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FINAL 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

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Executive Summary: This report summarizes the work conducted under FY05 CCDoTT program by the MAE department of California State University, Long Beach in collaboration with our research partner, the Computer Science Corporation (CSC). The overall goal of the project is to develop a comprehensive Multidisciplinary Design and Optimization (MDO) tool for multi-hull ships and test and validate the method by applying it to several practical applications. The MDO tool is unique in utilizing advanced multiobjective optimization methods, neural networks, and in its broad scope, integrating powering, stability, seakeeping, structural optimization, cost and payload capacity into a single design tool. The method is a comprehensive and efficient way for the designers to analyze various requirements at the preliminary design stage as well as the subsystem level. Building upon the developments in the FY 04 program, during the FY 05 program, the synthesis level MDO tool was substantially revised and enhanced. These enhancements included the development of new synthesis design model, development of seakeeping subsystem and their integration in the MDO process. The method was then applied to several High Speed ship concepts. Detailed studies were conducted in order to determine the best approach for the application of the MDO tool. Multiobjective optimization results are presented in the form of Pareto optimum solutions, allowing the designer to select the optimum solution of interest. Improvements to the neural network developments and optimization process were also made. Extension of the method to include hullforms optimization, more seakeeping assessment and structural load subsystem is planed for the next phase of the program. Details of various aspects of the FY 05 work are presented in four deliverable reports that have been submitted. This report is a summary of the deliverable reports

Objective: The overall objective of this project is to develop a multidisciplinary design and optimization method for use in the design of multi-hull ships. The MDO method is based on a Systems Engineering approach. Widely used in aerospace industry, Systems Engineering approach can be divided in three distinct phases. In the synthesis design phase the goal is to define the overall system architecture in terms of a limited number of (order of ten) design variables. In the subsystem design phase, the overall system architecture is used as input to define subsystems designs. The final stage of the System Engineering approach generally includes system evaluation and test and system build. In a complex design problem such as a multi-hull ship, many subsystems are multidisciplinary problems as well, thus the MDO methodology developed here can be applied at the system or subsystem level.

Using advanced multiobjective optimization, our method will integrate powering, stability, seakeeping, hullforms optimization, structural optimization, payload and ship cost into a single design tool. Building upon progress made in the FY 04 program [2], the objective of the FY05 program was to enhance and finalize the synthesis level MDO tool and apply it to several practical applications of interest. Furthermore develop the subsystem models for seakeeping, and structural loads and hullforms optimization, for extension of the tool to subsystem design stage.

Approach: The MDO method consists of various “models” to evaluate powering, cost, stability, seakeeping, structural loads, etc. The outcomes of these models are then used by a multiobjective optimization method such as MOGA to perform optimization. The entire process is “managed” by iSIGHT [3], commercially available software designed for optimization applications. This process is schematically shown in Figure 1.

