per say, but rather is used for stopping the training. The purpose of the VS is to avoid over fitting, which can occur with cascade correlation.

The Cascade Correlation (CasCor) Algorithm, first introduced by Fahlman and Liebere [Reference 6], is a supervised learning algorithm for NN. Instead of just adjusting the weights in a network of fixed topology, CasCor begins with a minimal network, then automatically trains and adds new hidden units one-by-one in a cascading manner. This architecture has several advantages over other algorithms: it learns very quickly; the network determines its own size

and topology; it retains the structure it has built even if the training set changes; and it requires no back propagation of error signals through the connections of the network. For a large number of inputs, the most widely used learning algorithm, back propagation, is known to be very slow. CasCor does not exhibit this limitation.

Also, and foremost, this method was chosen because the size of the network does not need to be determined in advance. Methods which use a fixed network topology involve evaluating in advance (before training) the type of network that would best suit the application (how many neurons, how many hidden layers…) to match the complexity of the NN to the complexity of the function. The training set and the validation set are generated using the MQLT method from Reference 5.

The training program is C++ software in which the Cascade Correlation algorithm is programmed. The outcome of the training is a NN in the form of an executable in which the proper number of hidden units and corresponding weights – found during training – have been implemented. This approach of generating such an executable for each network was selected for efficiency during the optimization process. The other approach would insist on printing a list of weights and hidden unit information. The information would have to be read at each function call during the optimization process, thus requiring a substantial amount of computer input/output (I/O) time when a short CPU time is needed for the actual computation. Error information (w.r.t TS and VS) are also printed. This helps the user to determine what accuracy is expected during the optimization.
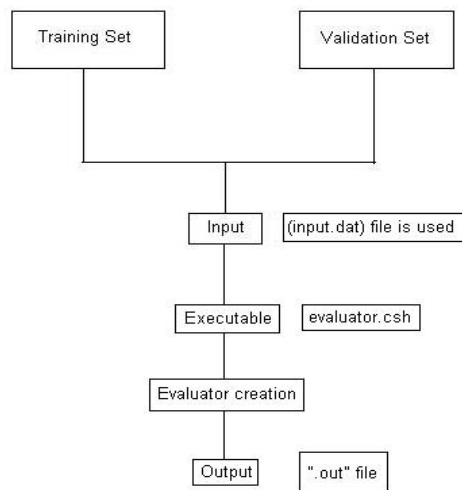
FIGURE 2: SYNOPSIS OF NEURAL NETWORK TRAINING.[1]

3.1.3 Engine Power estimate

This section provides an explanation of how the numbers of Diesel and Gas Turbine engines were chosen for this model, as well as the power they deliver. A C++ program was written to perform this selection. The number of engines depends on the full speed power needed. The calculations were made based on Table 2.

TABLE 2: TABLE DETERMINING THE NUMBER AND TYPE OF ENGINE NEEDED FOR THE TRIMARAN MODEL.

Total Required Power($P_{full-speed}$) - not to exceed the following amount [MW]	Number of Diesel engines (N_{diesel})	Total power output for the Diesel engines (P_{diesel})	Number of Gas Turbine engines(N_{GT})
<20	2	18MW	0
<40	2	18MW	1
<60	2	18MW	2
<80	2	18MW	2
<100	4	36MW	2
<120	4	36MW	2
<140	2	40MW	3
<160	2	40MW	4
<180	2	40MW	4
<200	-	0MW	5

The total output power for the Gas Turbine Engines (P_{GT}) is calculated with the following equation

$$P_{GT} = P_{full-speed} - P_{diesel}$$

EQUATION 47

3.2   Stability

This section determines the Metacentric height of the Trimaran in order to determine whether the ship is stable. The Metacentric height is then used in constraint equation 7. If the constraint is violated, the optimizer will discard this design. Figure 3 and 4 show the stability reference points in a conventional hull vessel, but all of the formulations in this section pertain to the determination of the Trimaran's stability.
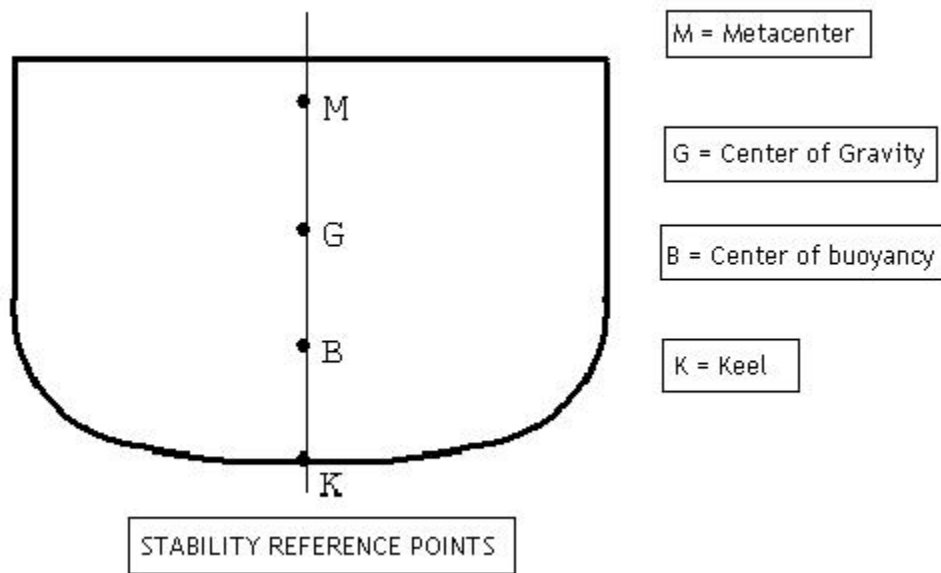
FIGURE 3: STABILITY REFERENCE POINTS OF A SHIP
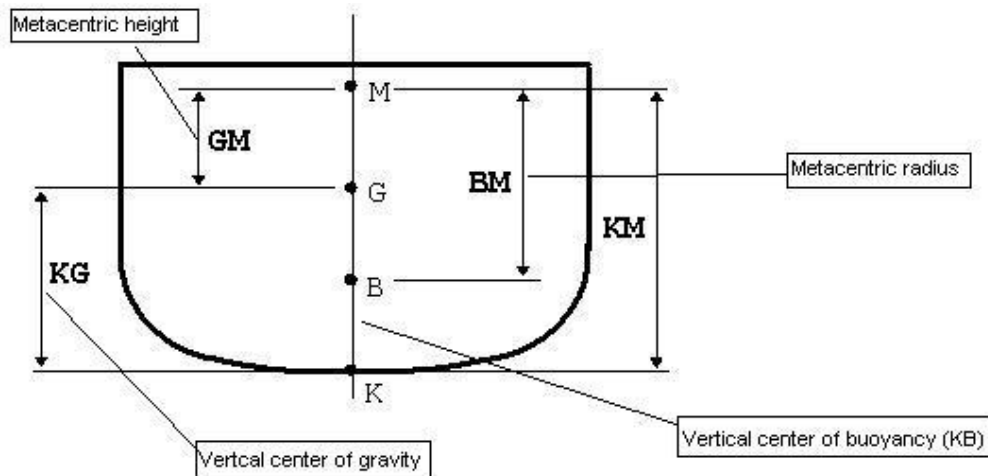
FIGURE 4: FIGURE SHOWING THE METACENTRIC HEIGHT AND METACENTRIC RADIUS

M - Metacenter: As the ship is inclined through small angles of heel, the lines of buoyant force intersect at a point called the metacenter (Figure 3). As the ship is inclined, the center of buoyancy moves in an arc as it continues to seek the geometric center of the underwater hull body. This arc describes the metacentric radius.

BM **- Metacentric Radius:** it is the distance between the Center of Buoyancy and the Metacenter. It is actually the radius of the circle for the movements of "B" at small angles of heel.

$$BM = (B_{ch}^2 \times (0.0106 + 0.0727 \times C_{wl}^{ch}) \times C_{wl}^{ch} \times B_{ch} \times L_{ch}) +$$
$$2 \times [((B_{sh}^2 \times (0.0106 + 0.0727 \times C_{wl}^{sh}) + b^2) \times C_{wl}^{sh} \times B_{sh} \times L_{sh}]/(V_{ch} + 2 \times V_{sh})$$

EQUATION 48

Where,

$$b = \frac{(1+\alpha) \times B_{ch}}{2} + \frac{B_{sh}}{2}$$

EQUATION 49

G - Center of Gravity: The point at which all forces of gravity acting on the ship can be considered to act. "G" is the center of mass of the vessel (Figure 3).

Vertical center of gravity for the center hull (KG_{ch}) is calculated as,

$$KG_{ch} = F_{ch} \times T_{ch}$$

EQUATION 50

Where,

F_{ch} = is the proportionality factor assumed to be 1.

Vertical center of gravity for center hull (KG_{sh}) is calculated as,

$$KG_{sh} = F_{sh} \times T_{sh}$$

EQUATION 51

Where,

F_{sh} = is the proportionality factor assumed to be 1.

Vertical center of gravity for the trimaran is calculated as,

$$KG = (KG_{ch} \times V_{ch} + 2 \times KG_{sh} \times V_{sh})/(V_{ch} + 2 \times V_{sh})$$

EQUATION 52

B - Center of Buoyancy: The geometric center of the ship's underwater hull body. It is the point at which all of the forces of buoyancy may be considered to act in a vertically upward direction (refer to Figure 2).

Vertical center of buoyancy for the center hull (KB_{ch}) is calculated as,

$$KB_{ch} = [T_{ch} \times (2.5 - C_b^{ch} / C_{wl}^{ch})] / 3 \qquad \textit{EQUATION 53}$$

Where,

$$C_{wl}^{ch} = 0.75$$

Vertical center of buoyancy for the side hull (KB_{sh}) is calculated as,

$$KB_{sh} = [T_{sh} \times (2.5 - C_b^{sh} / C_{wl}^{sh})] / 3 \qquad \textit{EQUATION 54}$$

Where,

$$C_{wl}^{ch} = 0.75$$

Vertical center of buoyancy is calculated as,

$$KB = (KB_{ch} \times V_{ch} + 2 \times KB_{sh} \times V_{sh}) / (V_{ch} + 2 \times V_{sh}) \qquad \textit{EQUATION 55}$$

K - Keel: The base line reference point from which all other reference point measurements are compared. (Figure 3).

GMt - Metacentric Height: This measurement is calculated by adding vertical center of buoyancy (KB) and metacentric radius (BM) and subtracting vertical center of gravity (KG). GM is a measure of the ship's initial stability (Figure 4).

$$GM_T = KB + BM - KG \qquad \textit{EQUATION 56}$$

3.3 Lightship Weight

This section provides an explanation of the formulation of weights. The lightship weight (LWT) or the Total weight of the trimaran is divided into four types: hull weight (W_{hull}), outfit weight (W_o), machinery and propulsion weight (W_m) and miscellaneous weight ($W_{LWT-misc}$).

$$LWT = W_{hull\_no\_deck} + W_{m\_GT} + W_{m\_diesel} + W_o + W_{LWT-misc}$$

EQUATION 57

The hull weight is the sum of the center hull weight, the side hull weight, the superstructure weight, Weight of bridge deck (W_{deck}) and the hull miscellaneous weights ($W_{hull-misc}$). The deck weight depends, however, on the dimension and number of decks, which are determined in the payload section (section 3.4). All other weights related to the ship are calculated in the Lightship section. The variables which come out of the Lightship calculation section are thus the Hull Weight ($W_{hull\_no\_deck}$) and Lightship Weight without deck (*LWT*).

$$LWT = W_{hull\_no\_deck} + W_{m\_GT} + W_{m\_diesel} + W_o + W_{LWT-misc}$$

EQUATION 58

With

$$W_{hull\_no\_deck} = W_{ch} + \left(2 \times W_{sh}\right) + W_{ss} + W_{hull-misc}$$

EQUATION 59

The hull weight without deck is calculated in the next subsection. The other weights are calculated in the following subsections.

Hull Weight ($W_{hull\_no\_deck}$) estimate without deck

The hull weight is comprised of the main hull structure (Weight of Center Hull (W_{ch}) and Weight of Side Hull (W_{sh}), superstructure weight (W_{ss}), Weight of bridge deck (W_{deck}), and hull miscellaneous weights ($W_{hull-misc}$), which constitute masts, kingposts, foundations, bulwarks, ramps, etc.

Weight of Center Hull (W_{ch})

The Weight of the Center Hull is the product of the Slenderness of the center hull (Sl_{ch}), the Volume of depth displacement for the center hull (Vd_{ch}), and the Center hull weight dimensional coefficient (K_{ch}).

$$W_{ch} = (0.1 \times Sl_{ch} + 0.2) \times Vd_{ch} \times K_{ch}$$

<div align="right">EQUATION 60</div>

Where, the Volume of depth displacement (Vd_{ch}) is the product of the block coefficient of depth volume of the center hull (C_{ch}^{d}), length of center hull (L_{ch}), beam of center hull (B_{ch}) and Height Water Clearance of center hull (HWC_{ch}),

$$Vd_{ch} = C_{ch}^{d} \times L_{ch} \times B_{ch} \times HWC_{ch}$$

<div align="right">EQUATION 61</div>

Where,

$$HWC_{ch} = (1 + h_{wc}) \times T_{ch}$$

<div align="right">EQUATION 62</div>

HWC_{ch} is the relative height of water clearance; its recommended value for initial optimization trials is $h_{wc} = 1$.

