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FINAL REPORT

Phase I Development of an Advanced System of Systems Design Capability Contract No. N00014-06-M-0250

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by

Frank DeBord
Tobin McNatt
Janel Nixon

Submitted to:

Office of Naval Research
One Liberty Center
875 North Randolph Street
Arlington, VA 22203-1995

Submitted by:

Chesapeake Marine Technology, LLC
7614 Thanksgiving Road
Easton, MD 21601

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1. EXECUTIVE SUMMARY

As Phase I of an STTR project, a system specification was developed and an inception-phase test case was completed, to determine the feasibility of creating an Advanced System-of-Systems (SoS) Design Capability to aid design and evaluation of alternate naval vessel designs as one component in a nested system-of-systems. This capability is intended to provide the Navy with a capability to quickly and accurately analyze trade-offs between vessel characteristics, vessel performance, mission capabilities and cost. The test case presented is a notional CG(X) with varying ship size and speed, and these varying parameters are related to mission capabilities in terms of a "Combat-Weapons Capability Index".

Results of this Phase I effort have lead to the conclusion that completing such an analysis is feasible, and in fact the technology already exists through a combination of the ship design software system *Flagship Designer* (Alion Science and Technology Proteus Engineering Division), and advanced modeling and visualization techniques developed at the Georgia Institute of Technology Aerospace Systems Design Laboratory.

During completion of this work, the project team has determined that the only major impediments to complete demonstration of this capability are inclusion of accurate mission systems performance models, and cost models for these systems and the ship. Since these models may be proprietary or classified, it is not believed to be practical to include them in an STTR Phase II Project. Therefore, it is recommended that further development of the Advanced System-of-Systems Design Capability continues as part of an ongoing ship design program rather than continuation of this STTR. This approach would provide the Navy with a direct benefit for the selected ship design program, as well as further development of the SoS design capability for future projects.

2. INTRODUCTION

This report contains the findings from Phase I of the STTR Project to investigate development of an Advanced System of Systems Design Capability for future U.S. Navy ship designs. The project team included Chesapeake Marine Technology, Alion Science and Technology Proteus Engineering Division, and the Georgia Institute of Technology Aerospace Systems Design Laboratory.

The overall objective of the System of Systems (SoS) Design Tool is to permit evaluation of alternate ship design variations with the ship as the central component in a nested set of systems and sub-systems, as illustrated in Figure 2.1. Such a tool would permit early-

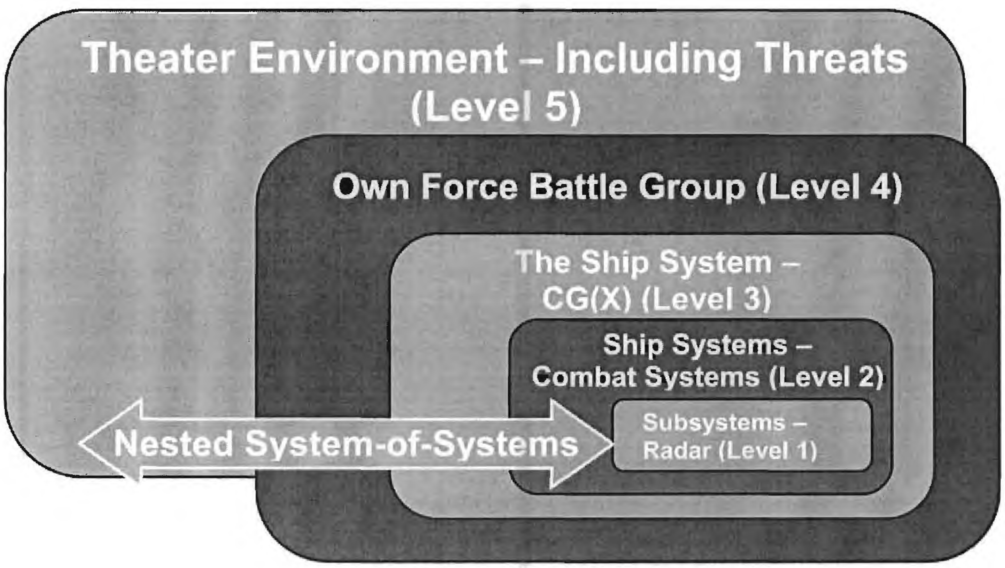

Figure 2.1 – Nested, Ship-Centered System of Systems

stage evaluation of ship capabilities as compared to mission needs, and would also permit trade-off analyses of ship capabilities and characteristics versus cost. Given realistic modeling of the interactions between the different system levels shown in Figure 2.1, the methodology would also permit designers and users to track the effects that changes to any component system would have on parent systems and mission capabilities.

As stated in the Phase I STTR proposal:

The ultimate objective of the Phase I work is to demonstrate the feasibility of an advanced SoS design tool that enables ship-centric capability analysis early in the design process. Fulfillment of this objective is dependent on the proposed approach to overcome several key technical barriers:

- A rapid, integrated, object-oriented ship design tool is needed to prototype future naval architectures that are based on emerging technologies.
- The design tool must facilitate system trades and technology identification without slowing the pace of the design process. "Analysis paralysis" must be avoided at all costs.
- A methodology that facilitates trade studies across a hierarchical system architecture comprised of heterogeneous systems such as surface vessels, aircraft, missiles, carrier battle groups, blast resistant coatings, and projectiles is required.
- Physics-based models across this hierarchy may be at different levels of fidelity. Qualitative and quantitative information may also be present at various levels.
- The proposed approach must avoid "point-designs" and must focus on traceable sensitivity analysis of system alternatives.
- Top-level (Campaign or Theater) simulations are often hard-coded for an example scenario. The design tool must be flexible, parametric, and transparent to the user to enable trade studies against variable threat systems under a variety of operating conditions.
- The significant amount of data generated by the design of advanced ship architectures and the heterogeneous systems that interact with them is nearly impossible to comprehend. An approach is needed that captures the physics of the problem, allows the decision maker to *visualize* the results, and facilitates real-time design in a system-of-systems framework.
- To facilitate the transition to Phase II, the proof-of-concept exercise should be a "plug-and-play" module into the broader simulation that addresses the multivariate tradeoffs applicable to simultaneous considerations of performance, capabilities, and cost parameters for a complex SoS.

As a starting point for developing these capabilities, the current Phase I project focused on evaluating the feasibility of combining two existing, relatively mature technologies. These technologies are:

1. *FlagShip Designer* – Proteus Engineering's integrated suite of ship design software; and
2. The advanced systems modeling and visualization capabilities of the Aerospace Systems Development Laboratory (ASDL) at Georgia Tech.

The combination of these two existing sets of tools is intended to provide the backbone of the System of Systems Design Capability, with *FlagShip Designer* contributing capabilities to rapidly produce high-fidelity, realistic ship designs, and the ASDL modeling and visualization technologies contributing capabilities to model the interactions of these ship designs with parent systems and mission capabilities.

Since this Phase I effort was a feasibility demonstration, the work included the following specific objectives:

1. Finalize the high-level strategic purpose of the System-of-Systems design capability and specify a business strategy for implementation,
2. Complete a Systems Analysis to define required development, and
3. Complete an initial development and implementation cycle to identify any problems with the proposed approach and more clearly define work required to meet system objectives.

The following sections of this report provide a discussion of the Phase I effort and results, and recommend an approach for implementing this technology.

3. PHASE I WORK PRODUCT AND FINDINGS

The Phase I effort included three tasks:

1. Definition of Business Strategy and Requirements,
2. Systems Analysis and Design, and
3. Implementation of Inception Phase Capability.

Results of each of these tasks are included in the following paragraphs.

3.1 Technical Strategy

The primary objective of the final environment is to support capability-based design trades for future naval systems. To accomplish this, the design tool must allow for both *top-down* and *bottom-up* design, and allow for both of those to be done in a timely fashion. The traditional systems engineering approach is based on an iterative top-down design approach, in which there exists a hierarchy of decision making levels. At the top level, some operational needs produce an overall capability description. This capability description is used to define and feed system level requirements into the next level, in which the system is described by certain performance characteristics. This then produces subsystem level requirements that are fed to the subsystem level. This process is depicted in Figure 3.1.