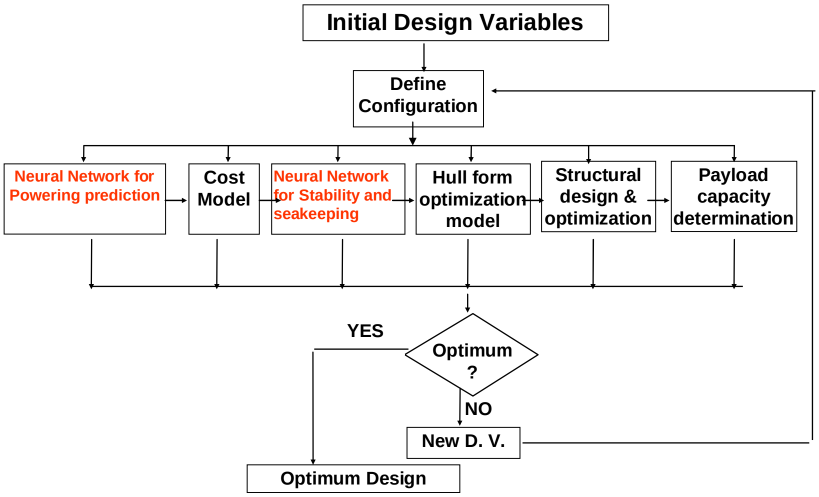

Figure 1: MDO approach

Advances in computational science such as CFD and Finite Element analysis make it possible to evaluate the performances of multi-hull ships' subsystems (such as powering, seakeeping, structural weight etc) to some level of accuracy. However these analysis methods are too complex and computationally intensive to be of practical use to most designers, particularly at the early stages of the design process. Synthesis design tools therefore, rely on empirical or simplified approaches for performance analysis such as powering and seakeeping [4]. Our approach is unique in that it uses artificial neural networks for evaluating such subsystem performances. The methodology has been developed at CSULB and successfully applied to applications in shape optimization under previous CCDoTT program [5] .Another unique feature of our approach is its scope. Unlike other multi-hull MDO tools [4] which are limited to hydrodynamics (powering and seakeeping), our approach integrates powering, seakeeping; cost, hullfroms optimization, structural design and payload capacity all into a single design tool.

The FY 05 program consisted of four tasks. The subsequent sections summarize accomplishments in each of these tasks. Separate deliverable reports with details have been submitted for each of the fours tasks.

Task 4.1 Synthesis Level MDO Tool Development: This task included the development of the synthesis model process and various design relationships for calculating areas, volumes, sizes, weights, stability and costs of multi-hull (trimaran) ships. These relationships are based on many technical literature sources and practical design experiences. Following the FY 04 work, during the FY 05 program, they were extensively revised and enhanced to be consistent with Navy's USCG, ABS regulations, and operational requirements for specific planned applications. They consist of more than 1800 equations organized in various Excel spreadsheets. Synthesis Design Model, in short, achieves a weight - buoyancy, and required - available area/volume balanced design, with required propulsion and auxiliary machinery and with a check on stability. Details of the synthesis design models are presented in Task 4.1 and Task 4.3 deliverable reports. The flow chart in Figure 2 shows the synthesis model process.

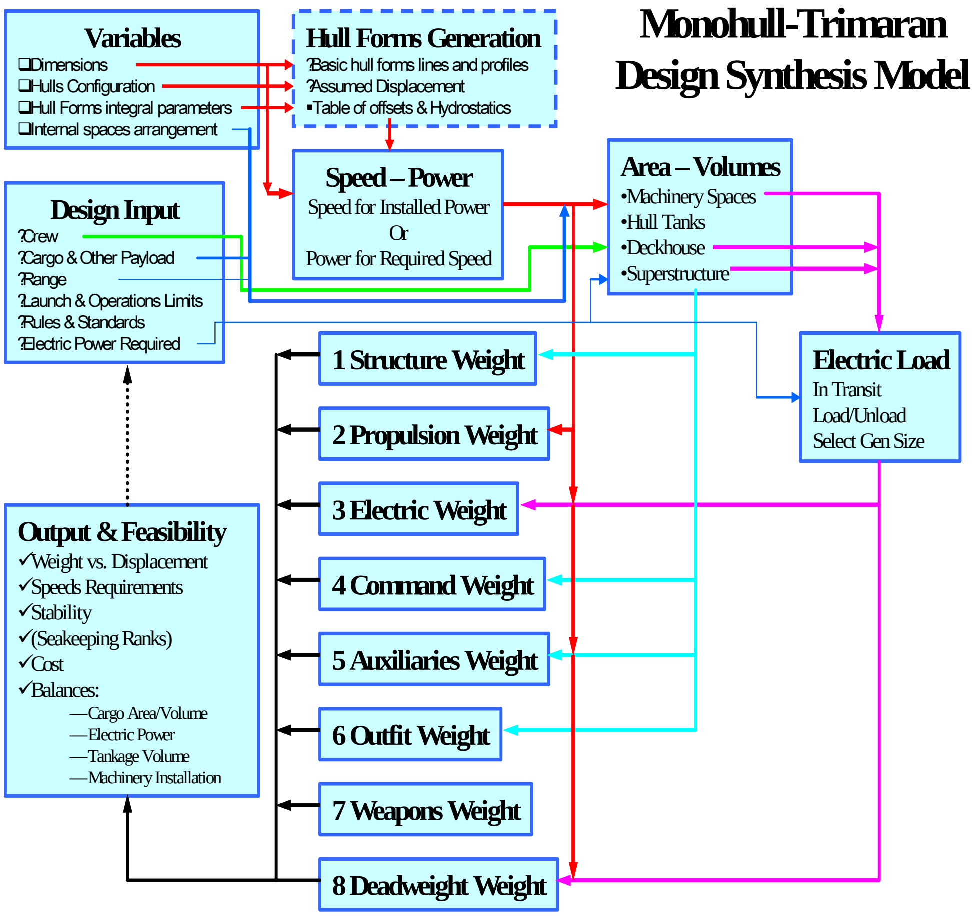

Figure 2: synthesis model process.