HWC_{ch} is in [m] and is the distance between the Center hull baseline and the bottom of the trimaran cross deck.

$$C_{ch}^{d} = \left(\frac{C_{b}^{ch}}{C_{m}^{ch}} \right) \left(\frac{T_{ch}}{HWC_{ch}} \right) \times \left(C_{m}^{ch} + \frac{\left(HWC_{ch} - T_{ch} \right)}{T_{ch}} \right)$$

<div align="right">EQUATION 63</div>

Where,

C_{m}^{ch} = 0.75 which is the Midship coefficient of center hull.
K_{ch} = 0.075 tons/m3

Weight of Side hull (W_{sh})

The formulation is being done for conventional type of side hull as well as for the SWA type of side hull.

a) *Conventional type*: Weight of the side hull is the product of Slenderness of the side hull (Sl_{sh}), Volume of depth displacement for side hull (Vd_{sh}), and the Side hull weight dimensional coefficient (K_{sh_conv}).

$$W_{sh} = (0.05 \times Sl_{sh} + 0.6) \times Vd_{sh} \times K_{sh\_conv}$$
<div align="right">EQUATION 64</div>

Volume of depth displacement (Vd_{sh}) is the product of the block coefficient of the depth volume of the side hull (C_{sh}^d), the length of the side hull (L_{sh}), the beam of the side hull (B_{sh}), and the depth of the side hull (HWC_{sh}).

$$Vd_{sh} = C_{sh}^d \times L_{sh} \times B_{sh} \times HWC_{sh}$$
<div align="right">EQUATION 65</div>

Where,

$$HWC_{sh} = H_{ship} - (T_{ch} - T_{sh})$$
<div align="right">EQUATION 66</div>

$$C_{sh}^d = \left(\frac{C_b^{sh}}{C_m^{sh}}\right)\left(\frac{T_{sh}}{HWC_{sh}}\right) \times \left(C_m^{sh} + \frac{(HWC_{sh} - T_{sh})}{T_{sh}}\right)$$
<div align="right">EQUATION 67</div>

Where,

C_m^{sh} = 0.75 which is the Midship coefficient of the side hull.
K_{sh_conv} = 0.1 tons/m3

b) *SWA Type*: Weight of the side hull is the product of Volume of depth displacement for side hull (Vd_{sh}) and Side hull weight dimensional coefficient (K_{sh_swa}).

$$W_{sh} = Vd_{sh} \times K_{sh\_swa}$$
<div align="right">EQUATION 68</div>

Where,

K_{sh_swa} = 0.13 tons/m^3

Weight of Superstructure (W_{ss})

Weight of the superstructure depends on the Number of Crew (N_{crew}) and the Number of Passengers (N_{pas}), Volumetric displacement (V) and the Superstructure Weight Dimensional Coefficient (K_{ss}).

$$W_{ss} = [(N_{crew} + N_{pas})/(470+0.94)] \times K_{ss} \times (V_{ch} + 2 \times V_{sh})$$
<div align="right">*EQUATION 69*</div>

Where, we assume

N_{crew} = 18
N_{pas} = 12
K_{ss} = 0.04 tons/m3

Miscellaneous Weights ($W_{hull-misc}$)

Miscellaneous weights is the product of the Miscellaneous Weight Dimensional Coefficient ($K_{hull-misc}$) and the sum of the volume displacement of the center hull and the side hull.

$$W_{hull-misc} = K_{hull-misc} \times (V_{ch} + 2 \times V_{sh})$$
<div align="right">*EQUATION 70*</div>

Where,

$K_{hull-misc}$ = 0.025 tons/m3

3.3.2   *Outfit Weight (W_o) estimate*

The parts that add up to the outfit weight include: joiner bulkheads, hawse pipes, deck fittings, cargo booms, hatch covers, anchors, rudder and stock, gallery equipment, non-propulsion mechanical equipment such as deck, machinery, steering engine, generators, ventilation systems, refrigeration systems, hull, piping systems and pumps, and electrical systems. Outfit Weight is the product of the volume of depth displacement (Vd) and a dimensional statistic coefficient (K_o).

$$W_o = K_o \times Vd$$
<div align="right">*EQUATION 71*</div>

Where,

$$Vd = Vd_{ch} + 2 \times Vd_{sh}$$ <div align="right">*EQUATION 72*</div>

K_o =0.03 tons/m3

3.3.3   *Machinery & Propulsion Weight (W_m) estimate*

Machinery & Propulsion weight depends on the power generated for gas turbines (P_{GT}) and the power generated for diesel engines (P_{diesel}).

$$W_{m\_GT} = K_{m\_GT} \times P_{GT}$$ <div align="right">*EQUATION 73*</div>

$$W_{m\_diesel} = K_{m\_diesel} \times P_{diesel}$$ <div align="right">*EQUATION 74*</div>

Where,
K_{m_GT} =13 tons/MW for gas turbine engines
K_{m_diesel} =25 tons/MW for diesel machinery
P_{GT} & P_{diesel} are calculated in section 3.1.3 of the powering model.

3.3.4   *Miscellaneous Weight ($W_{LWT-misc}$) estimate*

The Miscellaneous weight is the product of the Total volume of depth displacement (Vd) and the dimensional statistic coefficient ($K_{LWT-misc}$).

$$W_{LWT-misc} = K_{LWT-misc} \times Vd$$ <div align="right">*EQUATION 75*</div>

Where,

$K_{LWT-misc}$ =0.02 tons/m3

3.4   <u>Payload</u>

In this subsection, the Total Cargo Area needed to carry the Payload is solved in the function of the Payload and the LightShip Weight, which depends upon the size and number of decks. The cargo area required to carry the payload is evaluated, and since the number of decks and Payload are *a priori* unknown, we need to calculate the Payload. It can be expressed as

$$Payload = \left(\frac{DWT}{1.1} \right) - WFUEL$$

EQUATION 76

With

$$DWT = Displ - LWT$$

EQUATION 77

And *LWT* being the only unknown. The Weight of Fuel is known and can be calculated as a function of the Power requirements for the ship (see next subsection).

So, we can calculate.

$$DWT = Displ - LWT_{no\_deck} - W_{deck}$$

EQUATION 78

With W_{deck} being the unknown,

$$Payload = \left(\frac{Displ - LWT_{no\_deck} - W_{deck}}{1.1} \right) - WFUEL$$

EQUATION 79

There must be enough area to carry the Payload, the Required Cargo Area (R_CARGO_{area}):

$$R\_CARGO_{area} = Payload \times STOW_{TEUTRAI}$$

EQUATION 80

The Available Cargo Area ($CARGO_{area}$) depends on the size and dimension of the deck(s) and can be expressed as follows:

$$CARGO_{area} = N_d \times (NTEUTRAI_{rows} - 1) \times Area\_C_{deck}$$

EQUATION 81

Where, for Trailers, the number of rows $NTEUTRAI_{rows}$ = 2 and for TEU cargo, $NTEUTRAI_{rows}$ value can be set to any number of rows but chosen to be 2 in this application.

We must have

$$R\_CARGO_{area} = CARGO_{area} \qquad \qquad EQUATION\ 82$$

We can now combine equations 79, 80 and 81 and solve for the Total Deck Area.

$$N_d \times (NTEUTRAI_{rows} - 1) \times Area\_C_{deck} = \left[\left(\frac{Displ - LWT_{no\_deck} - W_{deck}}{1.1}\right) - WFUEL\right] \times STOW_{TEUTRAI}$$

EQUATION 83

$$N_d \times (NTEUTRAI_{rows} - 1) \times Area\_C_{deck} + \frac{W_{deck}}{1.1} \times STOW_{TEUTRAI} = \left[\left(\frac{Displ - LWT_{no\_deck}}{1.1}\right) - WFUEL\right] \times STOW_{TEUTRAI}$$

EQUATION 84

$$N_d \times (NTEUTRAI_{rows} - 1) \times Area\_C_{deck} + \frac{K_{bd} \times N_d \times Area\_C_{deck}}{1.1} \times STOW_{TEUTRAI} =$$
$$\left[\left(\frac{Displ - LWT_{no\_deck}}{1.1}\right) - WFUEL\right] \times STOW_{TEUTRAI}$$

EQUATION 85

We finally find the Total Deck Area needed to carry the Payload:

$$Total\_Deck\_Area = N_d \times Area\_C_{deck} = \frac{\left[\left(\frac{Displ - LWT_{no\_deck}}{1.1}\right) - WFUEL\right] \times STOW_{TEUTRAI}}{\left((NTEUTRAI_{rows} - 1) + \frac{K_{bd}}{1.1} \times STOW_{TEUTRAI}\right)}$$

EQUATION 86

Let us define

$$Area\_C_{deck-MAX} = CDAU \times BOL \times L_{d\_MAX} \qquad \qquad EQUATION\ 87$$

$$BOL = \left[B_{ch} \times (1 + \alpha)\right] + 2 \times B_{sh} \qquad \qquad EQUATION\ 88$$

$$L_{d\_MAX} = a + 1.25 \times \lambda_{sh} \times L_{ch}$$

<div align="right">*EQUATION 89*</div>

$$N_{d\_MAX} = 4$$

<div align="right">*EQUATION 90*</div>

$$a = \beta \times L_{ch} \times (1 - \lambda_{sh})$$

<div align="right">*EQUATION 91*</div>

$$N_d = \min(ceil(\frac{Total\_Deck\_Area}{Area\_C_{deck\_MAX}}), N_{d\_MAX})$$

<div align="right">*EQUATION 92*</div>

The Number of Decks equation is calculated as the minimum of either rounding (ceiling function) up to the nearest integer the ratio ($\frac{Total\_Deck\_Area}{Area\_C_{deck\_MAX}}$) or the maximum number of decks N_{d_MAX}. The trimaran is supposed to have less than 5 decks ($N_{d\_MAX.}$ = 4).

And the Deck Area can be calculated as the minimum of the ratio $\frac{Total\_Deck\_Area}{N_d}$ or the maximum deck Area.

$$Area\_C_{deck} = \min(\frac{Total\_Deck\_Area}{N_d}, Area\_C_{deck\_MAX})$$

<div align="right">*EQUATION 93*</div>

Now the deck Length can be calculated (we assume that the Beam Overall length is defined by the current positioning of the side hulls) so $BOL = [B_{ch} \times (1 + \alpha)] + 2 \times B_{sh}$.

$$L_d = \frac{Area\_C_{deck}}{CDAU \times BOL}$$

<div align="right">*EQUATION 94*</div>

In addition, the deck weight, the Number of TEU/Trailers can now be calculated:

$$W_{deck} = K_{bd} \times N_d \times Area\_C_{deck}$$

<div align="right">*EQUATION 95*</div>

$$W_{hull} = W_{hull\_no\_deck} + W_{deck}$$
$$LWT = LWT_{no\_deck} + W_{deck}$$

<div align="right">*EQUATION 96*</div>

$$N_{TEUTRAI} = \text{int} \left(\frac{CARGO_{area}}{STOW_{TEUTRAI} \times W_{TEUTRAI}} \right)$$

<div align="right">EQUATION 97</div>

With

$$CARGO_{area} = (NTEUTRAI_{rows} - 1) \times N_d \times Area\_C_{deck}$$

<div align="right">EQUATION 98</div>

The payload can now be calculated as a function of the number of trailers

$$Payload = N_{TEUTRAI} \times W_{TEUTRAI}$$

<div align="right">EQUATION 99</div>

We can now introduce the constraint on the payload:

$$G6 = \frac{Payload_{MIN}}{Payload} \leq 1$$

<div align="right">EQUATION 100</div>

The Annual Cargo can now be calculated:

$$AnnualCARGO = Payload \times NTRIP$$

<div align="right">EQUATION 101</div>

With

$$NTRIP = TOP \times 24 / T_{trip}$$

<div align="right">EQUATION 102</div>

$$T_{trip} = T_{full-speed} + T_{pilot} + T_{aux}$$

<div align="right">EQUATION 103</div>

$$R_{pilot} = 50 \text{ nm}$$
$$V_{pilot} = 10 \text{ knots}$$

$$T_{pilot} = R_{pilot} / V_{pilot} = 5\ HRS \qquad\qquad \textit{EQUATION 104}$$

$$T_{aux} = 5\ HRS \qquad\qquad \textit{EQUATION 105}$$

$$T_{full-speed} = (R - R_{pilot}) / V_k \qquad\qquad \textit{EQUATION 106}$$

Weight of Fuel

The total weight of fuel is the sum of the weight of fuel at full speed ($WFUEL_{full-speed}$), the weight of fuel at pilotage ($WFUEL_{pilot}$), and the weight of fuel for auxiliary engines ($WFUEL_{aux}$).

$$WFUEL = WFUEL_{full-speed} + WFUEL_{pilot} + WFUEL_{aux} \qquad\qquad \textit{EQUATION 107}$$

Weight of fuel at full speed ($WFUEL_{full-speed}$)

Weight of fuel at full speed is the product of specific fuel consumption (SFC), time at full speed per trip ($T_{full-speed}$) and power at full speed $P_{full-speed}$:

$$WFUEL_{full-speed} = (SFC_{GT} \times P_{GT} + SFC_{diesel} \times P_{diesel}) \times T_{full-speed} \qquad\qquad \textit{EQUATION 108}$$

Where,

$$T_{full-speed} = (R - 50) / V_k \qquad\qquad \textit{EQUATION 109}$$

Where,

R = 800nm
V_k is a design variable.
SFC_{GT} = 0.210 kg per hour and per kW for gas turbine at full speed
SFC_{diesel} =0.16 kg/hr/kW for diesel at full speed.

Weight of fuel at PILOTAGE ($WFUEL_{pilot}$)

Weight of fuel at pilotage is the product of specific fuel consumption at pilotage (SFC_{pilot}), time at pilotage (T_{pilot}), and required power for low speed – for pilotage (P_{pilot}).

$$WFUEL_{pilot} = SFC_{pilot} \times T_{pilot} \times P_{pilot}$$

<div align="right">EQUATION 110</div>

Where,

SFC_{pilot} = 0.25 for diesel at pilotage. T_{pilot} = 5 hrs

P_{pilot} is calculated as

$$P_{pilot} = P_{full-speed} \times 1000/(V_s^3)$$

<div align="right">EQUATION 111</div>

Weight of fuel for auxiliary engines ($WFUEL_{aux}$)

Weight of fuel for auxiliary engines is the product of engines time (auxiliary engines for generators) (T_{aux}) and power of auxiliary engines (P_{aux}).

$$WFUEL_{aux} = SFC_{aux} \times T_{aux} \times P_{aux}$$

<div align="right">EQUATION 112</div>

SFC_{aux} = 0.16

T_{aux} = 5 hrs

P_{aux} is 1% of required power at full speed ($P_{full-speed}$) and is formulated as,

$$P_{aux} = 0.01 \times P_{full-speed}$$

<div align="right">EQUATION 113</div>

<div align="center">Height of ship</div>

The height of the ship depends on HWC_{ch}, deck clearance ($Deck_{cl}$), Number of decks (N_d), and height of deck structure ($H_{deck\_structure}$).

$$D_{ch} = HWC_{ch} + Deck_{cl} \times (N_d - 1) + H_{deck\_structure}$$

<div align="right">EQUATION 114</div>

$Deck_{cl}$ is the Cargo Deck Clearance in [m] and is the distance between the cargo decks. The recommended value for initial optimization is 2.25m.

$H_{deck\_structure}$ is Deck Structure Height, which is the distance between the first cargo deck and Height of Water Clearance (HWC_{ch}). The recommended value for initial optimization is 2.25m.

3.5 <u>Cost</u>

3.5.1   Building Cost

The ship building cost calculated in ($) is an estimate that is based on light ship weight. The light ship weight includes the material that is used for the trimaran construction (It consists of: the hull weight; machinery weight; the outfit weight; and miscellaneous weight). The ship cost is the sum of hull cost (C_HULL), machinery cost ($C_MACHINERY$), outfit cost (C_OUTFIT) and miscellaneous cost (C_MISC).

$$SCOST = C\_HULL + C\_MACHINERY + C\_OUTFIT + C\_MISC$$

EQUATION 115

Cost of hull

The Manufacturing cost incurred for the hull consists of the hull weight (W_{hull}), the productivity rate for hull manufacturing and assembly (H_H), the labor rate for hull construction (R_H), and the relative material costs for hull (M_H). The hull cost is formulated as given below,

$$C\_HULL = W_{hull} \times (H_H \times R_H + M_H)$$

EQUATION 116

Where,

W_{hull} is calculated from the light ship weight model.
H_H = 90 hrs/ton
R_H = 50 $/hr
M_H = 720 $/ton

Cost of Machinery

Machinery cost consists of Machinery & propulsion weight (W_m), the productivity rate for machinery assembly & installation (H_M), the labor rate for machinery installation (R_M), and relative material costs for machinery (M_M). The Machinery cost is formulated as below,

$$C\_MACHINERY = W_m \times (H_M \times R_M + M_M)$$

<div align="right">*EQUATION 117*</div>

Where,

W_m is calculated from light ship weight model.
H_M = 120 hrs/ton.
R_M = 60 $/hr.
M_M = 27800 $/ton for gas turbines and 10000 $/ton for diesel engines.