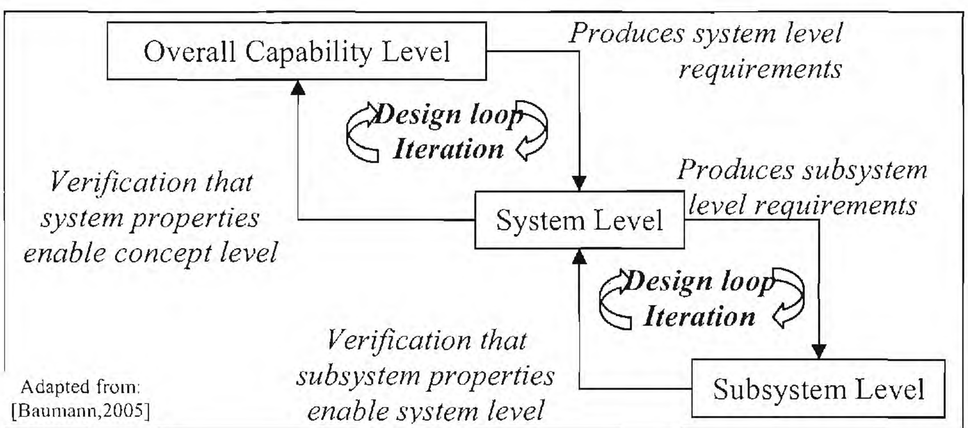

Figure 3.1 - Top-Down Flow of Hierarchical Requirements

The drawback to this top-down process is that there is no direct flow between nonadjacent hierarchy levels. As a result, there must be iterations between all levels to ensure that the design solution satisfies all requirements. This process is often extremely cumbersome for large, complex problems that have many requirements that must be satisfied. For this reason, there is the need for a new process that enables rapid manipulation across a hierarchy of decision making levels.

Accomplishing this goal relies, in part, on the ability to populate the design space with enough data points to adequately represent the entire region of interest. However, that requires the ability to rapidly manipulate the design across the entire systems-of-systems hierarchy in order to collect the large number of data points needed. Since this is not usually feasible for traditional, physics-based modeling and simulation tools, surrogate models of these tools are often created to provide for faster manipulation. These surrogate models are created using a relatively sparse set of seed data from the original modeling and simulation code. Once created, the surrogate models are then used to perform a Monte Carlo simulation, in which the design space is populated with a very large number of data points created by the surrogate model.

With the design space fully populated, the designer is then able to visualize the impact of each of the independent variables on each Measure of Effectiveness (MOE). This allows the designer to identify trends, verify that that original analysis is performing as expected, and identify designs that meet all the constraints. In addition, this environment allows for nearly instantaneous bottom-down or top-up design trades.

3.2 Technical Approach

To address the basic modeling of the ship and its systems and subsystems, Proteus Engineering's *FlagShip Designer* was used. The architecture and capabilities of *FlagShip Designer* are shown in Figure 3.2.

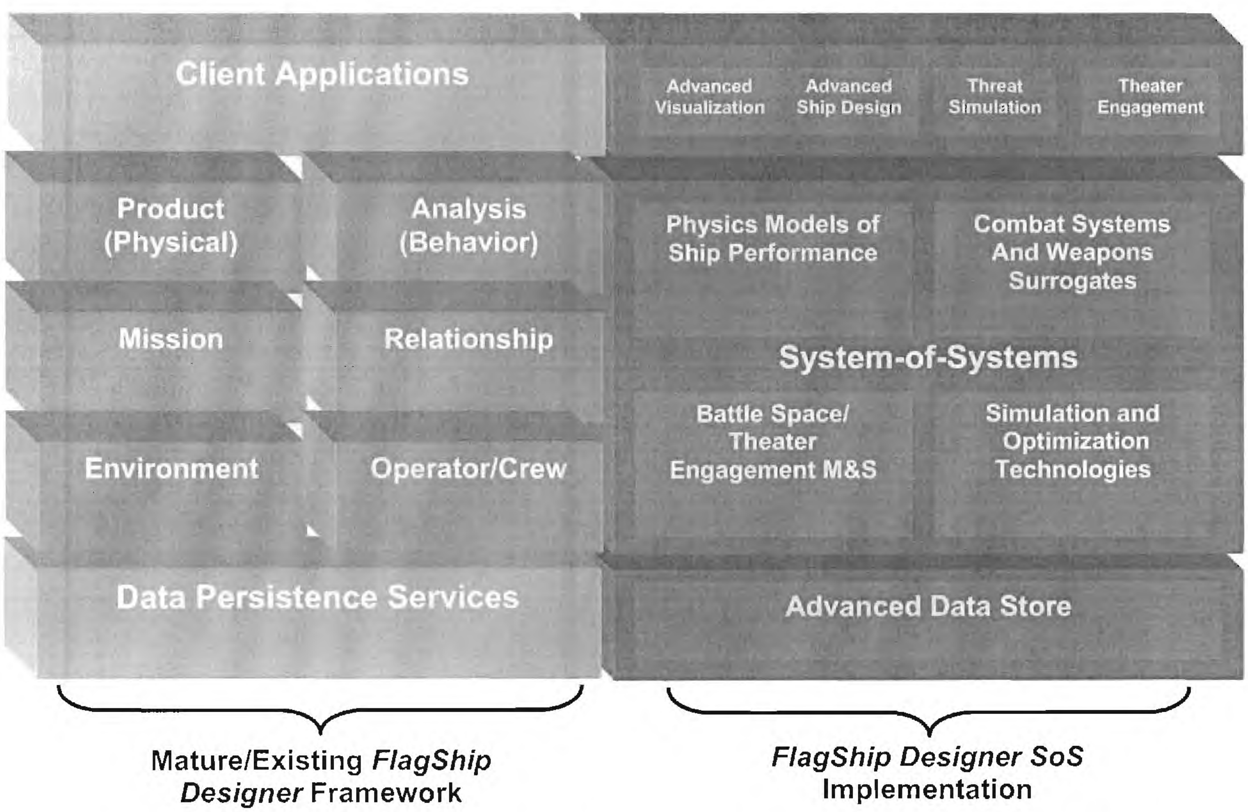

Figure 3.2 - Existing Flagship Designer Framework Applied to the Implementation of a System-of-Systems Advanced Ship Design Capability

On the left side, Figure 3.2 illustrates the three-tier, object-oriented architecture of the *FlagShip* Smart Product Model framework. On the right side, Figure 3.2 identifies specific major components of the *FlagShip SoS* product that will be developed. Note that the *FlagShip* existing framework is a mature software product that is in use within the industry for ship design and engineering. Key technology components of the system include:

- *Use of* FlagShip Designer *Framework for initial system modeling* –The paradigm shift in design capability comes from the architectural framework of the environment, which will allow the individual models/systems/subsystems to interact with each other within prescribed scenarios.
- *Development of Surrogate Models* – Traditional modeling and simulation approaches require extensive computation that is not well-suited for problems of this scale. Surrogate models such as RSEs and neural nets are needed to facilitate agent-based modeling at the system-of-systems level and enable physics-based technology forecasting techniques developed under ONR's affordability initiative.
- *Creation of Agents* – Creation of an agent-based design structure begins with those same agents. Each individual ship, submersible, aircraft, satellite, missile, engine, system or subsystem must be defined in terms of design variables, performance and costs. The creation of these agents will involve a combination of first order methods, empirical legacy codes, surrogate models in the form of RSEs or neural networks, and physics based design tools. The partnership's knowledge and experience with aircraft, UAV's, propulsion systems, ships, submarines, torpedoes, missiles, sea-basing platform concepts and associated technologies provides the necessary experience for the creation of the variety of agents required for the architecture.
- *Technology Propagation* – With the creation of agents and the architecture framework, the next focus is on the application of technologies and technology portfolios. While *FlagShip* provides the designer with top level vision and control, it also allows for changes at the subsystem level. A crucial element in the design environment is the ability to track how these new technologies propagate up through the system-level and impact the requirements, tactics, scenarios, and theater-level capabilities.
- *Full System Tradeoff* – While the technology impacts are the most critical tradeoffs, it is important to view the impacts of varying requirements, vehicle attributes, tactics and scenarios as well. Combining all of these factors together allows for a complete view of the twenty-first century battlefield. These trades give complete control to the designer and allow for a truly global optimization of design and technology choices. At this stage, it is also important to provide the designer with adequate control to manage the large number of variables.
- *Probabilistics* – The ability to add probability distributions to technology parameters or design variables is an important attribute of the environment. The addition of probabilistics allows the decision makers to capture and quantify

uncertainty associated with technology program development, greatly reducing the associated risk. This technique also creates probability of success statistics for a detailed analysis of the success or failure of agents, missions or tactics.