The overall MDO method includes the following calculations:

- Speed-power and endurance fuel calculations.
- Area/volume calculations including:
    - ✓ Required length, height and volume for machinery spaces for required propulsion plant and auxiliary machinery.
    - ✓ Required tankage volume for required endurance fuel.
    - ✓ Determines remaining hull area/volume available for payload items.
    - ✓ Sizes superstructure and deckhouse above the main deck to exactly provide area/volume for the remainder of required payload and crew.
- Electric load calculations.
- Weight and center of gravity calculations.
- Required vs. available GM per USCG windheel criteria.
- Cost model.
- Seakeeping and structural loads

Throughout the optimization loop, the powering (Coefficient of Residual Resistance) is evaluated with a neural network trained as a response surface method, using the Cascade Correlation Algorithm. 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 se, but rather is used for stopping the training. The purpose of the VS is to avoid over fitting which can occur with cascade correlation. Details of NN approach and its applications in the MDO process are presented in Task 4.4 deliverable report. A similar approach for inclusion of seakeeping in the method is developed under the FY 05 program which is summarized in the next section. Details are presented in Task 4.2 deliverable reports.

Task 4.2 MDO subsystem developments: Work conducted under this task included the development of nomenclature for seakeeping, the definition of criteria, constraints, and approach for seakeeping performance, and structural loads assessment of multi-hull ships, and integration of seakeeping into multi-hull MDO tool. Similar to evaluation of powering, neural networks were used for inclusion of seakeeping in the MDO process. Once again, the process encompasses three steps.

1. Generating seakeeping and structural loads training set (TS) data using CFD,
2. Training neural networks (NN) for seakeeping subsystem MDO,
3. Integrating the trained neural networks in the MDO process.

The CFD program WASIM was used to generate the seakeeping training set (TS) data. WASIM program solves the fully 3-dimensional radiation/diffraction hydrodynamic problem by a Rankine panel method. For these methods panel models are required for both the hull and the free surface. A typical panel model that is used for generating the seakeeping data is shown in Figure 3

To generate the training set data, sixteen ship responses were evaluated using WASIM code. They include roll, pitch, vertical and transverse accelerations, bending moment, shear force, propeller emergence, etc. These responses are evaluated at sea states 4, 5, 6 and 7, three speeds of 15, 25 and 35 knots and 5 headings of 0, 45, 90,135 and 180 degrees. Hull configurations consist of the following variations:

- stagger of side hulls 0.00, 0.24, 0.40 & 0.80
- separation of side hulls 0.36, 0.75, 1.25
- overall vessel size 150m, 200m, 250m & 300m

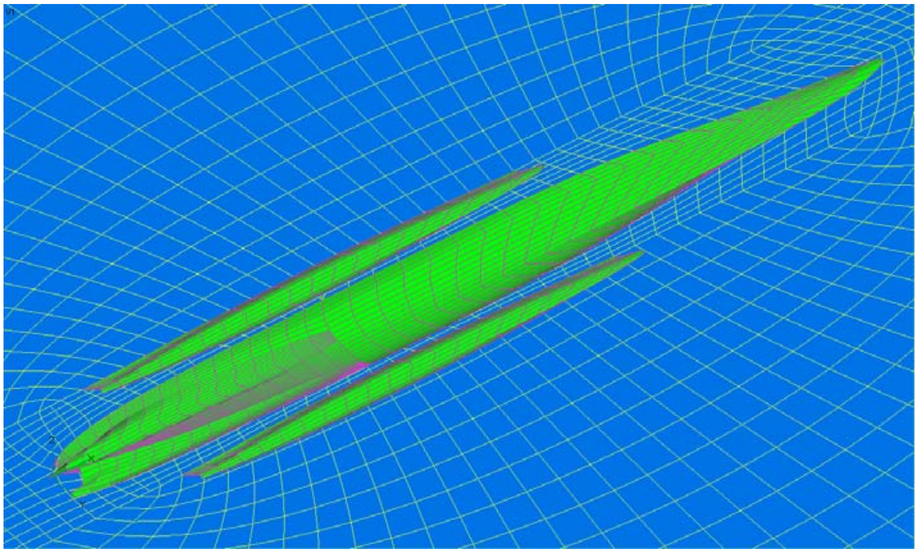

Figure 3: Trimaran paneling for WASIM

The ranges of these parameters were selected based on the initial results, and in order to avoid studying options that were undesirable or unreasonable. These configurations represent 48 hull variations at 60 environments and 16 Criteria leading to a total of 46,080 data points for the training set.