Cost of Outfit

Outfit cost consists of the Outfit weight (W_o), the productivity rate for outfit systems (H_o), the labor rate for outfit works (R_o), and the relative material costs for the outfit (M_o). Outfit cost is formulated as below,

$$C\_OUTFIT = W_o \times (H_o \times R_o + M_o)$$

<div align="right">*EQUATION 118*</div>

Where,

W_o = Outfit weight is calculated from light ship weight model
H_o = 80 hrs/ton
R_o = 50 $/hr
M_o = 4000 $/ton

Miscellaneous Costs

Miscellaneous costs consist of light ship weight miscellaneous weight ($W_{LWT-misc}$), productivity rate for other systems (H_{misc}), labor rate for engineering and shipyard support (R_{misc}) and relative material costs for electric, electronics, navigation ($M_{LWT-misc}$).

$$C\_MISC = W_{LWT-misc} \times M_{LWT-misc} + LWT \times (H_{misc} \times R_{misc})$$

EQUATION 119

Where,
$W_{LWT-misc}$ is calculated from light ship weight model
LWT = total light ship weight calculated from light ship weight model
H_{misc} = 15 hrs/ton
R_{misc} = 60$/hr
$M_{LWT-misc}$ = 17500 $/ton

Operating Cost

This section deals with the income statement on the operating expenses that arise during the short sea shipping operations. Operating expense consists of salaries paid to employees, Vessel maintenance, machinery maintenance, annual fuel costs, annual cargo handling and other costs incurred. The cost is calculated in term of U.S. Dollars ($).

Annual Operating Expenses

Vessel Payroll

The payroll for the crew is considered on an annual basis. The vessel payroll is the product of the number of crew (N_{crew}) and the average annual cost of 1 member of the crew (AAC_{crew}).

$$C_{crew} = N_{crew} \times AAC_{crew}$$

EQUATION 120

Where,

N_{crew} = 18
AAC_{crew} = 140000 \$/year

Vessel Maintenance & Insurance

The vessel maintenance and insurance is proportional to the general annual cost of ship maintenance ($COST_{maint}$), annual insurance cost ($COST_{ins}$) and ship cost ($SCOST$).

$$C_{M\&I} = (COST_{maint} + COST_{ins}) \times SCOST$$

<div align="right">*EQUATION 121*</div>

Where,

$COST_{maint}$ = 1% of $SCOST$
$COST_{ins}$ = 0.8% of $SCOST$

Annual Consumables and Supplies

The annual consumables and supplies depend on the provision and hotel supply ($COST_{supply}$), the number of crew (N_{crew}), the number of passengers (N_{pas}), and the annual operational period (TOP).

$$C_{C\&S} = COST_{supply} \times (N_{crew} + N_{pas}) \times TOP$$

<div align="right">*EQUATION 122*</div>

Where,

$COST_{supply}$ = 100 \$/day/1person.
N_{crew} = 18
N_{pas} = 12
TOP = 350

Annual Cost of Machinery Maintenance

Annual cost of machinery maintenance ($C - M_M$) depends on the cost of machinery maintenance for gas turbines ($COST\_M_{maint}GT$), the cost of machinery maintenance for diesel engines ($COST\_M_{maint}diesel$), Total time for trip (T_{trip}), number of gas turbines (N_{GT}), number of diesel engines (N_{diesel}).

$$C\_M_M = (COST\_M_{maint}diesel \times N_{diesel} + COST\_M_{maint}GT \times N_{GT}) \times T_{trip}$$

EQUATION 123

where,

$COST\_M_{maint}diesel$ for gas turbine is $ 150 per 1 hour.
$COST\_M_{maint}GT$ =$ 25 per 1 hour of diesel operations.

Annual Fuel Costs (ACF)

Annual cost of fuel is the product of the number of trips ($NTRIP$), cost of fuel ($COST\_FUEL$) and total weight of fuel ($WFUEL$).

$$ACF = NTRIP \times COST\_FUEL \times WFUEL$$

EQUATION 124

where,

$NTRIP$ is calculated from payload model
$COST\_FUEL$ = 400 $/ton
$WFUEL$ can be calculated from payload model.

Annual Cost of Lube Oil (for GT) ($ACLO$)

Annual cost of lube oil is the product of specific lube oil consumption ($SLOC$), the number of gas turbine engines (N_{GT}), time at full speed per trip ($T_{full-speed}$), and the cost of lube oil ($COST_{LUBE}$).

$$ACLO = COST_{LUBEOIL} \times SLOC \times N_{GT} \times T_{full-speed}$$

EQUATION 125

Where,

$SLOC$ = 0.45 kg/hr for gas turbines.

$COST_{LUBE}$ = 8.96 \$/kg

$$\text{Cost of Pilotage } (AC_{Pilot})$$

Cost of pilotage (AC_{Pilot}) is the product of pilotage cost per port ($COST_{pilot}$), and twice the number of trips ($NTRIP$).

$$AC_{Pilot} = COST_{pilot} \times 2 \times NTRIP \qquad \qquad \textit{EQUATION 126}$$

Where,

$COST_{pilot}$ = 650 \$/port

$$\text{Annual Cost of Cargo Handling } (AC_{CH})$$

Annual cost of cargo handling is the product of twice the number of equivalent 20` containers (TEU)/Trailers per trip ($N_{TEUTRAI}$), cargo handling cost at port (TEU) ($COST_{TEUTRAI}$), and number of trips ($NTRIP$).

$$AC_{CH} = 2 \times N_{TEUTRAI} \times COST_{TEUTRAI} \times NTRIP \qquad \qquad \textit{EQUATION 127}$$

Where,

$N_{TEUTRAI}$ is calculated from payload model.

$COST_{TEUTRAI}$ = \$ 125 for TEU and \$ 30 for trailer. The cost is calculated in US Dollars \$/1container.

$$\text{Capital Costs}$$

Annual capital cost is the product of capital cost coefficient ($KOEF_{cap\_cost}$) and the ship cost ($SCOST$).

$$ACC = KOEF_{cap\_cost} \times SCOST \qquad \qquad \textit{EQUATION 128}$$

Where,

$KOEF_{cap\_cost}$ = 0.115

Annual Cost per 1 vessel fleet

Annual cost of fleet is the sum of the payroll for the crew (C_{crew}), cost of vessel maintenance and insurance ($C_{M\&I}$), cost of consumables and supplies ($C_{C\&S}$), annual cost of machinery maintenance (C_M_M), annual cost of fuel (ACF), annual cost of lube oil ($ACLO$), cost of pilotage (AC_{Pilot}), annual cost of cargo handling (AC_{CH}), and annual capital cost (ACC).

$$ACFLEET = C_{crew} + C_{M\&I} + C_{C\&S} + C\_M_M + ACF + ACLO + AC_{Pilot} + AC_{CH} + ACC$$

EQUATION 129

Annual Freight Volume per 1 vessel fleet

Annual freight volume per 1 vessel fleet is the product of the number of equivalent 20` containers (TEU)/trailers per trip ($N_{TEUTRAI}$) and number of trips ($NTRIP$).

$$AF_{volume} = N_{TEUTRAI} \times NTRIP$$ *EQUATION 130*

Required Freight Rate (RFR)

Required freight rate includes the annual cost of fleet ($ACFLEET$), annual freight volume (AF_{volume}) and range/length of shipping line of operation (R). RFR is calculated in \$/TEU/nm or \$/Trailer/nm

$$RFR = ACFLEET / AF_{volume} / R$$ *EQUATION 131*

4.   Results:

4.1   CO estimation with Training Set and Validation Set

The Neural Network was trained with a Training Set of 578 points and a Validation Set of 17 points. The Validation set was obtained by combining the original set from SAIC and adding a Latin Hypercube distribution of interior points. The stopping criterion used for stopping is the stopping criterion PQ<0.075 [Reference 6]. The Network was trained with 7 candidate hidden units (HUs) and 10 Networks were generated from which the one with the best minimum

validation error was chosen. The range of the DV's is compatible with the range of the variables for the optimization, i.e:

$$\begin{cases} 6 \le Sl \le 12 \\ 0 \le \beta \le 1 \\ 0 \le \alpha \le 2 \\ 0.2 \le F_n \le 1 \end{cases}$$

EQUATION 132

The Training and Validation Set points were calculated using the MQLT method [Reference 5]. The Training and Validation Sets are in Appendix A. Also, a Validation Set of 17 points was calculated with the MQLT method using a Latin Hypercube distribution in the same range of variables as defined above. The Validation Set (VS) is used to tell the Neural Network (NNet) when to stop training on the TS [Ref 2]. This VS ensures that the NN does not over fit the TS and performs well everywhere in the training space defined by the min. and max. values for each variable. The resulting NNet has the number of HUs that leads to the minimum squared error on the validation set *(E2/p)* (31 HUs).

$$(E2/P) = \frac{1}{2 \cdot P\max} \sum_{p=1}^{P\max} \left\| y_p - t_p \right\|^2$$

EQUATION 133

Where *Pmax* is the size of the set used to calculate the error (here the VS), y_p is the output for the pth pattern from the NNet, and $t_{,p}$ is the corresponding target.

The following figures show the relative error (in percentage) on the Validation set for the TS and VS on the network. The relative error (*Error*) is defined as:

$$Error = \left| \frac{(y_p - t_p)}{\frac{1}{P\max} \sum_{p=1}^{P\max} t_p} \right| \cdot 100$$

EQUATION 134

As can be seen, the maximum relative error on the VS is 24.1% (Figure 1). Also,
Table 3 shows the results on the squared error and the relative error on the TS and VS. The average error is 10% on the VS. At this point, it should be added that the CO accounts for about 2/3 of the drag and, as such, the average percentage error on the drag would be around 6.7%.
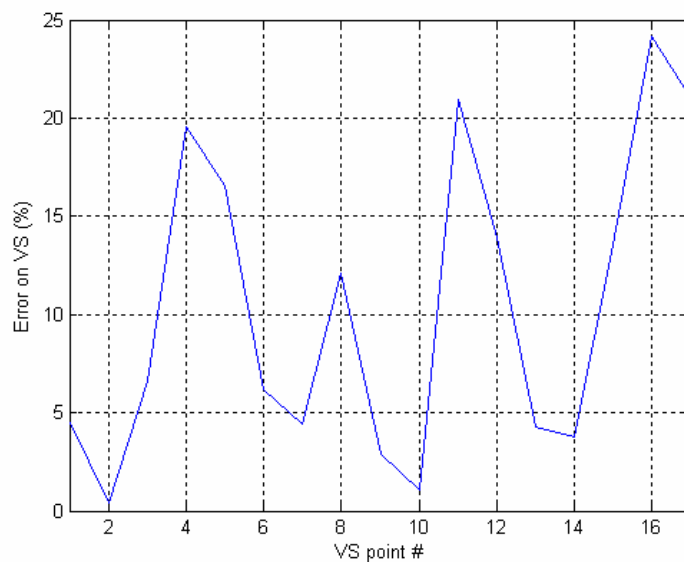
FIGURE 5: ERROR ON THE VALIDATION SET USING NNET (16 HUS).
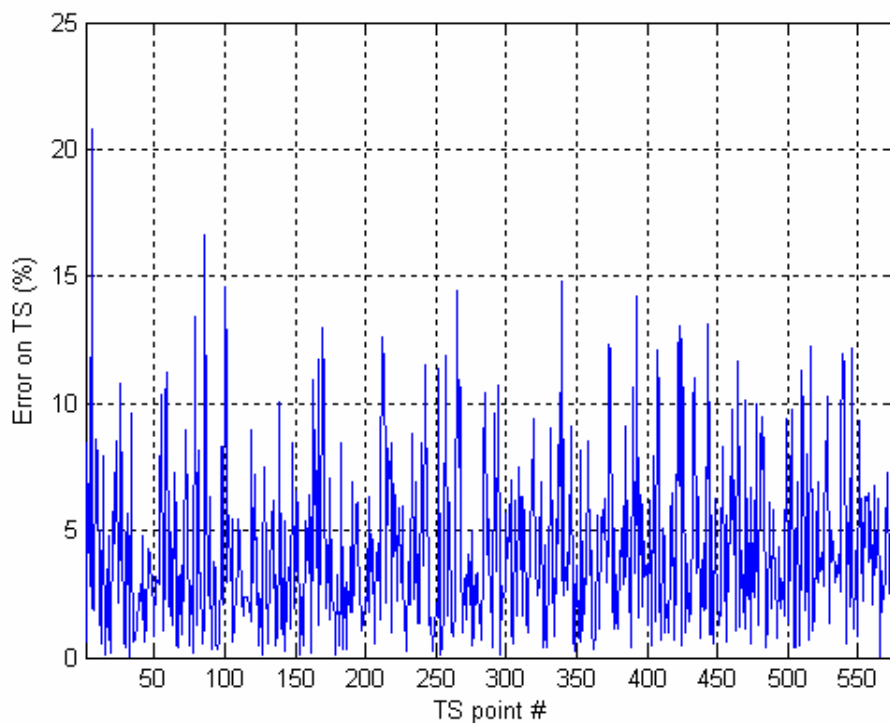
FIGURE 6: ERROR ON THE TRAINING SET.

TABLE 3: SUMMARY RESULTS OF NEURAL NETWORK TRAINING

	(E2/P) in %	Max(Error) in %	Average Error in %	Standard deviation of Error (%)
TS with NNet	.14	20.4	4.2	6.0
VS with NNet	.82	24.1	10.0	7.8

4.2 <u>Optimization</u>

4.2.1 Single Objective

Three single objective optimizations were run using the NLPQL method from the iSIGHT [iSIGHT Task Plan]: Minimize RFR, Maximize Annual Cargo and Minimize Building Cost. Results are summarized in Table 4. Details corresponding to these results are presented in Appendix 2.

TABLE 4: SINGLE OBJECTIVE OPTIMIZATIONS RESULTS

Objective	Max Annual Cargo	Min. SCOST	Min. RFR
DV's			
Cbsh	0.6	0.45	0.6
Cbch	0.6	0.45	0.6
Vk	30	25	25
Bch	24	12	17.99
Bsh	8	3.91	7.88
Tch	12	4	11.99
lambda	0.1134	0.03	0.03
lamdash	0.6604	0.1	0.1107
Lch	222.20	122.64	206.60
Beta	0.0122	1	0.4414
alpha	0.5	2	1.29
OBJECTIVE			
AnnualCargo	**464,488**	21,000	262,710
SCOST	299,890,428	**16,658,916**	135,757,373
RFR	0.7951	1.18	**0.6313**
Some Dependent Variables			
Tsh	7.99	3.94	7.89
Sl	7.26	8.49	6.61
Displ	50,910	2,890	29195
Pfullspeed	177.50	13.31	46.62
Ndiesel	2	2	2
Ngt	4	0	2
GMt	15.52	12.40	2.74
Nd	4	1	4
Ld	184.37	44.99	108.73
BOL	52.0	43.83	56.99
Hship	33.0	10.25	32.99
Nteutrai	1,935	100	1251
LWT	28,148	1,716	15,112
ACFLEET	295,460,939	19,841,783	132,683,251

A single objective optimization run takes between 60 to 240 minutes CPU time on a PC. The CPU time depends on the cases, the number of iterations and the termination accuracy values that are defined. The results presented here are obtained with 200 iterations and a termination accuracy value of 0.0001, which were found to be optimum values.