Using the technical strategy described above, an approach was developed for testing during Phase I. Figure 3.3 shows a notional example of what the trade environment looks like for the notional CG(X) demonstration example. All of the levels in this figure represent either direct inputs or direct outputs from *FlagShip Designer*. Each of these inputs our outputs can be classified as either Operational-Level variables (usually outputs that describe operational aspects of the ship), Scenario-Level variable (usually outputs that describe ship performance), or Subsystem-Level variables (usually inputs that describe the weapons systems).

Within this technical approach, *FlapShip Designer* was used to provide initial data representative of the design space. To do this, the various Subsystem-Level (weapons, radar), and Systems-Level (physical ship characteristics) variables were varied over some range of viable settings. This data from *FlagShip Designer* was used to create the surrogate model of *FlagShip Designer* that will be valid only for the design variable ranges being investigated. The environment shown in Figure 3.3 was then generated using a commercial statistical software package. The design space was populated with many data points that are linked, using response surfaces, in all of the dimensions displayed. As such, one can apply constraints in one or more of the dimensions, and visualize how these constraints affect the other dimensions. Thus, this process enables a response to be treated as an independent variable, and information can flow in either direction of the hierarchy without internal iterations. For the CG(X) example, the designer could determine how increasing capabilities at the operational level affect the displacement of the ship, or conversely, how radar properties at the lowest subsystem level affect the ship's displacement. In effect, the designer can simultaneously see how top-level requirements flow down and how bottom-level attributes filter up.

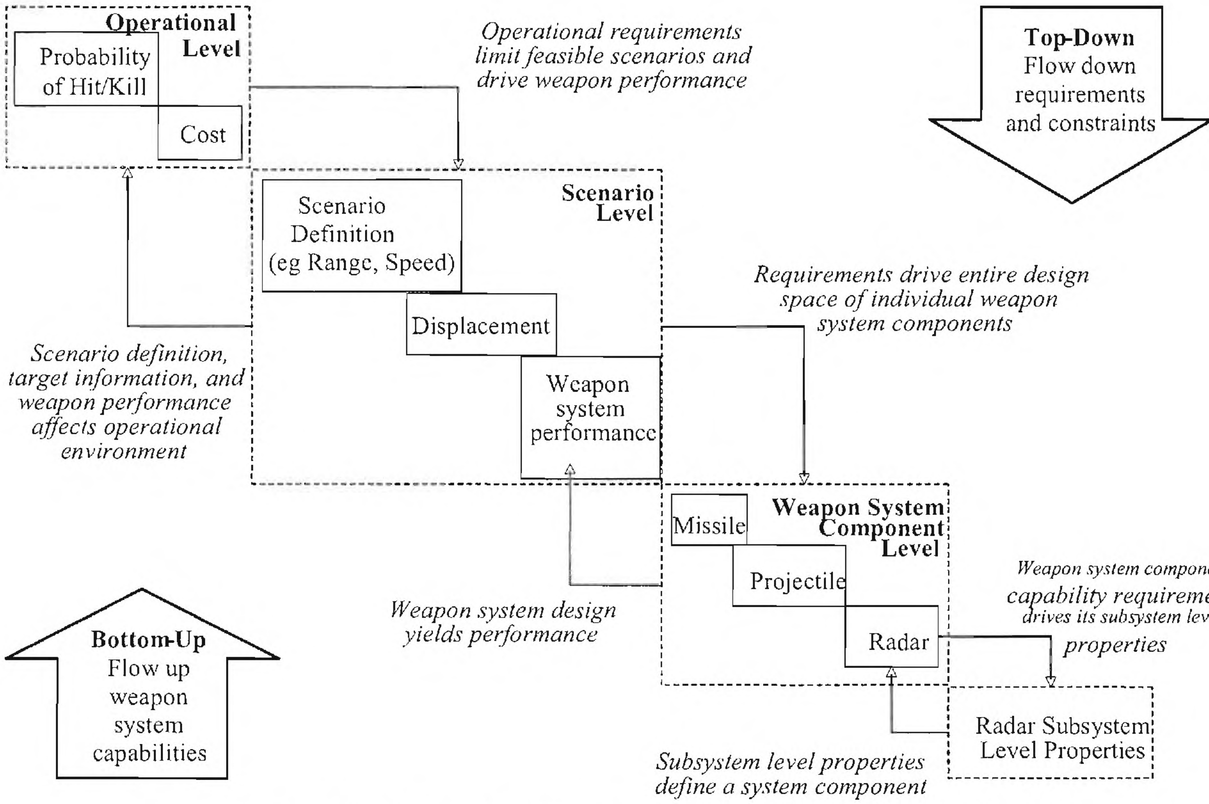

Figure 3.3- Notional Arrangement of Top-Down / Bottom-Up Flow

In order to provide a better idea of what the final environment will look like, Figure 3.4 shows a populated design space for a target intercept problem. In this example, there is an attacking enemy firing weapons. The success of the mission is dependent on multiple capabilities. At the top level, these capabilities mainly include the ability to 1) detect the threats, 2) intercept those threats, and 3) do so in a cost effective manner.