Two approaches were studied for the integration of the seakeeping in the MDO process. The first approach is based on computing a seakeeping index as described in reference [6]. This “seakeeping index” can then be minimized as one of the objective functions in the multiobjective optimization process. The second approach is the direct imposition of seakeeping constrains based on some acceptable transit motion criteria. The motion and seakeeping criteria for the vessel while under transit conditions have been derived from the seakeeping criteria for the transit and patrol mission for a NATO Generic Frigate [7]. The limits for the transit condition are listed in Table 1 as single amplitude RMS values of roll motion; pitch motion, vertical and lateral acceleration, bottom slamming and propeller emergence.

Parameter	Limit Value
Roll Angle	4.0 deg
Pitch Angle	1.5 deg
Vertical Acceleration	0.2 g
Lateral Acceleration	0.1 g
Bottom Slamming Index	20 per hour
Propeller Emergence Index	90 per hour

Table 1– Transit Criteria

The roll angle criterion for the transit condition is independent of the roll period. The pitch angle criterion is independent from the pitch period of the vessel.

While imposition of all constraints for all environmental conditions (speed, sea state and headings for a given configuration is impractical, selected representative constraints can be imposed. As an example, in our application, eleven criteria were retained; Roll <4 deg. (for

SS6, all speeds and 45, 90 and 135 deg, and Vertical Acceleration @ Stern Centerline<1.962m/s2 for SS7, 15 knots, 0 & 180 deg. Eleven neural networks corresponding to these criteria were trained and the outputs were combined into a MATLAB program which gives the eleven constraints for each combination of ship length, stagger and separation during the MDO process. Details of the method are presented in the Task 4.2 deliverable report. Some results are presented in Task 4.3 deliverable report. Using other constraints and using the seakeeping index approach is planed as part of the next phase of the work.

Task 4.3 Application: In this task, the MDO method was applied to three different design requirements of interest. Several single and multiobjective optimizations with and without seakeeping constraints, have been performed. A very detailed study has been conducted in order to determine the best approach for application of the method. Results of this section indicate that a careful optimization process, including selections of proper algorithms and proper initial population, have to be followed in order to obtain complete and meaningful results. This process and results are described in detail in Task 4.3 deliverable report. A sample case is summarized here.

The application of the synthesis level MDO tool consists of

- Definition of the design space, constraints and measure(s) of merit
- Running the MDO program to search the multi-dimensional design space using single or multiobjective optimization algorithms
- Construction of feasible and Pareto optimum solution sets
- Subsystem requirement definition corresponding to optimum measure(s) of merit.

Applications in this work are based on different High Speed Sealift Ship (HSS) concepts such as basic Army and USMC requirements for JHSS concept, and High Speed Connector (HSC) concept such as basic JHSV. For high speed sealift applications, multicriteria optimization is generally necessary. More specifically, Lift-to-Drag, Light Weight (LWT) -to-Displacement and Cost are considered as objective functions. Furthermore, each requirement has its distinct constraints which are generally derived form mission requirements. Their purpose is to avoid exploring unreasonable designs.

The schematic of a generic trimaran configuration considered, is given in Figure 4. For synthesis level models, the specifics of the hull forms are not important, since all models (Stability, seakeeping, structural load, powering, weight, etc) are considered independent of hullforms. Configuration (spacing and stagger) however are considered as design variables. Incorporation of a parametric, non-dimensional offset representation of the ship hulls in the MDO along with means to transform offsets for variations in block and midship coefficients, center of buoyancy, widths and depth of transom length, area of bulb, etc are planned for the next extension of this work.