The results overall seem reasonable. As expected, minimizing the ship cost has led to a minimal sized ship. Also as expected, minimum RFR and RFR corresponding to max annual cargo are close. The minimum RFR of approximately $.6 per TEU per mile appears to be less than what was expected, but still reasonable. This outcome is largely influenced by the machinery cost and other economic information in the model. Future revision of this information should influence the results.

 Since the purpose of these test runs are to demonstrate the method, the feasible set of design variables and constraints are intentionally chosen to be very broad. Therefore, the results indicate quite different ships. Overall the program is very robust and efficient, and is thus useful for various future detailed studies. The details of the program's operation (referred to as MDO-v1) are presented in the accompanying user manual [Reference 7].

4.2.2   Multiple Objective

Next, a Multi Objective Genetic Algorithm (Neighborhood Cultivation Genetic Algorithm – (NCGA)) was run in iSIGHT with two objectives; minimize Building Cost and Maximize Annual Cargo. The results presented here are obtained with a population of 100 in 50 generations, which was found to be the optimum based on previous experience. With these parameters the entire run takes approximately 24 hours of CPU time on a PC. The resulting Pareto plot is shown in Figure 7. Looking at this plot, the designer can decide which is the best annual cargo for a given ship cost and make a decision on an optimal design. The method is readily capable of considering more objective functions such as lightship mass or effectiveness, etc.

The Synthesis level model indicates a linear relationship between the two objective functions considered. The single criterion optimization result for min ship cost is the lower boundary of the Pareto plot. The Pareto plot however does not extend to the max annual cargo point although clearly the single criterion optimized value is on the extension of the Pareto plot. This result is not obvious and is subject to further study.

The results obtained so far indicate the method is very efficient and robust. The issue of Pareto Optimality for given mission requirements is of particular interest. Such studies and extensive verification of this synthesis model for several types of multihull ships - Trimarans, Cats, SWATHs, Pents etc. is planned for the next phase of the program. Dependence of an objective function (such as Annual cargo) for a given design variable (such as length of the center hull) shown in Figure 8 is more useful information provided by the method.
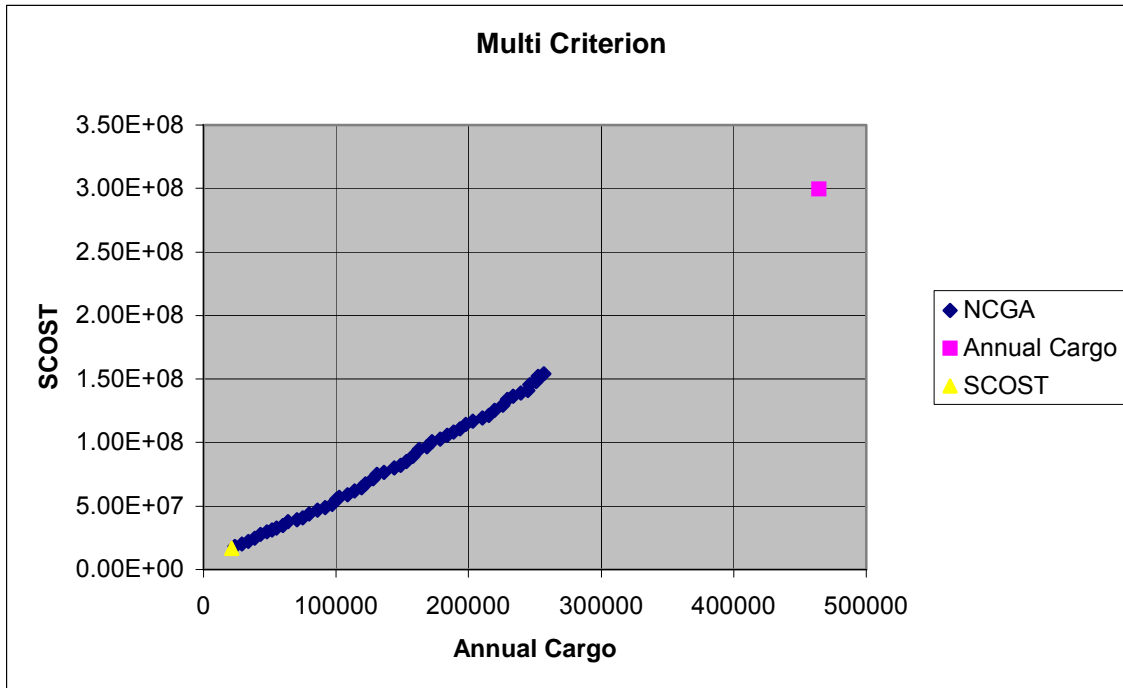
FIGURE 7 PARETO PLOT FOR NCGA OPTIMIZATION
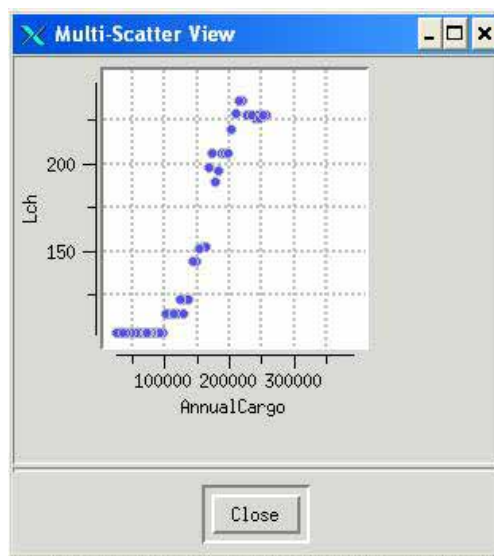
FIGURE 8 ANNUAL CARGO AS A FUNCTION OF CENTER HULL LENGTH

5. Future Extension of the Method:

As mentioned before, the focus of this first phase of the program was the development and demonstration of the synthesis level optimization tool MDO-v1 . This section describes the future extension of the method to include more advanced models for the prediction of powering, and the inclusion of seakeeping, as well as subsystem optimization models for hull shape and structures.

    5.1   <u>Powering</u>

We will continue to use the methodology described in section 3.1.2 for powering estimate. The approach is based on application of trained Neutral Networks in the optimization process.

5.1.1 Neural Networks in the design cycle

Because of the cost associated with the use of an extensive computer model such as advanced computational fluid dynamics tools and finite element methods, these are usually introduced later in the design process when general layouts have already been determined in the synthesis level design. Instead, the higher levels (synthesis level) rely on semi-empirical/analytical models for determining subsystem requirements. In addition, when they do get used at the lower levels, the cost associated with their use, both in terms of man and computer power required, usually limit the exploration of the design space.

Neural Networks offer the opportunity to indirectly insert these tools (via the NN) at all levels of the system design and on a much broader basis. The task then consists of having the specialist(s) who uses the advanced computational tool(s) (but who are often remotely connected to the design loop) integrate the design cycle by generating a computational database representative of the problem at hand over the desired design space. For example, the database might consist of a few hundred CFD analyses performed for a configuration represented by tens of widely varying design parameters. This database is then used to train – hence, its name, Training Set– a Neural Network which is then inserted in the design loop. At this point, the designer (not the specialist) can use the NN and get a solution for a variety of designs extremely rapidly.

Similar uses of Neural Networks can be made when dealing with the availability of large databases. Such databases may be from one or more sources, either numerical or

experimental. In this case, the database can be used to directly train the NN and the latter can be integrated into the design loop (Figure 9).
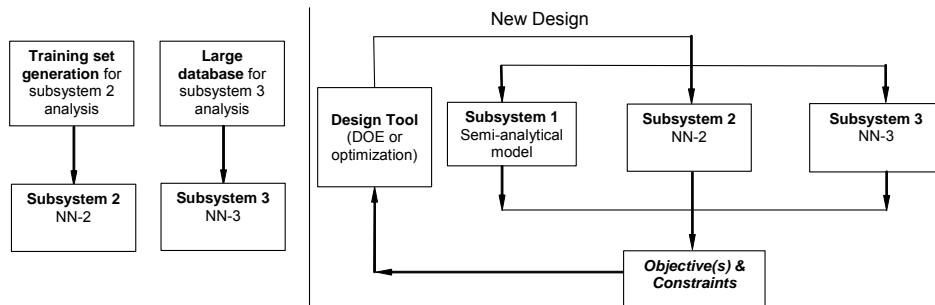
FIGURE 9: SYSTEM DESIGN LOOP UTILIZING NEURAL NETWORKS. THE NN'S ARE GENERATED OUTSIDE THE DESIGN LOOP BASED ON COMPUTATIONALLY EXTENSIVE MODELS AND/OR LARGE DATABASES.

The result is a design loop where the solution to a particular set of design variables, either selected by the designer or by the computer ("design tool") can be obtained quasi-instantaneously. Used in such fashion, NN are particularly well suited for problems, which exhibit the following characteristics:

- Problems with a large number of design variables (30 to 100)
- Approximation of functions (objective or constraints) with highly non-linear behaviors
- Availability of large databases
- Problems where the objective functions likely exhibit multiple minima/maxima.

In practical terms, the introduction of NN has allowed for the extraction of a time-consuming or difficult operation (performing an advanced numerical analysis or extracting information from a large and evolving database) from the design loop while still keeping their influence on the outcome of the design process via the NN. Instead, the cost has been moved to the training set generation (if it was not already available) and to the training of the network. This ability to efficiently evaluate new design, allows for the use of global optimization tools such as Genetic Algorithms instead of having to rely on local optimization methods or exploring a restricted part of the design space. The Neural Network methodology described above has been successfully applied by CSULB to the shape optimization under realistic operating conditions [Reference 8] as well as in the synthesis level-powering model of the present work as described in section 4 above.

Using MQLT for training and Validation sets for NNet

Similar to the approach of the synthesis level method, we will use a trained NN for the prediction of powering in the optimization process. Expanded training and validation sets using the MQLT method will be developed and used.

Developed in the previous CCDOTT projects, MQLT methodology is a numerical technique for high-speed trimaran resistance calculations. The technique is based on the modified viscous-inviscid interaction concept and the quasi-linear theory of wave resistance. The key element of the technique, which is called the Modified Quasi-Linear Theory (MQLT) method, is an account of Froude number influences on the ship trim, transom drag and wetted surface. This influence leads to the appearance of a drag component that significantly depends on both the Reynolds number and the Froude number.

The Modified QLT (MQLT) calculations of residuary drag of the trimaran take into account the following drag's components:

- Wave resistance at its dynamic trim and sinkage;
- Form resistance (including the transom's contribution);
- Friction's variation due to the dynamic variations of the wetted surface.

The application of MQLT to the Viscous-Inviscid Resistance calculations for resistance prediction in the multihull Hull Forms optimization subsystem and in the synthesis model is based on the following:

We define the coefficient of the total resistance as the following:

$$CT(F_N, R_E) = CW(F_N) + CFOR(F_N, R_E) + CF0(R_E) \qquad \text{\textit{EQUATION 135}}$$

Here
Fn – Froude number;
Re – Reynolds number;

CT – Coefficient of the total resistance;

CW – Coefficient of the wave resistance;

CFOR – Coefficient of the viscous-inviscid form resistance, which takes
account of transom, and form viscous-inviscid parts of the resistance
moreover, part of the friction drag due to the change of the dynamic wetted
surface. All components of the CFOR are dependent from Fn and Re.
CF0 – ITTC friction drag

Correspondingly, we would define:

CR(Fn, Re) = CW + CFOR, where CR – Coefficient of the residual resistance.

In model scale, formula (136) becomes:

$$CT_M = CW_M + CFOR_M + CF_{0M} = CR_M + CF_{0M}$$
<div align="right">*EQUATION 136*</div>

In addition, in the ship scale:

$$CT_S = CW_S + CFOR_S + CF_{0S} + CA$$
<div align="right">*EQUATION 137*</div>

where CA – correlation allowance coefficient, is taken {according to the David Taylor
Model Basin recommendation) to be "0" in the HALSS power prediction [Reference 9].

To calculate (Equation 138) we use conventional and new considerations based on MQLT
methodology and calculation results. The conventional approach is that CWm = CWs. Based on
MQLT, we take into account the viscous-inviscid interference drag components, thus we cannot
assume that CFORm = CFORs. The corresponding difference is defined in previous reports as
the Scale Correlation Coefficient – SCC. As estimated from the MQLT calculations and a
comparison of CRm and CRs, this coefficient can be introduced to Equation 138:

$$CT_S = CR_M + SCC + CA$$
<div align="right">*EQUATION 138*</div>

Where SCC = CRs – CRm = CFORs – CFORm

5.2   Seakeeping

The synthesis level model developed in this first phase of the program only includes the stability criterion in the optimization process. Seakeeping, of course, is an important aspect of ship design, which must be considered later in the design process.

For seakeeping calculations, Salvesen's strip theory method can be used. These calculations should be coupled with the hull forms generation procedure, which is described in the Hull Forms MDO Subsystem, as the proposed plan for further FY05-06 work. The usefulness of strip theory is more pronounced in the prediction of the shape of the response amplitude operator (RAO) curve near the resonance for the vertical ship responses. This is essential for the multihull and optimization procedures. To use this theory, the hull forms should be presented by the main parameters such as length, beam and draft, as well as by KB(x) – the centroid of the section. The three-dimensional panel code SWAN, described in the Structural Subsystem section, can be used for this purpose to assess the calm and rough water performance of the multihull hulls form; this code requires the mathematical representation of the hulls forms.

The seakeeping objective function of the MDO design procedure can be chosen in different ways which account for the characteristics of the RAO curves. For example, the objective functions can be chosen as the sum of the peak RAO values for vertical acceleration and relative motion at a point 0.1*Lch behind the forward perpendicular in head waves. The operability indexes currently in practice quantify the effect of seakeeping responses on humans, whereas the latter is related to the seakeeping events (slamming, deck wetness, etc.). Other responses with RAO curves exhibiting resonance as added resistance in waves, could also be included in the optimization functions. However, because added resistance depicts trends for multihulls similar to those of vertical acceleration and relative motion, its incorporation in the object function does not really affect the outcome of the optimization procedure and can be checked at the stage of analysis of the optimum design solution. Accounting for the seakeeping in MDO procedures demonstrates the Multi Criteria nature of ship design tasks.

6.   Subsystem Optimization Models:

In systems engineering, a system is decomposed into subsystems. For a ship design, those would correspond to the hull shape design, the propulsion system, structural design, the general /cargo arrangement subsystems, etc. This system decomposition approach, originated in the aerospace industry [Reference 10], can be applied at the ship design level as well as at lower levels in the system's architecture. For example, this systems approach may also be used to

design a particular piece of equipment, which will be integrated into the ship, based on requirements established at higher levels.