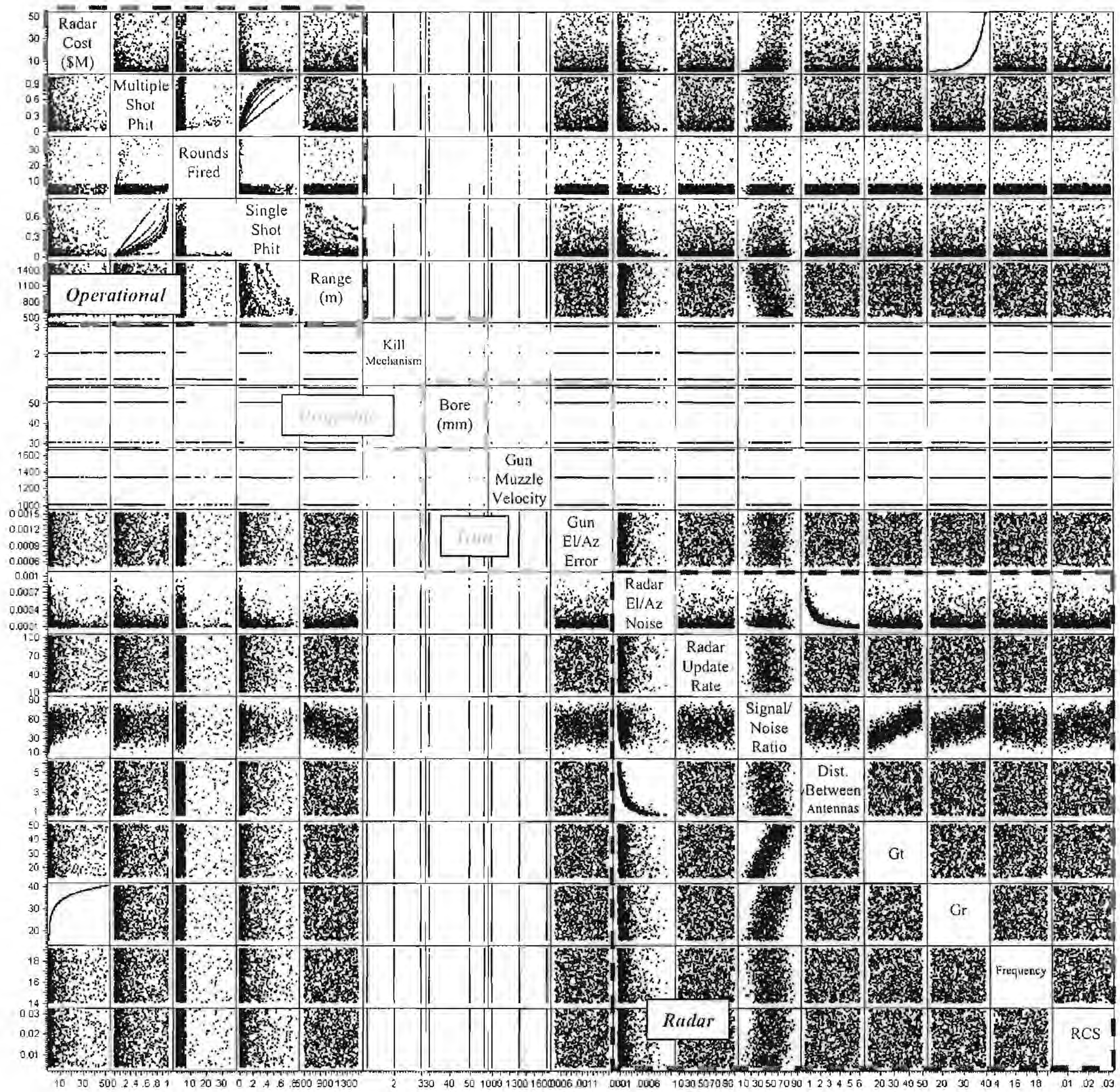

Figure 3.4 –Example of an Assembled Hierarchical Environment

These top-level capabilities translate to radar requirements, types and amount of weapons available, the performance of those weapons (accuracy, range, etc.), and how these systems integrate with the total ship system. At the next level, the specific subsystem characteristics are given for each of three subsystems: (1) the projectile; (2) the gun (firing mechanism); and (3) the radar. Figure 3.5 shows this same example, but with a constraint applied to one of the responses. The points are then color coded such that the red points are those that meet the constraint. This allows the designer to see exactly where those points lie in each dimension of the design space. In this fashion, the designer can whittle the design points by successively applying constraints, and eliminating points until a select few candidate designs remain. These design points will then be used to determine which system concepts warrant further investigation.

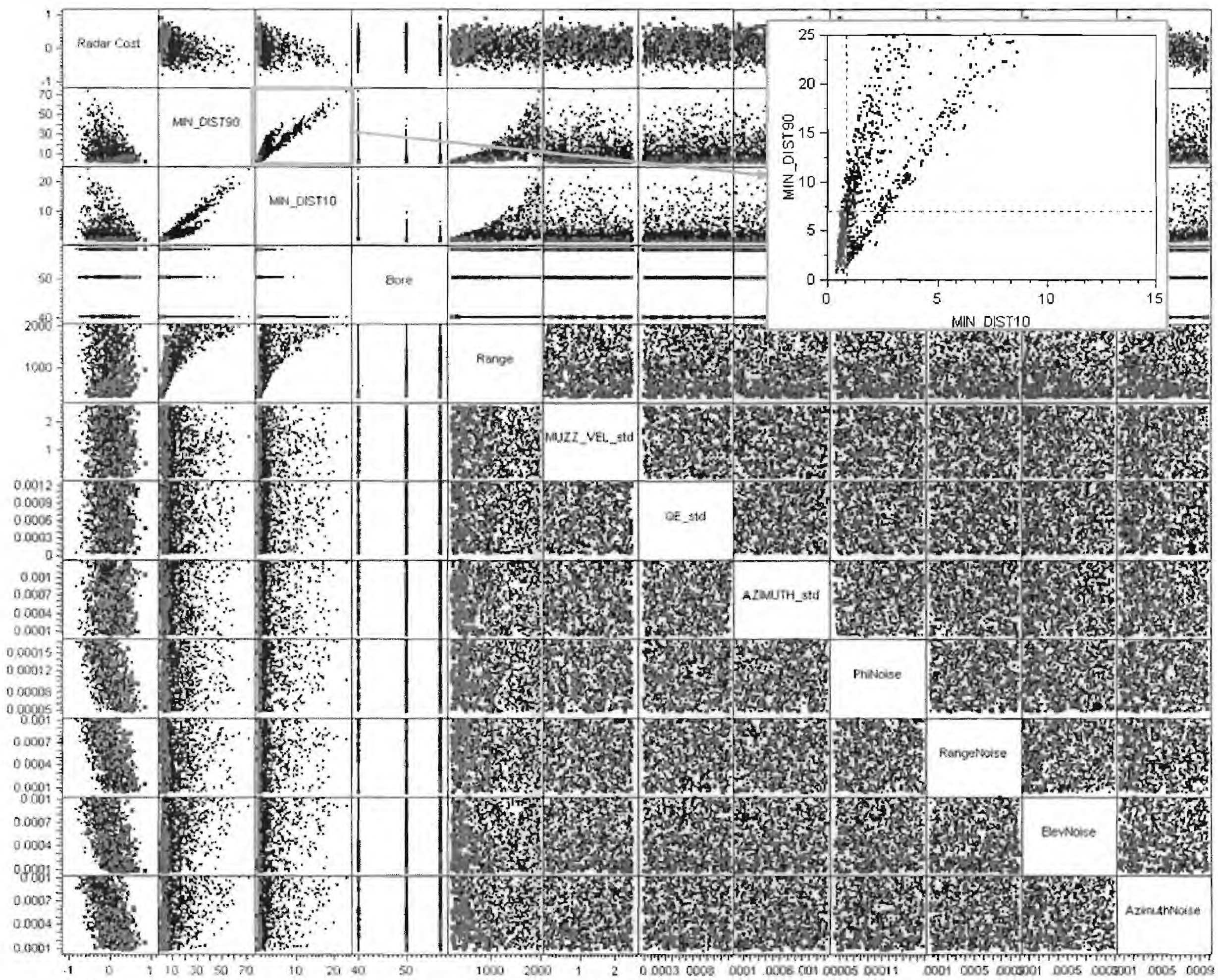

Figure 3.5 - Example of a Constraint Applied to the Hierarchical Environment

3.3 Formulation of Advanced System-of-Systems Design Capability

In order to create a hierarchical environment for feasibility testing, *FlagShip Designer* has been used to model the ship as the central system in this process and create the initial data for a surrogate model. Given the time and resources available for acquiring data, the ASDL advised Alion as to how to set up a Design of Experiments (DoE), for specifying what data was needed to create the surrogate model. It is important that this DoE is set up correctly in order to provide a good, representative set of data that generates a sufficient amount of information in as few runs as possible.

After the DoE cases were run, ASDL used the resulting data to build a surrogate model based on the *FlagShip Designer* results. Results of this feasibility testing are given in

Section 3.6. This process is applicable to the interaction of any of the interfaces between the nested systems and sub-systems, and forms the basis of the approach.

3.4 Preliminary List of Use Cases

To ensure that the strategy and technical approach described above, as well as future development efforts, are consistent with the overall project objectives, a preliminary set of use cases has been developed. These use cases have not been tested during Phase I, but all Phase I work has proceeded such that the final product is capable of addressing them.