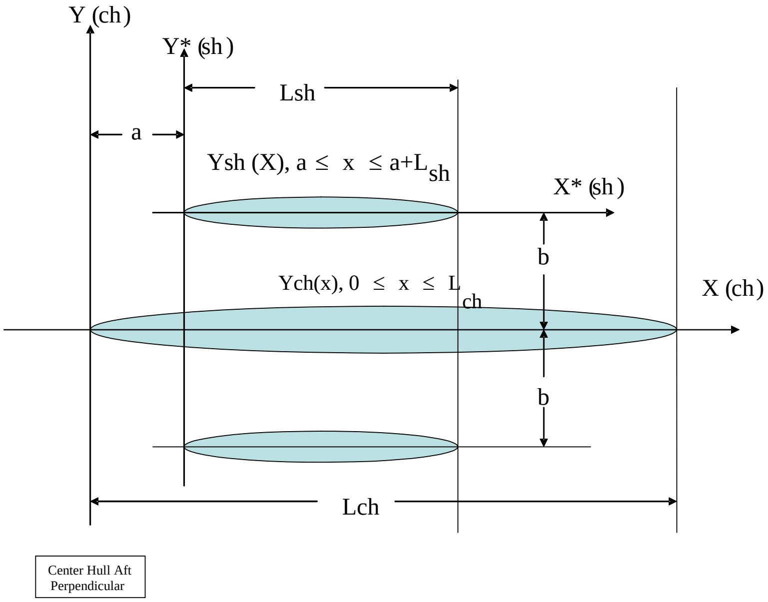

Figure 4: Trimaran Configuration (Top View)

The group of Design Variables defines the Trimaran geometry. This group includes the major hull dimensions and coefficients, basic configuration features and dimensional constraints. Since the hull dimensions include the draft this input establishes an assumed ship displacement with which to begin analysis. The configuration options include flooding standard (one or two compartment) which will control transverse bulkhead spacing and choice of freeboard deck (main or second deck) which will affect the stability analysis and extent of tankage. The dimensional constraints include both operational and building/launching considerations.

The example cases reported here is based on a High Speed Sealift (HSS) concept similar to the Army requirements of JHSS. Table 2 shows the design variables and their prescribed range. Table 3 shows other constraints that are imposed on the optimization process.

DESIGN VARIABLES	**LOWER BOUNDS**	**UPPER BOUNDS**	**Description**
Lch	800	1000	Length on Waterline Center Hull
Bch	70	80	Beam Center Hull
Dch	40	55	Depth Center Hull
Tch	20	30	Draft Center Hull
Cbch	0.45	0.70	Block Coefficient Center Hull
Cmch	0.66	0.80	Max Section Coefficient Center Hull
Lsh	200	300	Length on Waterline Side Hulls
Bsh	10	15	Beam Side Hulls
Dsh	30	55	Depth Side Hulls
Cbsh	0.45	0.70	Block Coefficient Side Hulls
Cmsh	0.66	0.8	Max Section Coefficient Side Hulls
Alpha	0.75	2.0	Separation
Beta	0	0.85	Stagger

Table 2: Design variables for HSS

Constraints	**lower bounds**	**upper bounds**	**description**
Tsh	3	30	Draft of Side Hull
cwtdispl	-300	300	Calculated Weight – Assumed Displacement
inrepower	-10000	100000	Installed – Required Power
chfb	15	30	Center Hull Freeboard

Table 3: Constraints for HSS

Here the center hull freeboard (chfb) is the difference between Depth of center hull (Dch) and Draft of center hull (Tch), “inrepower” is the difference between installed power and required power. Installed power is the amount of power generated by ship using advanced water jet propulsion for gas turbines as per the specifications to power generation.

The two objective functions for this case are to minimize the Lightship to Displacement Ratio (Wlsoverd) and to maximize the Lift over Drag (Loverd). Several optimization cases were run. Single objective optimization Sequential Quadratic Programming (NLPQL) and Multi-Island Genetic Algorithm (MIGA) were run for each objective (Lightship to displacement ratio and Lift over Drag). Multiobjective Genetic Algorithm (MOGA) which is a global search method was run using the Neighborhood Cultivation Genetic Algorithm (NCGA). Figure 5 below shows the results of single objective cases (max L/D and min Wls/D) and the distribution of the Pareto optimum solutions between the (two) single objective optimized solutions. It also shows the distribution of the 369 specified initialization points