Following this approach, the design of a "system" usually includes the process shown in Figure 10. In practical cases, the "design tool" may be either an optimization or design-of-experiment (DOE) software, or a set of test cases identified by an experienced designer interested in conducting trade studies. The analyses performed at each subsystem level rely, in general, on a combination of semi-analytical models, advanced numerical methods such as CFD or finite element analysis, and the use of existing databases. In practical ship design problems, most subsystems analysis such as hull shape and structural design, are complex problems involving large numbers of design parameters and objective functions.
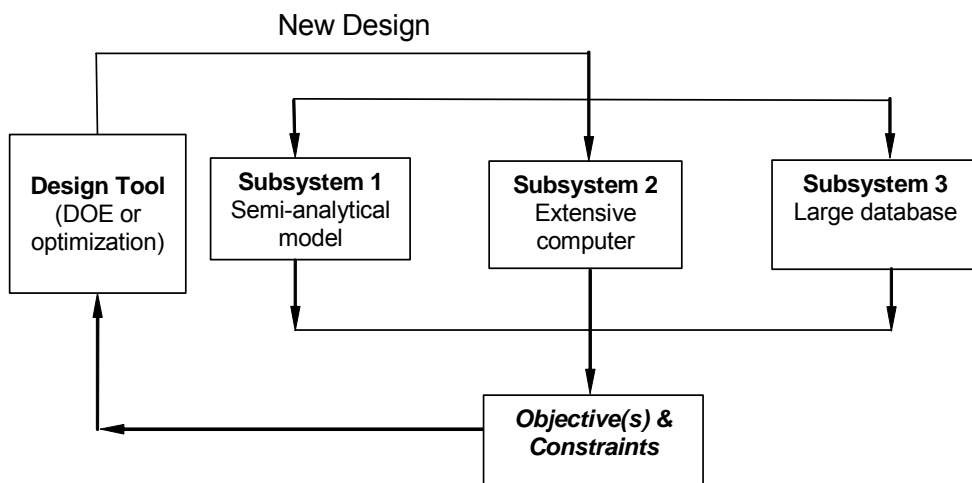
FIGURE 10: SCHEMATIC OF A DESIGN SYSTEM

Hull Shape Optimization

Many design evaluation methods, such as resistance, stability, seakeeping, calculation techniques, etc., use the major shape parameters of the hull to calculate their results. These parameters typically include length, beam draft, prismatic coefficient (Cp), longitudinal center of buoyancy (lcb), and midship coefficient (Cm). It is difficult to perform parametric or sensitivity studies using these techniques because all of the variables are interrelated and may change at the same time. For example, when a vessel's length is varied, its Cp, lcb and displacement values all change at the same time. It would be desirable to be able to change any one of these

major design variables, while maintaining constant values for the rest. Of course, this is impossible, because as one variable changes, at least one other variable must change to compensate.

Previous work in the area of hull shape creation approached the problem in three different ways: the series approach (such as Series 60), hull variation or distortion from a parent hull, and hull shape creation using form parameters. Many of these methods overlap, some are automatic, and some require user intervention. In the further development of MDO tools, it is necessary to create computer methodology that uses specific hull variation or distortion techniques due to their generality and their fully automated approach to generate multihull hull forms. The major requirement is that this methodology would allow for the automatic variation of the shape of a parent hull using any of the major design variables. A design constraint can be selected to control which variables are fixed and which variables are free to change. A search technique is applied to create the derivative hull with the desired values of the major parameters. An inspection routine is then used to extract all of the hull shape dimensions required by the evaluation routine (resistance, stability, seakeeping and structural calculation). This process of automatic hull variation and evaluation collects all input, intermediate, and final results for printing, plotting, and contouring.

FIGURE 11: HULL VARIATION /EVALUATION PROCESS

The overall process flow is shown in Figure 11. The program method starts with a parent hull and automatically varies the shape according to the designer's input. Each derivative hull shape is automatically evaluated, with the results printed, plotted, or contoured. Each box of the diagram is explained in the following sections.

The purpose of this approach is to show the feasibility of carefully controlled hull variation for use by the Hull Forms Design Optimization Subsystem. The overall design optimization is not fully automatic. It is under the control of the designer who can carefully vary one or two major shape variables at a time and evaluate the results. By graphing and contouring these results, the designer can quickly study tradeoffs for a wide range of hull shapes and progress toward an optimal design shape.

6.1.1 Create Parent Hull Shape

There are many ways to define a hull shape for use by a computer program. The most common methods are: Station definition using offsets, used for volumetric calculations; B-spline (NURBS) surface definition, used for fairing and construction; Ruling line definition, used to define developable plates, Wireframe definition & Station definition plus control lines; Polyhedron mesh definition, used for flow and structural calculations.

Although all of these hull definition methods could be applied to these techniques, for the MDO Hull Forms Subsystem, which we suggest for the CCDOTT FY05-06 program, we would use a station definition of the full for the hull variation and evaluation program, since a perfectly fair hull surface is not required for the MDO approach and the resistance, stability, and seakeeping evaluation.

This approach for MDO tools development allows us to create a station definition of a hull by typing in a table of offsets, by digitizing a body plan, by reading an existing offset file (SHCP-Ship Hull Characteristics Program, GHS-General Hydrostatics, etc.), or by converting a B-spline surface definition to a station definition. Once a station definition of a hull (parent hull) is created and stored in the vessel's database, the hull variation and evaluation program can be started.

6.1.2 Input Definition

This approach starts by reading the station definition of the parent hull from the vessel's database. Since the evaluation method being applied to the hull is a resistance calculation, the

input values must either come from the shape of the ship or input from the designer. These inputs are listed below.

Basic input from the designer - This data includes things that are not dependent on the shape of the ship, such as ship velocity, water type, and drag options.

Input from the shape of the hulls - All hull shape data required by the design calculation is obtained during the hull "Inspection" routine, discussed later in the report.

Input of the hull variation constraints - This input tells the program which variables to vary in order to maintain the proper hull constraints.

Input of the calculation and output choices - This input tells the program whether to perform a single calculation, a print or plot over a range of values, or a contour plot over a matrix of input values. The print or plot option allows the designer to vary one of the major design parameters while holding the rest of the variables constant. The contour plot allows the designer to vary two major design variables while holding the rest constant.

Once all user-defined input variables have been entered, the program begins its automatic hull variation and evaluation process.

6.1.3. Hull Variation

The process of hull variation produces a derivative hull from a parent hull by specifying new values for any of the following major parameters:

1. Length of the center and side hull waterlines (Lch and Lsh)
2. Beam of the center and side hull waterlines (Bch and Bsh)
3. Depth of the ship (Depth)
4. Draft of center and side hulls (Tch and Tsh)
5. Displacements of center and side hulls (Disp_ch and Disp_sh)
6. Prismatic coefficient of the center and side hulls (Cp_ch and Cp_sh)
7. Longitudinal centers of buoyancy (lcb_ch and lcb_sh)
8. Parallel middle body - forward (Pfwd_ch and Pfwd_sh)
9. Parallel middle body - aft (Paft_ch and Paft_sh)
10. Midship coefficient factor (Cmfact_ch and Cmfact_sh)

Because many of these parameters are interrelated, the designer must choose whether the calculations are done for a fixed draft or for a fixed displacement. These variables fall into one of

the following hull variation routines: **Stretch**, **Balance**, **Lackenby**, or **CmVary**. Each of these will be discussed below.

STRETCH

This hull variation routine varies any or all of the three major dimensions (length, beam, and depth) by a scale factor. This is a very simple hull variation applied to all offsets of the station definition.

BALANCE

This step does not actually change the shape of the station definition, but it does modify some of the major parameters. If the user selects a constant displacement hull variation constraint, then this routine will raise or sink the hull to search for a new draft (T) which maintains a constant displacement. This is done with a searching technique, which maintains zero trim while searching for the desired displacement. Note that if the draft changes, the length and beam will likely change. If a constant draft option is selected, this routine calculates the new displacement for the current hull shape.

LACKENBY

This is a technique for hull variation developed by H. Lackenby, which allows the designer to vary any of the following variables, without affecting the length, beam and depth of the vessel.

- Prismatic coefficient (Cp)
- Longitudinal center of buoyancy (lcb)
- Parallel middle body - forward (Pfwd)
- Parallel middle body - aft (Paft)

The Lackenby method is a quadratic variation of the "one minus prismatic" approach whereby the lengths of the parallel middle body can be controlled independently of lcb and the prismatic coefficient. The sectional area curve is calculated for the hull and the curve is shifted to achieve the target values. Half-breadths and heights of the offsets in the station definition are not changed using this method; only the longitudinal locations of stations are shifted. It can take a few iterations using this method to zero in on the desired values. The more stations in the definition, the more accurate it is and the fewer iterations it takes. The program can be developed for this goal to make the Lackenby hull variation calculation until all four variables are within a small tolerance of the target values. Although the Lackenby hull variation technique allows the designer to vary and set any one or all of these variables, the displacement does change for a constant draft.

CMVARY

This is a hull variation technique, developed by Stephen M. Hollister, which allows the midship shape of the vessel to change independently of the beam and depth of each station. It uses a value called Cmfact, which varies the shape of each section diagonally in the direction of the bilge corner, defined as the intersection of the maximum beam and depth of the station. A Cmfact value of 1.0 means that each section shape is rectangular. (See Figure 12)
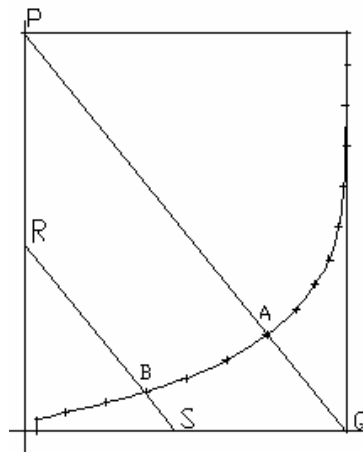
FIGURE 12: CMFACT STATION SHOWING CMFACT DIAGONAL.

The CMFACT value for a particular station is the percent distance of the station curve from point P (0, 0) toward point Q (1, 0). The overall CMFACT for the hull I the largest CMFACT of all the stations and is the value used by the CmVary routine to vary the shape of the hull.

Cmfact is related to the midship coefficient (Cm) of a vessel, except that it is based on the overall maximum beam and depth of the vessel, rather than the waterline beam and the draft. Since all of these hull variations affect the entire hull shape, a Cm-type factor was created that also affects the entire section, rather than just the area below the waterline. This makes the factor independent of the draft and displacement.

OTHER VARIATIONS

There are many more potential avenues for hull variation, such as: Variation of the deadrise angle; Variation of the profile of the ship; Change sections from U-shapes to V-shapes; Change section shapes while maintaining constant LWL, BWL, draft, and section area. Many of these hull variations are important in their own right, but for the calculation evaluation routine described in this approach, they play a smaller role than varying the major hull shape parameters.

6.1.4. Hull Constraints

The **Stretch** variation changes the length, beam, and depth of the hull, and the displacement, Cp, lcb, etc. all change. **Balance** determines the new draft (T) for a given displacement, and the length, beam, Cp, etc. all change. **Lackenby** maintains constant LWL, BWL, and draft, while varying Cp, lcb, Pfwd, and Paft, but displacement changes. **CmVary** maintains constant length, beam, and draft, but varies the displacement and prismatic coefficient. It is impossible to fix all of these major design variables to create one specific derivative hull shape. If one variable is set or changed by the program, then at least one other variable must change at the same time. The goal, however, is to allow the designer to change the major design variables in a controlled manner using constraints.

The following equations show the relationships among many of the major design variables:

$$Cp = \frac{Vol}{LWL \cdot Am}$$

$$Am = Cm \cdot BWL \cdot T$$

$$Cp = \frac{Vol}{\dddot{\dots} \approx \dddot{\quad}L \cdot T}$$

$$lcb = \frac{\int x \cdot sa(x) \cdot dx}{\dots}$$

$$Cp = \frac{\int x \cdot sa(x) \cdot dx}{LWL \cdot Cm \cdot BWL \cdot T \cdot lcb} ,$$

Where sa(x) is the sectional area at x.

In an ideal case, the designer should be able to vary any parameter in the above equation and to select any other parameter to balance the equation so that the rest of the parameters remain fixed. This may be possible, but it might require a whole range of constraint maintenance routines. The program described in this paper only allows the designer to vary either the draft or the displacement to obtain target values of the major design parameters. For example, a designer might vary LWL, while maintaining fixed values for the rest of the parameters, except for draft, which would have to vary to maintain constant displacement.

Another way of looking at the problem is to fix all parameter values but one, and then solve (search) for a derivative hull that meets those set values. That is what the program in this paper does. Specifically, this program can generate a derivative hull shape with any values for the major variables, except for displacement and draft. If the draft constraint is set by the designer,

the program will vary displacement to achieve all of the other target values. If the displacement constraint is set, the draft of vessel changes while achieving the rest of the target variables. This hull variation and constraint search loop is shown in Figure 13 below.

FIGURE 9: HULL VARIATION / CONSTRAINT LOOP

Given target values for length, beam, depth, Cp, lcb, Pfwd, Paft, and Cmfact, this search loop will vary either draft or displacement to create a derivative hull with the desired values. This non-linear Hull Variation and Constraint search loop has gone through many variations to speed up the search process. It uses a form of a conjugate direction search technique to zero in on a solution. The balance step is performed after each hull variation step, since all parameters are very sensitive to draft and displacement.

This is just one approach to the constraint maintenance problem. One could derive a hull variation and constraint search loop based on varying any of the major design variables. Note that a new search technique would be needed by this program if both the displacement and the draft of the ship are to be fixed.

6.1.5. Hull Inspection Routine

Once the hull variation and search loop is complete, this routine determines all of the hull shape information that is required by the Hull Evaluation routine. Exactly what is calculated here depends on the needs and sophistication of the evaluation routine. For many calculation programs, this might mean calculating simple information, such as volume, wetted surface,

waterplane area, and the half angle of the waterplane entry. Most of these values should be determined automatically from the hydrostatic calculations in the Balance routine.

In addition, this inspection routine can also calculate the righting moments and righting arm areas of the vessel for any heel angle, with automatic balancing for trim. This allows the designer to study the trade-offs between resistance, stability and seakeeping.

6.1.6. Hull Evaluation Routine

In discussing the automatic hull variation and Multi hull MDO process the specific type of evaluation routine would be used to analyze the shape of the hulls. In general this hull variation and constraint technique can be used with any hull shape evaluation technique.

1. Geosim Coefficient Resistance Evaluation - These techniques break the overall resistance of the vessel into their component parts, such as viscous and residual resistance. Residual resistances can be determined from MQLT Multihull resistance CFD codes.

2. Ship Motion and Structural Loads Prediction Methods – These techniques include table of offsets or a polyhedron mesh as input data for various computer programs like SPECTRA, VERES, LAMPS, SWAN/WASIM, etc.