The specific use cases that have been identified are:

Types of Vessels and Missions to be Included

A. Surface Combatants (Blue Water and Littoral)
   1. Air Defense for Own Ship and Group
   2. ASW for Own Ship and Group
   3. Surface-to-Surface Engagement
   4. Shore Bombardment
   5. Mine Warfare
   6. Transit and Patrol Capabilities
   7. Special Operations
B. Auxiliaries and Sealift Vessels
   1. Sealift
   2. Fleet Supply
   3. Interfaces with Sea-Bases, Ports and/or Delivery Vessels or Aircraft (RO/RO, LO/LO, Airlift)
   4. Self-Defense
C. Amphibious and Assault Ships
   1. Troop and Equipment Transport
   2. Delivery of Troops and Equipment to Shore
   3. Special Operations
   4. Interfaces with Sea-Bases, Sealift Ships and Auxiliaries
   5. C^3
   6. Self-Defense

D. Sea-Base Platforms
   1. Transit to and Linger at Target Operation Area
   2. Transport Troops, Equipment, Aircraft, Vessels
   3. Onboard Storage and Accommodation
   4. Receive Troops and Equipment from Sealift or Auxiliaries
   5. Transfer Troops and Equipment to Assault and Amphibious Ships
   6. Service and Supply Aircraft
   7. Fleet Supply
   8. C^3
   9. Self-Defense

Phase I development efforts to date, and the Phase I Option demonstration focus on one of these use cases, a surface combatant (notional CG(X)) combat-weapons effectiveness.

3.5 Systems Analysis and Design

Based on the strategy identified in Task 1, ASDL, Proteus, and CMT collaborated to identify the baseline test case, and define the parametric variations used to create a surrogate model of ship principal characteristics and performance versus mission systems capabilities. This process is outlined in Figure 3.6. It was decided that the test case would be a combatant generically similar to DD(X), and that there would be three basic independent variables.

The independent variables are those given in the "Ship and Ship Performance Variations" box. These are listed, along with the initial planned ranges of variation from the base ship, in Table 3.1. Although not an independent variable in the classic sense, a fourth related parameter is one which we call "Combat-Weapons Capability Index". This performance index represents the ship's mission capability level in terms of how installed mission systems scale with physical ship characteristics such as displacement, volume and stability. The reason that this performance index is not an independent variable is that it will be estimated based on the results of FlagShip Designer analyses. Therefore it is really a calculated value rather than an input value.

Table 3.1 - Preliminary Variations for Independent Variables

Length	**-5 to +1%**
L/B	**-12.0% to +14.7%**
Maximum Speed	**Base -3kts, Base +3kts**

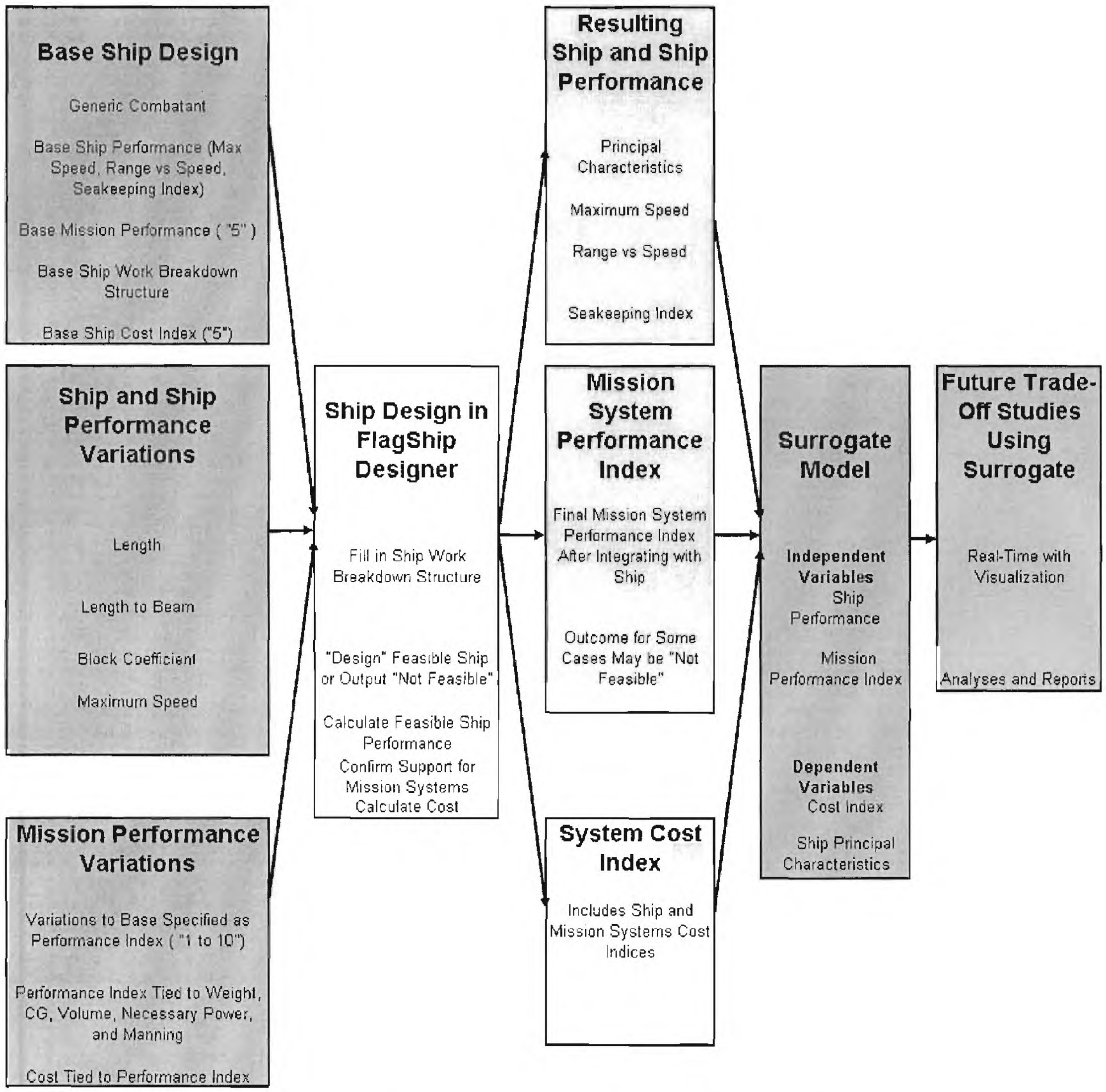

Figure 3.6 - Process for Identifying Baseline and Creating a Surrogate Model

Referring back to Figure 3.6, the overall process proceeds as follows:

1. A Baseline ship is designed in *FlagShip Designer*;
2. Based on a Design of Experiments Analysis from ASDL, a series of Parametric variations to the Baseline Ship is run in *FlagShip Designer*;
3. For each parametric variation, output includes ship principal characteristics, ship performance measures, and a "mission performance index"; and
4. A surrogate model is developed using the results of the parametric *FlagShip Designer* runs that permits evaluation of performance versus ship characteristics in a continuous manner over the complete analyzed design space.

For the range of independent variables defined above, a set of experimental runs was designed to extract the information necessary to create an interactive, real-time model of the relationships between these independent variables and the performance parameters. The designs of experiments were specified in terms of their normalized values. Those values were then converted to actual values input to *Flagship Designer*.

The project team has spent quite a bit of time trying to quantify how the process should function in order to relate global mission performance and mission systems to ship design characteristics and cost. In the end, we have come to the conclusion, that the knowledge necessary to formally do this does not exist within this project team, and in fact, during any ship design process this information will have to be obtained from experts within the Navy. Therefore, the approach outlined above provides the Navy with a tool that will predict platform performance and cost for a range of mission payload capacities and support infrastructure. The next step in this process, which would occur outside the design environment under development within this project, would be to relate specific mission capabilities to these ship capacities. However, we believe that in order to do this intelligently, we need to have a functioning design environment, such that the process can be viewed by potential users, and those that would provide the necessary input.

3.6 Creation of an Inception-Phase Test Case

3.6.1 Test-Case Overview

The test case was developed to exercise and show results from the initial development cycle of the SoS capability within the Phase I STTR project. The test case has two principal components: the *FlagShip Designer* based ship model, and the creation and analysis of a surrogate/hierarchical model based on the results of the *FlagShip Designer* runs. The *FlagShip Designer* modeling is summarized in Section 3.6.2 and the surrogate/hierarchical model under Section 3.6.3. A notional tumblehome surface combatant hull form was developed to serve as the baseline ship for the test case. This notional combatant was populated with a one-digit SWBS model of component weights that are parametrically linked to principal characteristics of the ship. A range of ship sizes was developed, with a total of twenty five unique hulls prepared, along with their corresponding SWBS weight group models. Using the one-digit weights, the specific SWBS 400+700, combat systems and weapons weight budget was calculated. This weight was then applied to a notional/non-dimensional metric to rate the performance of the combat systems and weapons for each hull. The twenty five hulls were also expanded into three speed cases for each hull, yielding a total of seventy five cases of the notional surface combatant.