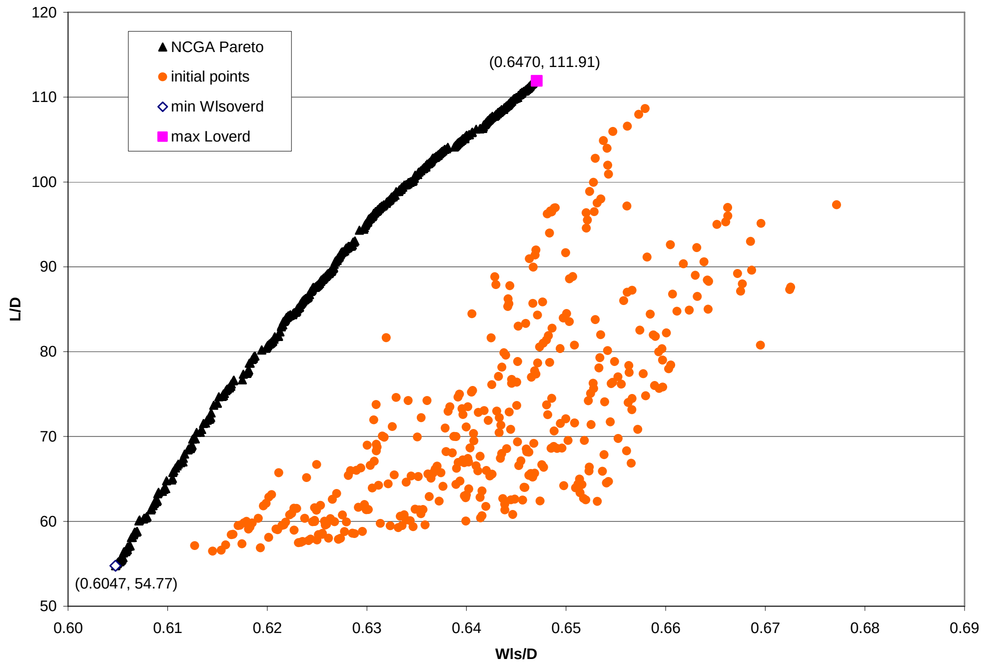

Figure 5: Optimization results (Wls/D vs L/D) for NCGA with 369 initial points

Close examination of the (500) Pareto optimum solutions indicate that they fall within approximately 30 distinct “ship categories” were the length of the center hull (Lch) is the main driving parameter. It is noteworthy that while the Lch range was designated from 800 to 1000 feet, Lch values in the Pareto set range from 935 feet to 1000 feet. No Pareto points were found for values of Lch ranging from 800 feet to 935 feet.

This case was repeated with inclusion of the above mentioned seakeeping constraints. Furthermore, two other cases have also been studied in detail. They are based on USMC requirement of JHSS (referred to as JHSS light) and a High Speed Intra Theater Ship concept similar to JHSV. Detailed of these cases and analyses of results are presented in the Task 4.3 deliverable report submitted.

Task 4.4 Improvement of Neural Networks for Numerical Optimization: The work conducted under this task consists of a comprehensive study of artificial neural networks for application in the numerical optimization process, as well as improvements to our previous neural network development.

The modern approach used in the design of a complex system (the ship or component inside the ship) usually includes at some level an optimization as shown in Figure 6. In practical cases, the *design tool* may either be an optimization or design-of-experiment 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 CFD and finite element analysis, and use of existing databases. Such optimization or trade study usually has to be able to handle a large number of design variables (say up to 30 or more) and explore the entire design space

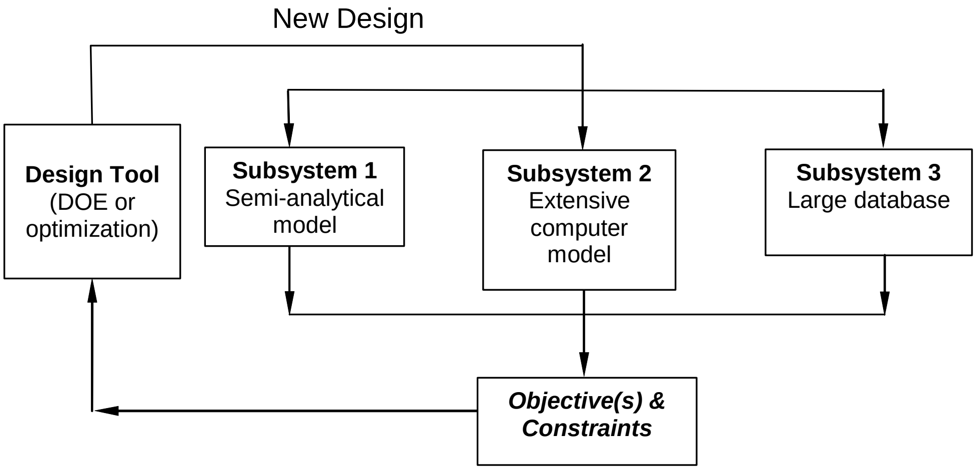

Figure 6: Generic system design loop

Building upon several previous successful applications, our optimization process utilizes a neural network-based Response Surface Method for reducing the cost of computer intensive optimizations for applications in ship design. Complex or costly subsystems analyses are replaced by neural networks which are used to estimate the value of the function(s) of interest.