3. Computational Fluid Dynamics Methods (CFD) - These techniques typically use a polyhedron mesh generated from the shape of the hull to perform a full 3D analysis of the resistance and flow pattern of the hull.

4. Finite Analysis Methods (FEM) - These techniques use a polyhedron mesh generated from the shape of the hull to perform a 3D structural finite element analysis of the hull shell.

The approach described in this paper demonstrates the ability to automatically vary the shape of a parent hull to obtain target values for major hull shape variables. Target values are achieved using a constant displacement or constant draft constraint. If a constant draft constraint is selected, then all of the target values are obtained by varying the displacement of the vessel. If a constant displacement constraint is selected, then the target values are obtained by varying the draft of the vessel. The multihull configuration parameters, stagger and clearance, are added to the list of Hull Form MDO subsystem variables.

This approach only scratches the surface in the area of automatic hull variation with constraints. As mentioned previously, the designer should be able to achieve the desired target values for all major design variables by varying just one selected parameter. This can be achieved by varying

the draft or displacement. It should be a straightforward change, however, to vary another variable, such as LWL, to achieve the desired target values.

There are also an infinite variety of other hull variations to investigate, such as variable bilge radius, variable deadrise angle, adjustable rocker shape, and adjustable section shape. This approach focuses on variations of the major design parameters, since those variables had the greatest influence on the resistance, stability and seakeeping calculation technique.

An associated area of development is the automatic creation of hull shapes from a set of standard form parameters. One could automatically create an approximate hull shape from form parameters and use the automatic hull variation process to achieve the exact target values.

Another area of development is to separate the hull variation routine, the hull inspection routine, the hull evaluation routine, and the output results routine into separate modules or programs, linked by a simple data and geometry file. This would allow designers to replace the existing evaluation routine or program with their own, but still use the standard hull variation and results evaluation framework.

Another interesting area of development is in the automatic variation of CFD or FEM hull meshes. Rather than re-meshing after each hull variation (which may not be automatic), the hull variation could be performed directly on a parent hull mesh. This would eliminate the need for re-meshing after each step and would allow the analysis program to analyze many hull

6.2 Structural Optimization Overview

The objectives of structural optimization are: to reduce the vessel's weight; increase payload capacity; decrease production cost; decrease operational cost; and decrease life cycle maintenance cost. The structural optimization MDO subsystem model, based on unique optimization methodology and existing software for various related calculations would allow the client to specify a variety of constraints (specific yard, specific materials, production techniques, etc.) and to optimize the structural weight of the vessel while maintaining structural integrity.

Structural optimization programs should create structural design options which comply with user specified parameters. Full Finite Element Analysis (FEA) models should be the part of the structural optimization subsystem and should be rapidly created for each design option and verified against both rule and physical based calculations. One of the requirements for the use of FEA in the structural optimization subsystem is that as they are created, the FEA models

should be rapidly modified to account for structural changes such as stiffener spacing and size, plate thickness, and girder properties.

The structural optimization MDO subsystem concentrates on a number of structural variables including:

- Stiffener Spacing

Iterations on the spacing of the plate stiffeners to achieve the optimal balance of stiffener size vs. attached plate thickness

- Frame Spacing

Iterations on the spacing of the major framing to achieve the optimal balance of frame scantlings, plate stiffeners, and attached plate thickness

- Material Type

Evaluation of unique material types to study the benefit of reduced weight of the structure verses the increased expense of the material and increased labor and construction costs

- Stiffener Type

Evaluation of the effects of different stiffener shapes on the vessels structure.

The structural optimization subsystem should contain a library of structural properties and dimensions for various standard steel shapes, such as tees, angles, bulbs, flat bars, and other rolled and built up sections, as well as the ability to input unique structural properties for innovative new stiffing techniques. The subsystem model would also evaluate the effect of different stiffener shapes on the paint area of tanks to be coated.

- Length to Breadth ratio and trimaran configuration parameters

The optimization program iterates on the length to breadth ratio, stagger and clearances parameters to evaluate the effects on the structural design. The structural benefits of incremental changes in relative dimensions and configuration parameters are compared to the resulting changes in stability and vessel hydrodynamics.

The structural optimization begins with a definition of the global and local forces, which depend on the main variables of the MDO design problem.

The global and local loads modules enable the designer to evaluate those loads that noticeably affect the ship's structural design while being strongly dependent upon the stagger value. To this purpose, the following loads have to be taken into account:

a. Longitudinal global loads (shear and bending moment), particularly:

  Static loads (still water, hogging, sagging)

  Dynamic loads due to slamming (sagging)

 b. Transversal global loads (torque moment)

 c. Local loads (pressures)

Static loads have to be calculated first, assuming that the preliminary weight components distribution is determined at the synthesis level. Their calculation can be performed for different configuration parameters, including staggers, each time shifting along the hull all those weight components, which are dependent on the stagger itself, i.e. outriggers, cross-deck and passengers and crew weights. Loads evaluation has to be carried out in still water as well as in waves, always referring to static conditions; following this approach, global loads are evaluated as the difference between weight and buoyancy curves. The goal of these preliminary calculations is to obtain additional information about the relationships between Stagger value and the longitudinal global loads acting on the ship, between conditions (hogging or sagging and highest loads, and so on.

Slamming loads assessment requires the evaluation of vertical accelerations, which depend on the ship speed and the sea conditions taken as reference. The longitudinal shear and bending moment distributions occurring along the hull as consequence of the bow impact on waves (sagging conditions), have to be determined. To this aim, different methods can be applie; the trimaran can be considered as a monohull having same longitudinal weight distribution, as well as a total breadth of the cross sections equal to the sum of the breadths of the three hull components. This procedure leads to the assessment of slamming loads through the calculation of an auxiliary, fictitious, longitudinal weight distribution added to the static, real one. For the structural optimization subsystem, the final contribution of the longitudinal global loads module to the overall MDO procedure can be given in terms of two design criterions (shear and bending) calculated, as a function of the dimensions and configuration parameters, and as the maximum of the following longitudinal loads:

 a. Maximum shear and bending moment along the hull, in still water conditions.

 b. Maximum shear and bending moment in waves (static approach: hogging and sagging).

 c. Maximum shear and bending moments due to slamming phenomenon (sagging).
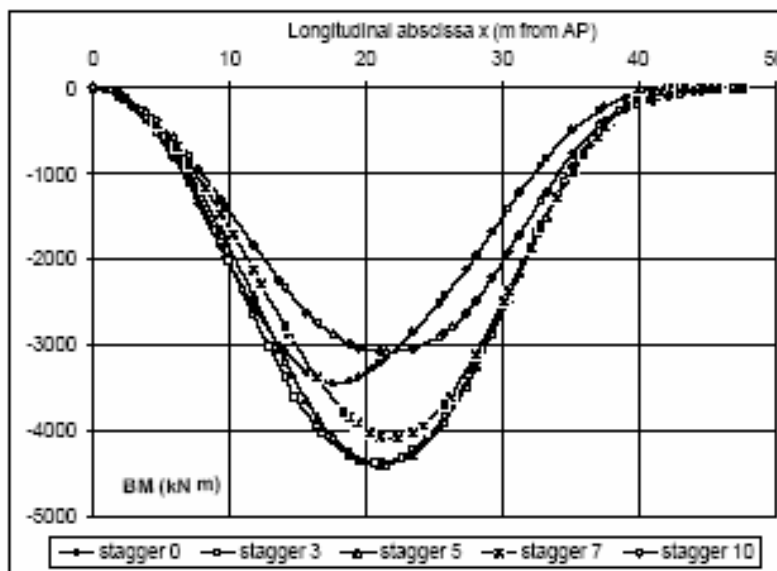
FIGURE 10 : BENDING MOMENT AS FUNCTION OF DIFFERENT STAGGER PARAMETERS (STAGGER 0 CORRESPONDS TO BETA=0, AND STAGGER 10 CORRESPONDS TO BETA=1). (FROM RIZOTTO 2004)

The structural scantlings and therefore structural weight will be entirely dependent upon the loads applied to the vessel while operating in its design environments. Transversal global loads acting on the ship have to be considered; unlike the monohull configuration, transversal shear, bending moment and torque moment can't be neglected, due to the large transversal extent of the cross-deck structure used to connect the component hulls. Transversal shear, bending and torque moment can be evaluated through different methods developed by NSWCCD (SPECTRA), DNV and Viking Systems (WASIM/SEGA), and also proposed by Coppola and Mandarino (2002).

The most adequate for multihull type of ships is the non-linear hydrodynamic analysis software WASIM, developed by DNV Software and a modified version of SMP84, which was modified as part of the Semi-Submerged Surface Ship innovation cell project.

DNV's WASIM code is based on the SWAN code and has been developed independently by DNV since approximately 1999. WASIM is a hydrodynamic program for the computation of global responses and local loading on displacement vessels, either stationary or moving at any forward speed. The simulations are carried out in the time domain, and also allow for transformation to the frequency domain using Fourier series transformations. The program solves the fully 3-dimensional radiation/diffraction problem by a Rankin panel method. Our recommendation is to use the WASIM program to take advantage of already existing interfaces

developed between WASIM and Viking Systems' structural modeling and advanced post-processing software SAGA.

A non-linear analysis can be performed to produce a realistic time history of the local and global loads for the given wave headings and critical sea states. The slamming pressures on the wetdeck can be predicted with empirical formulae based upon the number of wetdeck immersions, vessel accelerations, and wave velocities calculated within the non-linear hydrodynamic analysis.

A comprehensive list of the software proposed for the hydrodynamic task of Structural Optimization Subsystem is given below:

WASIM Pre - Preprocessor for hydrodynamic program; WASIM Nlin - Non-linear 3-dimensional radiation/diffraction hydrodynamic program; Postresp - Statistical post-processing of hydrodynamic analysis results; Xtract - Graphical program used to plot time histories and numerical model animations; FEMAP - Finite Element Modeling program for mass and structural models; SAGA – VSI's in house computer program for translation of models and the processing of data; WASIM Stru - Transfer of pressures and accelerations to a structural finite element model; MSC Nastran - Finite Element Analysis solver.

SAGA software is highly proficient in the creation, loading, and evaluation of structural finite element models. SAGA performs first principle and rule based evaluations for yielding, buckling, and fatigue life prediction.

In this regards, a scenario and the profile conditions of the multihull ship operation relevant to the hull and its structural components can be developed.

The SMP program, which can be used in parallel to WASIM, essentially adds non-linear heave and pitch damping due to having a small waterplane area. The damping values came from Dr. Dalzell's SWATH work and from K. McCreight's SWATH motion code.

In the development of the loads module, local loads acting on the trimaran hull also need to be considered; they are capable of strongly affecting the total trimaran hull weight. It seems therefore necessary to include them in the trimaran structural optimization procedure. The following local loads (pressures) have to be considered:

    1. Bottom impact pressure

2. Impact pressure acting on the under-side of the cross-deck.

These local pressures can be calculated as a function of the trimaran configuration variables, at 0.75 Lch from the after perpendicular and making use of the formulas provided by the Lloyd's Register for multihull vessels. Again, where required, the vertical acceleration of the center of gravity has to be taken from the results of the seakeeping analysis.

1. LOCAL STRUCTURAL CRITERIONS FOR STRUCTURAL SUBSYSTEM OPTIMIZATION

Among the several design parameters and criterions considered within the Synthesis and Structural Optimization Models the following attributes have to be used. They are:

- Area A1 under the righting arm curve
- Maximum longitudinal shear
- Maximum longitudinal bending moment
- Transversal torque moment
- Bottom impact pressure @ 0.75 Lch from after perpendicular
- Impact pressure on cross-deck @ 0.75 Lch from after perpendicular.

The content of the Structural Optimization Subsystem should consist of the following main parts:

1. Strength Analysis:

In order to verify that the ship's structure will be able to handle the loads encountered during operation in the required environments, structural finite elements models have to be constructed, loaded, and evaluated.

2. Global Model:

A global coarse mesh model needs to be created for the full extent of the vessel. The model will be created with 2D anisotropic (where applicable) plate elements to represent stiffeners. This global model will be used to evaluate the overall structure and provide accurate boundary conditions for intermediate models as well as more detailed localized models.

3. Intermediate Model:

An intermediate finite element model needs to be created to evaluate the structure in the same way as the midship section. The model has to be not less than five frames long and will be loaded at the cut sections with the deformations from the global model analysis. The local

pressures and accelerations generated from the hydrodynamic analysis will also be applied to the intermediate model. This model will be used to evaluate the strength and performance of the unique multihull structural concepts and construction materials employed in the vessel design.

4.   Model Building:

Practical computer programs (like SAGA) that facilitate the rapid creation of finite element models for ship shaped structures have to be employed. (SAGA is able to generate curved meshed surfaces for the hull of a vessel from a table of offsets, and apply varying structural properties from a property table defined by the user. SAGA is also capable of modeling the decks and bulkheads, and handling the internal structure / shell interactions).
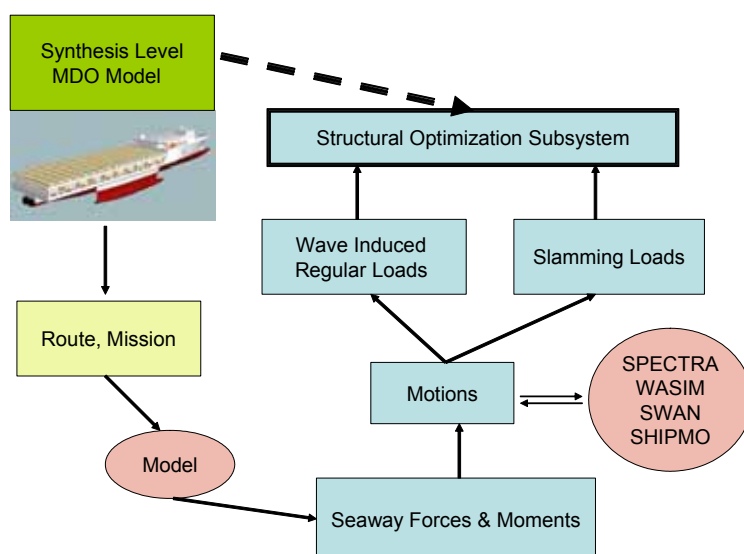
FIGURE 15: SCHEMATIC REPRESENTATION OF MAIN ELEMENTS OF THE STRUCTURAL OPTIMIZATION SUBSYSTEM

5.   Fatigue Analysis:

A fatigue analysis study on the proposed construction materials and details to compare the fatigue properties of the various concepts to the performance of standard steel ship details.

2. GENERAL DIRECTIONS OF MDO STRUCTURAL SUBSYSTEM DEVELOPMENT

Developing the Structural Optimization Subsystem we take into account that almost all of the commercial and a fair number of military vessels, even until recently, were designed primarily using empirical approaches and "cook-book" methodologies. In the commercial sector, the

Classification Societies and International Maritime Authorities provide these approaches in the form of design rules and guidelines. The military sector tends not to lean heavily on the empirical design methods, but uses first-principle approaches and model testing.