3.6.2 *FlagShip Designer* Modeling and Analysis/Results

FlagShip Designer Summary

The primary computational tool used in this task was *Flagship Designer*, an integrated ship hullform design, engineering and analysis toolset. *Flagship Designers'* flow activity is shown in Figure 3.7.

General computing tools such as Rhino Marine and MS Excel were also used to supplement *Flagship Designer* to analyze, develop and explore algorithms, create and enhance graphic representations and perform pre- or post-processing.

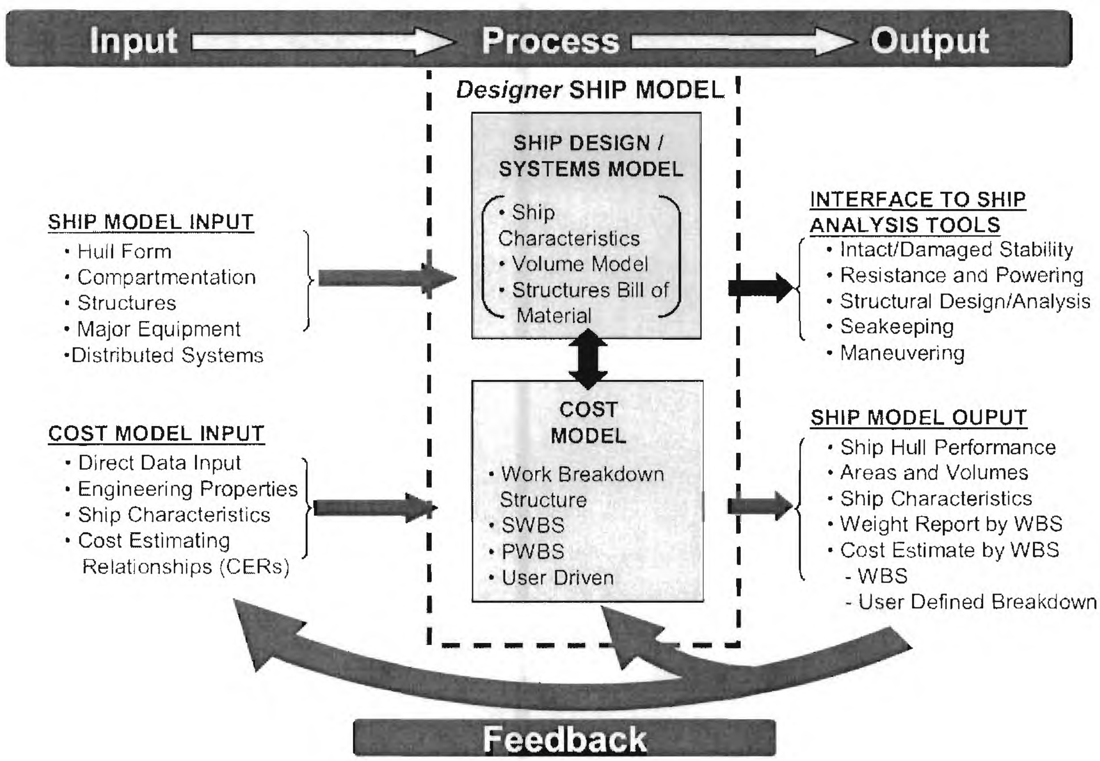

Figure 3.7 - Flagship Designer Process Flow

Analyses

Analyses, modeling, and simulation efforts performed under this task include the following. Unless otherwise noted, the analyses, modeling, and simulation efforts were performed using *Flagship Designer*.

- Hullform surface representation (import from FastShip)
- Weight and CG estimation to the one-digit SWBS level
- Stability analysis
- Ship speed/resistance calculations

- Ship powering and one-digit propulsion machinery selection
- Combat systems and weapons (SWBS Groups 400 and 700) capacity
- Combat systems and weapons performance assessment against a notional metric

Intact hydrostatic stability was analyzed for each test case hull, computing KM and GM. Cases with GM less than 3.5m or greater than 5.0m were considered infeasible. Bare hull resistance was calculated and used to determine powering requirements for the specific case's maximum speed capability. The powering requirements were parametrically linked with SWBS groups 200, 300 and 500 to generate appropriate changes in the weights of these SWBS groups as a function of power required. With a given test case displacement known, and with SWBS weights for all groups except combat systems and weapons (SWBS 400 and 700), the weight allowance or budget for the case was determined for its 'Combat-Weapon Block'. This weight was then used to assess the mission effectiveness performance for each ship studied.

Tumblehome Surface Combatant Notional Model

A notional tumblehome surface combatant hull form, Figure 3.8, was developed to serve as the baseline ship for the test case. This notional combatant was populated with a one-digit SWBS model of component weights that are parametrically linked to principal characteristics or main parameters of the ship (see Table 3.2 for a listing of typical ship main paramcters). *FlagShip Designer* uses a true geometric representation of each hull case, and performs direct calculations of stability and resistance from this geometry. As the ship is scaled into larger and smaller sizes, the linked principal characteristics modify SWBS weights via 'weight estimating relationships' (WER's). Likewise, the hull resistance is analyzed using accurate, computed hull wetted surface area and resistance versus speed models. The resistance is then used as an input to the propulsion plant and related hull, mechanical and electrical systems weight groups. Through this modeling and hull scaling process the twenty five hulls at three different speeds were used to create seventy five test case design points.

Table 3.2 - Notional Surface Combattant Main Parameters

MAIN PARAMETER
Length between perpendiculars
Maximum beam of craft
Maximum beam of each hull
Length of superstructure
Length of machinery space
Depth (baseline to weather deck)
Design draft
Lightship displacement
Full load displacement
Propulsion power
Speed
Crew (no. pers. * 250 Kg)
Accommodations (berths)
Weight of Combat Systems and Weapons (SWBS 400+700)

The *Flagship Designer* model accommodates more detailed parameters including, but not limited to, significant machinery and equipment definition, subdivision definition, and detailed (SWBS-based two, three and five digit) cost and weight estimating relationships. For the STTR Phase I project test case, one-digit WER's were used.

Design Space and Ship Variants

Appendix A provides the full set of seventy five test case design points, and illustrates the use of *FlagShip Designer* to rapidly generate multiple designs using a consistent model of the ship. These models include the parametric relationships for weight. The capability currently exists to populate a *Designer* model with analogous cost estimating relationships by SWBS item (one, two, three and/or five-digit level of detail). Cost modeling was not used during the short-term STTR Phase I project.

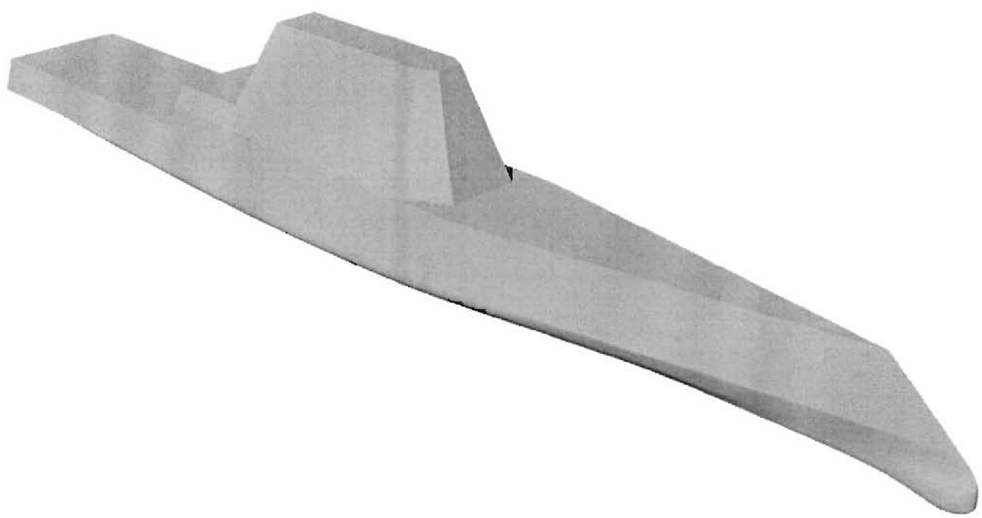

Figure 3.8 - Baseline Tumblehome Surface Combatant Hull Form

Parameters that were used for the test case study are listed below. Ship length, beam and speed were the independent parameters. Length and beam were established for a baseline tumblehome hull form, Figure 3.8. The baseline speed was 30 knots. Length and beam were then scaled across a range of lengths and beams with resultant dependent variables, see below and Appendix A.