The cost of the optimization is thus shifted to the generation of (smaller) data sets used for training the network. In some applications these data may already exist.

The focus of our work is on the use and analysis of constructive networks, as opposed to networks of fixed sizes, for treating problems with a large number of variables, say around 30. The advantages offered by constructive networks have led us to the selection of the Cascade Correlation algorithm. This topology allows for efficient neural network determination when dealing with function representation over large design spaces without requiring prior experience from the user. During training, the network grows until the error on a small set (validation set), different from that used in the training (training set), starts to increase.

In our study, the method was validated for a mathematical function for dimensions ranging from 5 to 30 and the importance of analyzing the error on a set other than the training set is emphasized. Improvements to the algorithm used the method of Ensemble Averaging, which consists of using an ensemble of networks to approximate the function instead of a single network. Ensemble averaging results show an average error 40% lower and a standard deviation 51.5% lower than the single best network. An example is shown in Figure 7.
Details of these developments are described in deliverable report for Task 4.4 as well as a paper submitted to the Journal of Ship Research for publication

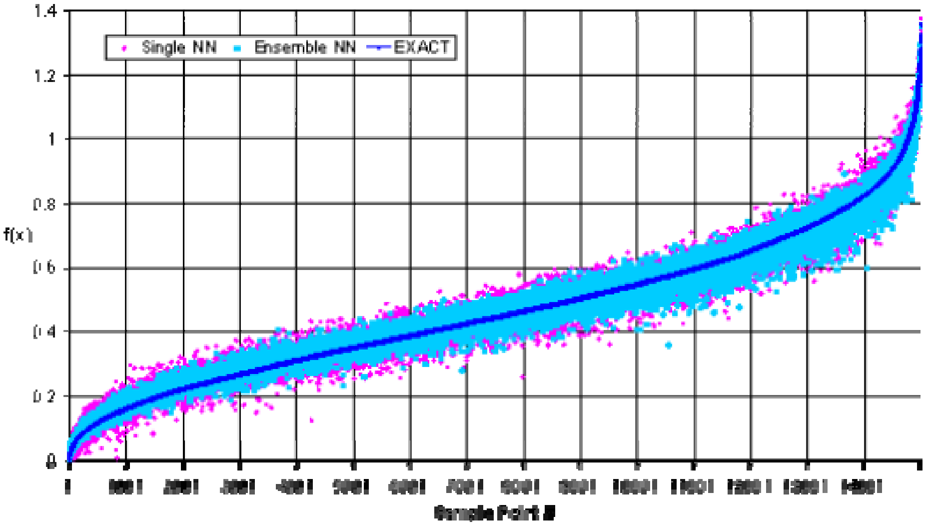

Figure 7: Comparison of NN values between the Ensemble Network and the "best out of ten" Network.

Conclusion: Building upon the FY 04 work, during the FY 05 program the synthesis level MDO design tool for multi-hull (trimaran) ships has been substantially enhanced to include new design relationships for calculating areas, volumes, sizes, weights, stability and costs of multi-hull (trimaran) ships, consistent with Navy's USCG, ABS regulations, and operational requirements for specific planned applications as well as seakeeping. The method has been applied to several High Speed Sealift applications for testing and validation. Extension of the method to included hullforms optimization, more detailed seakeeping and structural loads assessments, and structural optimization are planed for the next phase of the project.

Glossary of Acronyms:

ABS - American Bureau of Ships
CFD - Computational Fluid Dynamics
HSS - High Speed Sealift Ship
JHSS - Joint High Speed Sealift Ship
JHSV - Joint High Speed Vessel
LWT – Light Weight
MDO - Multidisciplinary Design and Optimization
MOGA – Multiopbjective Genetic Algorithm
MIGA – Multi-island Genetic Algorithm
NN- Neural Network
NLPQL - Sequential Quadratic Programming
NCGA – Neighborhood Cultivation Genetic Algorithm
TS – Training Set
VS – Validation Set
USCG – US Coast Guard
USMC- US Marine Corp

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