For commercial vessels, it is important that the design rules and guidelines ensure that the ships are built with an acceptable level of safety. One of the most catastrophic events a ship can experience is the collapse of the hull-girder. Such an event would imply a risk of loss of human lives and a risk of polluting the environment, depending on the type of ship. The difference between ship types is not yet reflected in the design rules regarding the longitudinal strength. In order to avoid collapse of the hull, the design rules prescribe a maximum stress level, which must not be exceeded, under a prescribed bending moment and shear force loading. This seems to be a rather simplified methodology to avoid an extremely complex event, and it must be expected that the safety level of ships varies significantly. In order to estimate the probability of collapse of the hull, it is necessary to have a tool that can calculate the strength of the hull.

Further, a probabilistic method to evaluate the probability that the loading on the hull exceeds the strength is also essential. Such a probabilistic analysis demands much computational work. Therefore, it is necessary that the calculation of the loads and strength of the hull is fast and effective.

Classification Society rules are based on analytical models for response and strength that are empirically modified to obtain agreement with observations. The safety level of existing ship structures is, hence, to a large extent, defined through registered failure statistics. Consequently, it is not straightforward to compare innovative multihull/trimaran designs if these designs are not closely related to traditional designs. These new types of ships are tending towards more use of innovative materials and the development of new design technologies. In these cases, it has become very important to estimate the actual safety level of ship structures, making it possible to compare traditional designs to new ones, aiming at the same level of safety.

The rules developed by Classification Societies have not been calibrated against a uniform reliability level. On the contrary, several analyses concerning specific structures have shown very large variations in safety and reliability levels. The two main objectives of any design tool development and calibration of partial safety factors are the determination of a method that is simple to use and yet achieves a uniform safety level for any design which is based on the

method. Unfortunately, simplicity and safety become conflicting objectives when ship designers work to meet time and cost limitations.

The results of several analyses from various sources have shown that a large scatter presently exists in the design safety levels of ships, even when the unified requirements of the Classification Societies are satisfied. However, these studies have demonstrated the usefulness of a reliability-based approach in the development of ship longitudinal strength requirements. The development of a semi-probabilistic design approach, comparable to the use of empirical design rules, certainly has significant merit, especially for unconventional ship types and hullforms. However, the evaluation of the target probabilities of failure can only be obtained through the results of an exhaustive set of reliability calculations carried out on a wide range of ship types and hullforms, rather than using the outcome of casualty returns, which are heavily affected by the corrosion condition of structures and the different operational profiles of ships. Over the last decade, several reliability-based design methods have been proposed by the research community, which the Classification Societies are now trying to adopt in evaluating new designs. However, the inclusion of the semi-probabilistic design philosophy in the rules remains to be seen.

Military vessel designs have their own sets of empirical methods, namely the U.S. Navy Design Data Sheets and NAVSEA Design Manuals. However, military ship designers also employ first-principles design philosophies featuring analytical and probabilistic approaches to complement the empirical methods. The analytical design process requires motions and loads estimation for the ship type, for a given hullform, and operational parameters. More often than not, an analytical design method needs either expensive simulation tools or experimental data. Apart from the extreme load predictions, the other side of the equation entails material property limits, which are well understood for conventional materials but, again, need design investigations for high-performance materials such as composites and new alloy grades. The commercial design community has also proposed first-principle design approaches such as the Dynamic Load Approach (DLA) of the American Bureau of Shipping (ABS), which requires hydrodynamic analyses to estimate the motions and loads in addition to performing a full-ship FEA of the ship structure to assess the design stress and safety levels.

7.   Conclusion

This report documents the successful development of a synthesis level multi disciplinary design and optimization MDO method and its application to a generic trimaran configuration for

demonstration. The method uses quadratic programming algorithm (NPLQ) for a single criteron and Neighborhood Cultivation Genetic Algorithm – (NCGA) for multicriteria optimizations. It integrates, powering prediction using Nural Networks, with syntehsis level models for stabilty, payload capcity, structure and cost into a single design tool. It is efficient, robust and produces reasonable results. It can be used for more detailed study of trimaran design. Extension of the method to include higher fidelity models for powering, seakeeping and hull shape and structural design subsystems optimization is also discussed.

8. Acknowledgment

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Appendix 1: Input Model Parameters

TABLE 4 LIST OF INPUT MODEL PARAMETERS

POWERING			
SR No	**Input Model Parameters**	**Values**	**Description**
1.	AA1	9.15	Shape coefficient
2.	v	1.187×10^{-6}	Viscosity (m^2/s)
3.	PEC	0.65	Propulsion efficiency coefficient
STABILITY			
4.	C_{wl}^{ch}	0.75	Waterline coefficient for center hull
5.	C_{wl}^{sh}	0.75	Waterline coefficient for side hull
6.	F_{ch}	1	Proportionality factor for center hull
7.	F_{sh}	1	Proportionality factor for side hull
LIGHT SHIP WEIGHT			
8.	K_{ch}	0.075	Center hull weight dimensional coefficient in tons/m^3
9.	C_m^{ch}	0.75	Midship coefficient of center hull
10.	K_{sh_conv}	0.1	Side Hull Weight dimensional coefficient (conventional type) in tons/m^3
11.	K_{sh_swa}	0.13	Side Hull Weight dimensional coefficient (SWA type) in tons/m^3
12.	C_m^{sh}	0.75	Midship coefficient of side hull
13.	K_{ss}	0.04	Superstructure weight dimensional coefficient
14.	N_{crew}	18	Number of crew
15.	N_{pas}	12	Number of passengers
16.	$K_{hull-misc}$	0.025	Miscellaneous weight dimensional coefficient of hulls in tons/m^3
17.	K_o	0.03	Dimensional statistic coefficient for outfit weight estimate in tons/m^3
18.	K_{m_GT}	13	Statistical dimensional coefficient for gas turbines in machinery and propulsion weight estimate in tons/MW

19.	K_{m_diesel}	25	Statistical dimensional coefficient for diesel in machinery and propulsion weight estimate in tons/MW
20.	$K_{LWT-misc}$	0.02	Miscellaneous weight dimensional coefficient of light ship in tons/m^3
PAYLOAD			
21.	K_{bd}	0.3	Deck weight dimensional coefficient in tons/m^2
22.	$CDAU$	0.75	Deck area utilization coefficient
23.	$NTEUTRAI_{rows}$	2	Number of rows for containers
24.	$STOW_{TEUTRAI}$	1.4865	Cargo stowage factor for TEU in m^2/ton
25.	$STOW_{TEUTRAI}$	1.6722	Cargo stowage factor for trailer in m^2/ton
26.	$W_{TEUTRAI}$	10	Weight of TEU in tons
27.	$W_{TEUTRAI}$	18	Weight of Trailer in tons
28.	SFC_{GT}	0.210	Specific fuel consumption for gas turbines in kg/hr/kW
29.	SFC_{diesel}	0.16	Specific fuel consumption for diesel engines in kg/hr/kW
30.	SFC_{pilot}	0.35	Specific fuel consumption at pilotage for gas turbines in kg/hr/kW
31.	SFC_{pilot}	0.25	Specific fuel consumption at pilotage for diesel engines in kg/hr/kW
32.	SFC_{aux}	0.16	Auxiliary specific fuel consumption in kg/hr/kW
33.	N_{d_MAX}	4	Maximum number of decks
34.	V_{pilot}	10	Speed at pilotage
35.	R_{pilot}	50	Range at pilotage in nm
36.	BOL_{max}	57	Maximum beam overall length in meters
COST			
37.	H_H	90 hrs/ton	Productivity rate for hull manufacturing and assembly
38.	H_M	120 hrs/ton	Productivity rate for machinery assembly and installation

39.	H_o	80 hrs/ton	Productivity rate for outfit sys
40.	H_{misc}	15 hrs/ton	Productivity rate for other systems
41.	R_H	50 \$/hr	Labor rate for hull construction
42.	R_M	60 \$/hr	Labor rate for machinery installation
43.	R_o	50 \$/hr	Labor rate for outfit works
44.	R_{misc}	60 \$/hr	Labor rate for engineering and shipyard support
45.	M_H	720 \$/ton	Relative material cost for hull
46.	M_M	27800 \$/ton	Relative material cost for machinery (Gas turbines)
47.	M_M	10000 \$/ton	Relative material cost for machinery (diesel engine)
48.	M_o	4000 \$/ton	Relative material cost for outfit
49.	$M_{LWT-misc}$	17500 \$/ton	Relative material cost for electric, electronics, navig.
50.	AAC_{crew}	140000 \$/yr	Average annual cost of 1 member of the crew
51.	$COST_{maint}$	1% $SCOST$	General annual cost of ship maintenance
52.	$COST_{ins}$	0.8% $SCOST$	Annual insurance cost
53.	$COST_{supply}$	100 \$/day/person	Provision & hotel supply

54.	TOP	350 days	Annual operational period
55.	$COST\_M_{maint}GT$	150 \$/hr	Cost of machinery maintenance for gas turbine
56.	$COST\_M_{maint}diesel$	25 \$/hr	Cost of machinery maintenance for diesel engine
57.	R	800 nm	Range / Length of shipping line of operation
58.	R_{pilot}		Range of pilotage
59.	T_{aux}	5 hrs	Engine time (Auxiliary engines for generators)
60.	$COST\_FUEL$	400 \$/ton	Fuel Cost
61.	$COST_{LUBE}$	8.96 \$/kg	Lube oil cost
62.	$SLOC$	0.45kg/hr	Specific lube oil consumption
63.	$COST_{pilot}$	650 \$/port	Pilotage cost per port
64.	$COST_{TEUTRAI}$	\$ 125	TEU cost
65.	$COST_{TEUTRAI}$	\$ 30	Trailer cost
66.	$KOEF_{cap\_cost}$	0.115	Capital cost coefficient

Appendix 2: Single Criterion Results

7.1. Maximize Annual Cargo

Execution Results Summary

Start time: Tue Jul 26 18:34:49 PDT 2005

End time: Tue Jul 26 19:16:25 PDT 2005

Task: Trimaran

  Total runs: 120

  Feasible runs: 35

  Infeasible runs: 85

  Failed runs: 0

  Database file: Trimaran.db

  Optimization Plan: NLPQL200

    Executed between RunCounter 83 and 202 (120 runs)

    Techniques used:

       Step1: Sequential Quadratic Programming - NLPQL

    Best design: currently   previously

      RunCounter   177   83

      ObjectiveAndPenalty -464488.582838336 -43890.4285543488

      Objective   -464488.582838336 -43890.4285543488

      Penalty   0.0   0.0

    Best design ObjectiveAndPenalty value improved by

    420598.1543 (-958.29%) after executing this Optimization Plan

    Best design parameter values:

      Cbsh   = 0.6

      Cbch   = 0.6

```
Vk            = 30.0080119791121
Bch           = 24.0
Bsh           = 8.0
Tch           = 12.0
lambda        = 0.113465199520456
lamdash       = 0.660479109663998
Lch           = 222.208668932482
beta          = 0.0122159170954494
alpha         = 0.5
Nd            = 4
CO            = 4.336546
CF            = 0.00137104157791533
RES           = 7465834.81478988
WS            = 10812.9067773504
PfullSpeed    = 177.504543363827
Fn            = 0.331060173468121
Displ         = 50910.8098319909
WSsh          = 2220.17586293355
WSch          = 6372.55505148333
CK            = -6.6626006797446e-05
V             = 49669.0827629179
RE            = 2489678876.64911
Sl            = 7.26849233207745
Displch       = 39357.5994413212
Displsh       = 5776.60519533484
Tsh           = 7.9999541883467
Peffective    = 115.377953186488
Vs            = 15.4541261692427
Vch           = 38397.6579915329
Vsh           = 5635.71238569253
REsh          = 1910793777.4395
REch          = 2893041959.20983
Slch          = 6.58657163000619
Slsh          = 8.24714841226592
CR            = 0.00564096157111788
Lsh           = 146.764183816148
```

```
GMt              = 15.5236189676499
KBsh             = 4.53330737339646
KBch             = 6.8
KGsh             = 7.9999541883467
KGch             = 12.0
KB               = 6.28561853774177
KG               = 11.0922680077796
b                = 22.0
BM               = 20.3302684376877
Ndiesel          = 2
Ngt              = 4
Pdiesel          = 40.0
Pgt              = 137.505
Ld               = 184.376853345675
a                = 0.921623575490005
Cdch             = 0.7
Cdsh             = 0.720000274870549
Wss              = 126.56155628212
BOL              = 52.0
Wdeck            = 8628.83673657759
Whullmisc        = 1241.72706907295
Wlwtmisc         = 2468.17877438244
Vd               = 123408.938719122
Wsh              = 1711.61311056077
Wch              = 5769.82421345359
Whull            = 19190.1757965078
AreaCargodeck    = 7190.69728048133
Hship            = 33.0
Vdch             = 89594.5353135767
Vdsh             = 16907.2017027727
Wo               = 3702.26816157366
LWT              = 28148.1877324639
AnnualCargo      = 464488.582838336
NTRIP            = 240.045779244618
CARGOarea        = 28762.7891219253
Paux             = 1.77504543363827
```

```
WFUELfullspeed    = 881.665787071004
Tfullspeed        = 24.9933251333696
Ppilot            = 48.0923626101477
WFUELaux          = 1.42003634691062
Payload           = 19350.0
Ttrip             = 34.9933251333697
WFUELpilot        = 60.1154532626846
WFUEL             = 943.201276680599
Nteutrai          = 1935.0
RFR               = 0.795124332237315
SCOST             = 299890428.46127
Cmi               = 32388166.2738172
Ccs               = 1050000.0
ACF               = 90564594.1781252
CMACHINERY        = 101573068.0
ACFLEET           = 295460939.408951
Ccrew             = 2520000.0
ACpilot           = 312059.513018003
CMm               = 22745.6613366903
ACLO              = 403.092347750985
CHULL             = 100172717.657771
COUTFIT           = 29618145.2925893
AFvolume          = 464488.582838336
ACC               = 52480824.9807223
ACch              = 116122145.709584
CMISC             = 68526497.5109102
G1                = 0.444441899352594
G2                = 0.5
G3                = 0.333335242163152
G4                = 0.542644186727885
G5                = 0.887522716819136
Fnvol             = 0.813966280091827
G6                = 0.0516795865633075
Whullnodeck       = 10561.3390599302
LWTnodeck         = 19519.3509958863
AreaCargodeckMAX  = 7190.69728048133
```

```
          TotalDeckArea      = 29186.6670929236
          LdMAX              = 184.376853345675
          HWCch              = 24.0
          HWCsh              = 19.9999541883467
          G7                 = 0.912280701754386
          Wmdiesel           = 1000.0
          Wmgt               = 1787.565
          CMACHINERYgt        = 84373068.0
          CMACHINERYdiesel = 17200000.0
```

7.2. Minimize SCOST

```
Execution Results Summary


Start time: Tue Jul 26 18:41:23 PDT 2005
End time: Tue Jul 26 23:19:47 PDT 2005



Task: Trimaran
  Total runs:       758
  Feasible runs:    159
  Infeasible runs: 599
  Failed runs:      0
  Database file:    Trimaran.db


  Optimization Plan: NLPQL200
    Executed between RunCounter 83 and 840 (758 runs)


    Techniques used:
        Step1: Sequential Quadratic Programming - NLPQL


    Best design:                currently                previously
    -------------------------------------------------------------
        RunCounter            819                      83
        ObjectiveAndPenalty   16658916.3915174  62258844.1077567
        Objective             16658916.3915174  62258844.1077567
```

```
     Penalty                 0.0                      0.0
```