Parameters
Independent Parameters

- Length at the Waterline (LWL)(m)
- Beam (m)
- Speed (kt)

Dependent Parameters

- Draft (m)
- Volume (m^3)
- Displacement (tonne)

- KM (m)
- GM (m)
- PE (kW)

Held Constant

- Center of Gravity (KG)
- Block Coefficient (Cb)

Calculated Dependent Parameters

- Combat-Weapon Block Weight (tonne)
- Combat-Weapon Block Capability Index

The complete data set is provided in Appendix A.

Combat-Weapon Block Capability Index

A key result from the test case study was to assess the impact of hull configuration on the ship's mission effectiveness. Within the Phase I STTR project, mission effectiveness was treated as a calculated dependent variable named 'Combat-Weapon Block Capability Index'. The index is dependent on the weight of the 'Combat-Weapon Block', which was treated as the sum of the SWBS Groups 400 plus 700. The strategy was to effectively relate the combat system weight allowance plus the weapons systems weight allowance for a specific hull configuration and speed capability to the mission effectiveness of the ship. In an actual ship design study the modeling of these SWBS groups could be extended to two and three digit levels of detail, and could also include cost estimating relationships (parametrically linked to the ship main parameters), in addition to weight estimating relationships.

In the test cases, referring to Appendix A, Cases 1-25 were analyzed for the baseline speed of 30 knots, Cases 26-50 at 33 knots, and Cases 51-75 at 27 knots. The shifts in propulsion/HM&E equipment associated with the variation in ship maximum speed capability influenced the resulting Combat-Weapon Block weight and effectiveness.

A relationship between Combat-Weapons Block Weight and Capability Index was developed to convey that as Combat-Weapon Block Weight increases, the Capability Index increases in a non-linear fashion (see Figure 3.9), and is expressed in the form:

$$M = Q + (R*Wcbs) + (S*(Wcbs)^2)$$

Where

M is the Combat-Weapon Block Weight Capability Index
Q is a constant (2.00)
R is a constant (0.00083)
Wcbs is the Combat-Weapon Block Weight in tonnes
S is a constant (0.000000572)

The values for Q, R, and W were selected so that the range of M varied from approximately 3 to 10. The actual calculated range of M for the cases studied is 2.82 –

10.09. Figure 3.10 shows the range in Combat-Weapons Block weight for each set of ship cases, grouped by speed.

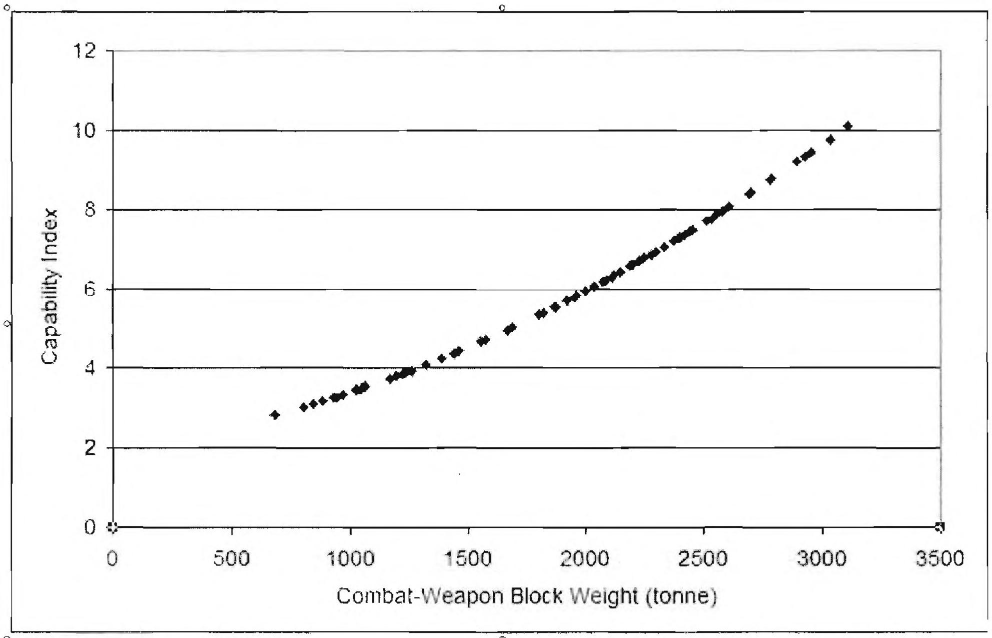

Figure 3.9 - Combat-Weapon Block Capability Index

Summary of Results

The twenty five unique hull forms varied in length from 185 to 215 meters and beam from 23.1 to 26.0 meters, with the depth and draft varying as necessary to maintain a constant block coefficient. The resulting displacement for the twenty five hulls ranged from 14,754 to 21,925 metric tons (tonnes). The range of beam variation created some hulls that are considered infeasible due to basic stability requirements, so the design space considered includes 'infeasible' designs along edges of the space.

Figure 3.11 plots the results of the seventy five test cases in terms of Combat-Weapon Capability Index versus ship displacement. The data are grouped into the three ship maximum speed cases as indicated.