Best design ObjectiveAndPenalty value improved by
45599927.72 (73.24%) after executing this Optimization Plan

Best design parameter values:


```
     Cbsh              = 0.45
     Cbch              = 0.45
     Vk                = 25.0
     Bch               = 12.0
     Bsh               = 3.91527862944062
     Tch               = 4.0
     lambda            = 0.030250020634215
     lamdash           = 0.1
     Lch               = 122.640829335859
     beta              = 1.0
     alpha             = 2.0
     Nd                = 1
     CO                = 3.437005
     CF                = 0.00148784326105475
     RES               = 672177.820706509
     WS                = 1534.28116203849
     PfullSpeed        = 13.3142914486097
     Fn                = 0.371255316859623
     Displ             = 2890.12036271064
     WSsh              = 45.8907699887695
     WSch              = 1442.49962206095
     CK                = 0.000232077511992423
     V                 = 2819.62962215672
     RE                = 1258626504.10913
     Sl                = 8.49995048391085
     Displch           = 2715.26796149592
     Displsh           = 87.4262006073618
     Tsh               = 3.94736670227789
     Peffective        = 8.6542894415963
```

```
Vs              = 12.875
Vch             = 2649.04191365455
Vsh             = 85.2938542510847
REsh            = 133024488.432956
REch            = 1330244884.32956
Slch            = 8.86350448403583
Slsh            = 2.78609443064175
CR              = 0.00515692577304718
Lsh             = 12.2640829335859
GMt             = 12.405650536727
KBsh            = 2.49999891144266
KBch            = 2.53333333333333
KGsh            = 3.94736670227789
KGch            = 4.0
KB              = 2.53131659943329
KG              = 3.99681568331572
b               = 19.9576393147203
BM              = 13.8711496206094
Ndiesel         = 2
Ngt             = 0
Pdiesel         = 13.3143
Pgt             = 0.0
Ld              = 44.9934959383128
a               = 110.376746402273
Cdch            = 0.525
Cdsh            = 0.525496705069369
Wss             = 7.18468498447374
BOL             = 43.8305572588812
Wdeck           = 443.720250000329
Whullmisc       = 70.490740553918
Wlwtmisc        = 131.643371115267
Vd              = 6582.16855576333
Wsh             = 14.8256752246527
Wch             = 503.612877379239
Whull           = 1054.65990336726
AreaCargodeck   = 1479.0675000011
```

```
Hship            = 10.25

Vdch             = 6181.09779852729

Vdsh             = 200.53537861802

Wo               = 197.4650566729

LWT              = 1716.62583115543

AnnualCargo      = 21000.0

NTRIP            = 210.0

CARGOarea        = 1479.0675000011

Paux             = 0.133142914486097

WFUELfullspeed   = 63.90864

Tfullspeed       = 30.0

Ppilot           = 6.23844493792884

WFUELaux         = 0.106514331588878

Payload          = 1000.0

Ttrip            = 40.0

WFUELpilot       = 7.79805617241105

WFUEL            = 71.8132105039999

Nteutrai         = 100.0

RFR              = 1.18105851316282

SCOST            = 16658916.3915174

Cmi              = 1799162.97028387

Ccs              = 1050000.0

ACF              = 6032309.68233599

CMACHINERY       = 5725149.0

ACFLEET          = 19841783.0211354

Ccrew            = 2520000.0

ACpilot          = 273000.0

CMm              = 2000.0

ACLO             = 0.0

CHULL            = 5505324.6955771

COUTFIT          = 1579720.4533832

AFvolume         = 21000.0

ACC              = 2915310.36851554

ACch             = 5250000.0

CMISC            = 3848722.24255706

G1               = 0.657894450379648
```

```
        G2                  = 0.75

        G3                  = 0.330623672669449

        G4                  = 0.729234071294046

        G5                  = 0.0665714572430485

        Fnvol               = 1.09385110694107

        G6                  = 1.0

        Whullnodeck         = 610.939653366936

        LWTnodeck           = 1272.9055811551

        AreaCargodeckMAX    = 4132.35096734558

        TotalDeckArea       = 1479.0675000011

        LdMAX               = 125.706850069255

        HWCch               = 8.0

        HWCsh               = 7.94736670227789

        G7                  = 0.768957144892653

        Wmdiesel            = 332.8575

        Wmgt                = 0.0

        CMACHINERYgt        = 0.0

        CMACHINERYdiesel = 5725149.0
```

7.3. Minimize RFR

```
   Execution Results Summary


Start time: Wed Jul 27 10:30:33 PDT 2005
End time: Wed Jul 27 16:20:38 PDT 2005



Task: Trimaran
  Total runs:        716
  Feasible runs:    157
  Infeasible runs: 559
  Failed runs:       0
  Database file:    Trimaran.db


  Optimization Plan: NLPQL200
    Executed between RunCounter 83 and 798 (716 runs)
```

```
Techniques used:

    Step1: Sequential Quadratic Programming - NLPQL


Best design:                  currently              previously
--------------------------------------------------------------

    RunCounter            756                    83

    ObjectiveAndPenalty   0.631319949061912      1.80477676618233

    Objective             0.631319949061912      1.80477676618233

    Penalty               0.0                    0.0


Best design ObjectiveAndPenalty value improved by
1.173456817 (65.02%) after executing this Optimization Plan


Best design parameter values:


    Cbsh              = 0.6

    Cbch              = 0.6

    Vk                = 25.0

    Bch               = 17.9999075429203

    Bsh               = 7.88921041613189

    Tch               = 11.9993031947179

    lambda            = 0.03

    lamdash           = 0.110731283486786

    Lch               = 206.604798744201

    beta              = 0.441467157810163

    alpha             = 1.29004527638756

    Nd                = 4

    CO                = 3.548763

    CF                = 0.00139806352036239

    RES               = 2353713.75998253

    WS                = 5623.17591485522

    PfullSpeed        = 46.6216379381155

    Fn                = 0.286035554107052

    Displ             = 29195.3689639833

    WSsh              = 184.543552635326

    WSch              = 5254.08880958456
```

```
CK              = -1.98143962326031e-05
V               = 28483.2867941301
RE              = 2110171714.089
Sl              = 6.61107068431339
Displch         = 27443.6468261443
Displsh         = 875.861068919499
Tsh             = 7.89070539962709
Peffective      = 30.3040646597751
Vs              = 12.875
Vch             = 26774.2895864822
Vsh             = 854.498603823901
REsh            = 248145987.527998
REch            = 2240974544.08727
Slch            = 6.90612475057147
Slsh            = 2.41086903648764
CR              = 0.00492701212412979
Lsh             = 22.8776145394745
GMt             = 2.74273067548082
KBsh            = 4.47139972645535
KBch            = 6.79960514367348
KGsh            = 7.89070539962709
KGch            = 11.9993031947179
KB              = 6.65991281864039
KG              = 11.7527873270125
b               = 24.5549068301047
BM              = 7.83560518385288
Ndiesel         = 2
Ngt             = 2
Pdiesel         = 18.0
Pgt             = 28.6216
Ld              = 108.733084256193
a               = 81.1095178233249
Cdch            = 0.7
Cdsh            = 0.720656591351393
Wss             = 72.5781291734743
BOL             = 56.9990240763412
```

```
Wdeck             = 5577.91171867225
Whullmisc         = 712.08216985325
Wlwtmisc          = 1352.94951200966
Vd                = 67647.4756004828
Wsh               = 186.4093909601
Wch               = 4172.96535538991
Whull             = 10908.3561550091
AreaCargodeck     = 4648.25976556021
Hship             = 32.9986063894358
Vdch              = 62473.3423684586
Vdsh              = 2587.06661601213
Wo                = 2029.42426801449
LWT               = 15112.8107350332
AnnualCargo       = 262710.0
NTRIP             = 210.0
CARGOarea         = 18593.0390622408
Paux              = 0.466216379381155
WFUELfullspeed    = 266.71608
Tfullspeed        = 30.0
Ppilot            = 21.844686389478
WFUELaux          = 0.372973103504924
Payload           = 12510.0
Ttrip             = 40.0
WFUELpilot        = 27.3058579868475
WFUEL             = 294.394911090352
Nteutrai          = 1251.0
RFR               = 0.631319949061912
SCOST             = 135757373.154962
Cmi               = 14661796.3007359
Ccs               = 1050000.0
ACF               = 24729172.5315896
CMACHINERY        = 25302213.76
ACFLEET           = 132683251.054444
Ccrew             = 2520000.0
ACpilot           = 273000.0
CMm               = 14000.0
```

```
ACLO              = 241.92
CHULL             = 56941619.1291475
COUTFIT           = 16235394.1441159
AFvolume          = 262710.0
ACC               = 23757540.3021184
ACch              = 65677500.0
CMISC             = 37278146.1216989
G1                = 0.438397978703774
G2                = 0.375019850128545
G3                = 0.333270179558544
G4                = 0.495983556621866
G5                = 0.233108189690578
Fnvol             = 0.743975334932798
G6                = 0.0799360511590727
Whullnodeck       = 5330.44443633683
LWTnodeck         = 9534.89901636097
AreaCargodeckMAX  = 4689.8741149973
TotalDeckArea     = 18593.0390622408
LdMAX             = 109.706535997668
HWCch             = 23.9986063894358
HWCsh             = 19.890008594345
G7                = 0.999982878532302
Wmdiesel          = 450.0
Wmgt              = 372.0808
CMACHINERYgt      = 17562213.76
CMACHINERYdiesel = 7740000.0
```

Appendix 3: Multiple Criterion Results

Execution Results Summary

```
Start time: Tue Jul 26 19:24:01 PDT 2005
End time: Wed Jul 27 17:24:11 PDT 2005



Task: Trimaran
  Total runs:       5000
  Feasible runs:    4306
  Infeasible runs: 694
  Failed runs:      0
  Database file:    Trimaran.db


  Optimization Plan: NCGAgene40
    Executed between RunCounter 83 and 5082 (5000 runs)


    Techniques used:
        Step1: Neighborhood Cultivation Genetic Algorithm - NCGA


    Best design:                currently              previously
    -----------------------------------------------------------------
        RunCounter          4982                   83
        ObjectiveAndPenalty 18258730.295631        62214953.6792023
        Objective           18258730.295631        62214953.6792023
        Penalty             0.0                    0.0


    Best design ObjectiveAndPenalty value improved by
    43956223.38 (70.65%) after executing this Optimization Plan


    Best design parameter values:


        Cbsh             = 0.479379285602954
        Cbch             = 0.47660390751812
        Vk               = 26.9466384593397
```

```
Bch                = 13.0074826888631
Bsh                = 6.80693562095985
Tch                = 4.31080386022222
lambda             = 0.0395708022786494
lamdash            = 0.144005677078576
Lch                = 103.810630820817
beta               = 0.229737989961905
alpha              = 1.94708846089543
Nd                 = 2
CO                 = 3.647572
CF                 = 0.0015095664306655
RES                = 733704.922817934
WS                 = 1365.05352274021
PfullSpeed         = 15.6646213305715
Fn                 = 0.434944549804941
Displ              = 3088.03320751014
WSsh               = 62.5436822895391
WSch               = 1239.96615816113
CK                 = 0.000288568107537549
V                  = 3012.71532440013
RE                 = 1118476340.78107
Sl                 = 6.9893044995233
Displch            = 2843.64130454156
Displsh            = 122.195951484287
Tsh                = 2.44388407519848
Peffective         = 10.1820038648715
Vs                 = 13.8775188065599
Vch                = 2774.28419955274
Vsh                = 119.215562423695
REsh               = 174776303.229657
REch               = 1213676479.81191
Slch               = 7.38796530556248
Slsh               = 3.03745924531048
CR                 = 0.0054457065382005
Lsh                = 14.9493201793058
GMt                = 28.0911737527323
```

```
KBsh             = 1.51588232841425
KBch             = 2.67920501048469
KGsh             = 2.44388407519848
KGch             = 4.31080386022222
KB               = 2.58713778680774
KG               = 4.16305283285567
b                = 22.5705688793027
BM               = 29.6670887987803
Ndiesel          = 2
Ngt              = 0
Pdiesel          = 15.6646
Pgt              = 0.0
Ld               = 20.3482571102068
a                = 20.4148188921612
Cdch             = 0.556037892104473
Cdsh             = 0.581358340477879
Wss              = 7.67668575461875
BOL              = 51.9480733795652
Wdeck            = 475.673739078276
Whullmisc        = 75.3178831100033
Wlwtmisc         = 145.450478357618
Vd               = 7272.5239178809
Wsh              = 30.0446224810474
Wch              = 455.785466730498
Hwc              = 0.0
Whull            = 1074.54301963549
AreaCargodeck    = 792.78956513046
Hship            = 13.1216077204444
Vdch             = 6473.3297989564
Vdsh             = 399.597059462249
Wo               = 218.175717536427
LWT              = 1829.78421552954
AnnualCargo      = 23757.1723926084
NTRIP            = 222.02964852905
CARGOarea        = 1585.57913026092
Paux             = 0.156646213305715
```

```
WFUELfullspeed    = 69.758311517646
Tfullspeed        = 27.832785196257
Ppilot            = 5.86117147394469
WFUELaux          = 0.125316970644572
Payload           = 1070.0
Ttrip             = 37.832785196257
WFUELpilot        = 7.32646434243087
WFUEL             = 77.2100928307215
Nteutrai          = 107.0
RFR               = 1.14864990995219
SCOST             = 18282487.4680236
Cmi               = 1974508.64654655
Ccs               = 1050000.0
ACF               = 6857171.90964017
CMACHINERY        = 6735778.0
ACFLEET           = 21830939.1435905
Ccrew             = 2520000.0
ACpilot           = 288638.543087765
CMm               = 1891.63925981285
ACLO              = 0.0
CHULL             = 5609114.56249726
COUTFIT           = 1745405.74029142
AFvolume          = 23757.1723926084
ACC               = 3199435.30690413
ACch              = 5939293.09815209
CMISC             = 4192189.1652349
G1                = 0.377947153932523
G2                = 0.754353660629816
G3                = 0.928431329188834
G4                = 0.777386867459287
G5                = 0.0783231066528576
Fnvol             = 1.16608030118893
G6                = 0.934579439252336
Whullnodeck       = 598.869280557215
LWTnodeck         = 1354.11047645126
AreaCargodeckMAX  = 1523.43449017651
```

```
TotalDeckArea     = 1585.57913026092
LdMAX             = 39.1014691162935
HWCch             = 8.62160772044444
HWCsh             = 6.7546879354207
G7                = 0.911369708413425
Wmdiesel          = 391.615
Wmgt              = 0.0
CMACHINERYgt       = 0.0
CMACHINERYdiesel = 6735778.0
```

Appendix 4: Flow of Variables