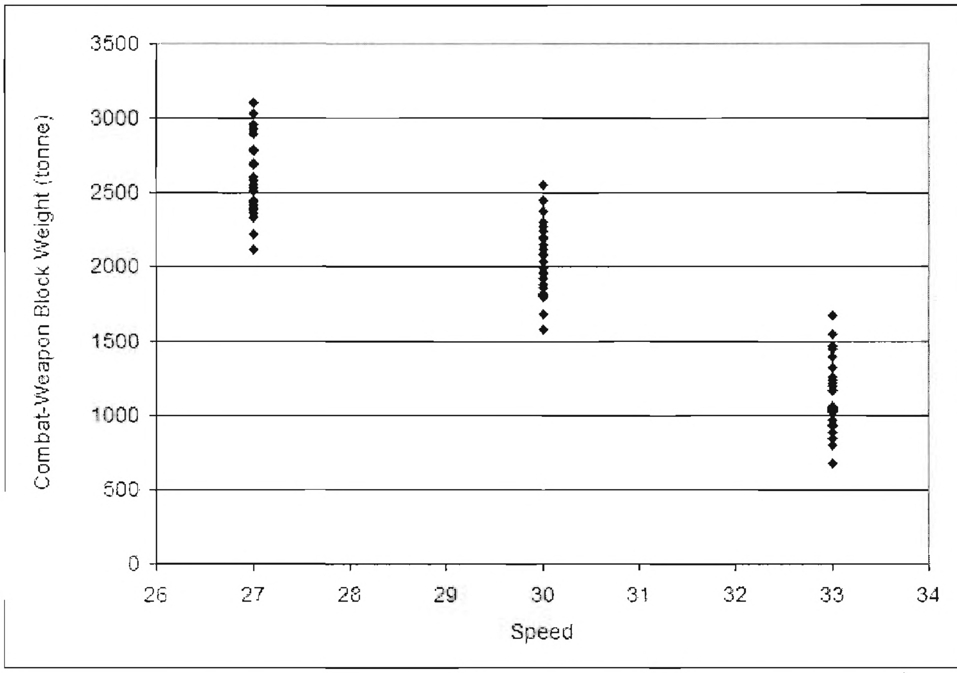

Figure 3.10 - Combat-Weapon Capability Index versus Ship Speed

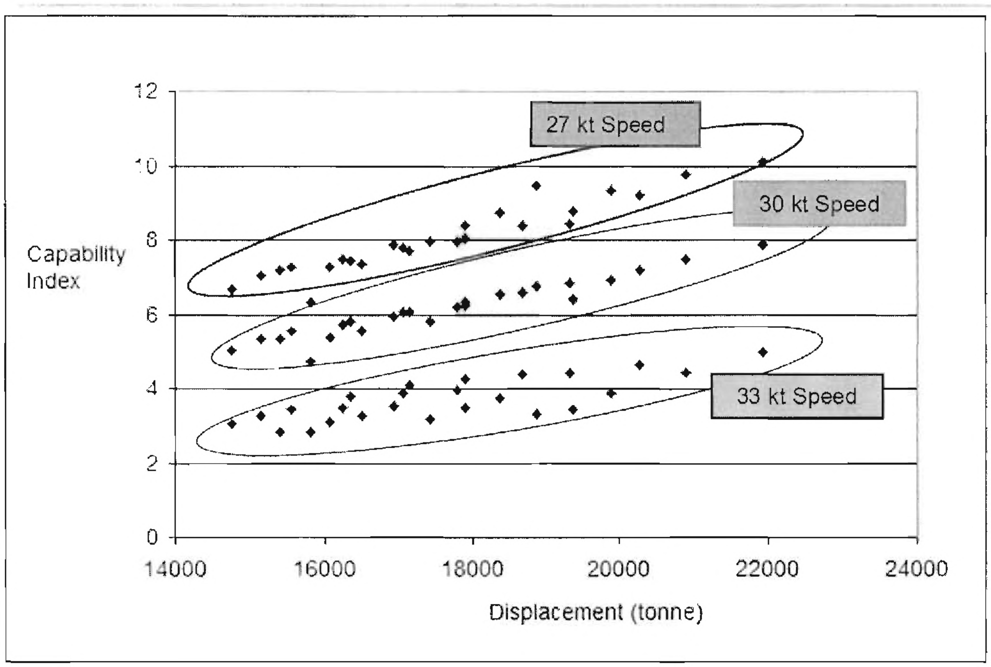

Figure 3.11 - Combat-Weapon Capability Index versus Ship Displacement

3.6.3 Surrogate Model Based on Inception-Phase Test Case

To create the test case, the three independent parameters were varied over the ranges specified earlier to create 75 design points. These design points were then used to fit a surrogate model to the data. Using a commercial statistical software package, the model fit to this data was used to create a parametric environment for visualizing how changes in the independent variables affect the outputs. This parametric environment, also called a Prediction Profiler, is shown in Figure 3.12.

Normally, this kind of information is shown in a static fashion, using charts that rely on assumed settings for a long list of variables not being represented in the chart. In the case of the prediction profiler, the underlying relationships are linked for all of the variables, allowing the user to effectively run a new trial and obtain new outputs in real time. For example, if the user grabs the vertical red hairline that represents the beam setting, and moves it to the right to signify an increase in its value, an upward shift in nearly all of the other curves present in the prediction profiler would be observed. This signifies that all of the curves shown in the profiler are essentially only valid for one set of input values. As soon as even one input value is changed, all other curves are updated to reflect that change. This allows the user to actively see how changes in the input settings can affect the outputs.

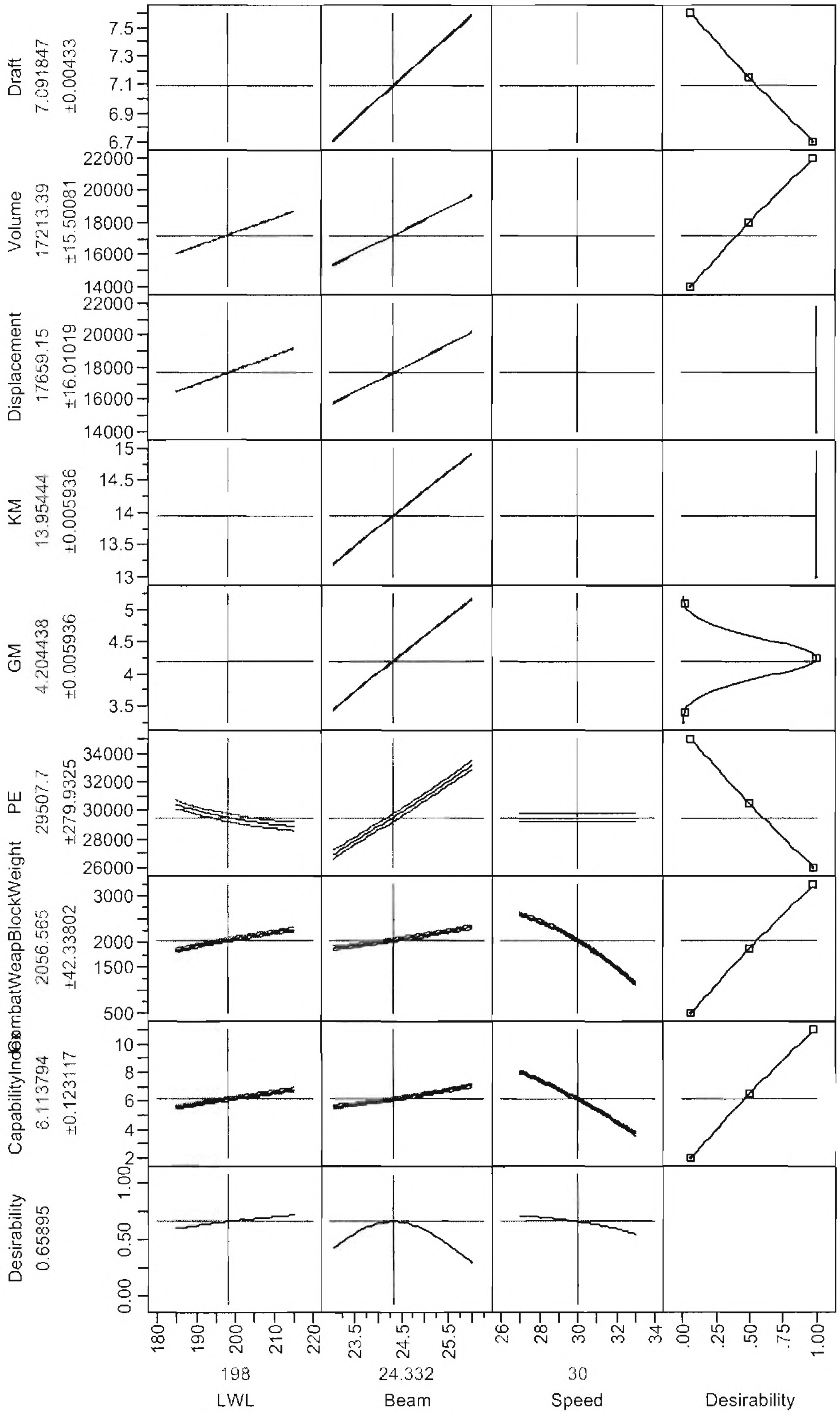

Figure 3.12 -Prediction Profiler

After a model is fit to the data, the next step is to use that model to then rapidly simulate many more trials in order to populate the design space. The result of this step is shown in Figure 3.13, which is called a Multivariate Scatterplot. This plot shows 1000 simulated trials fit using the surrogate model that was created in the previous step. Like the prediction profiler, this plot is interactive, not only allowing the user to visualize trends, but also to perform top-down and bottom-up design trades. These trade studies allow the designer to see how requirements on one level filter up or down to another level.

To demonstrate this concept in this Multivariate Scatterplot, all those design points for which the speed is greater than 30 knots were colored red. Color coding points in this way allows the designer to more easily see design trends, identify which design points meet certain objectives and to observe the tradeoffs that need to be made in other dimensions. In this example, one can readily see that there is a tradeoff to be made between having a high-speed capability, and possessing a high weapons capability index. All of the red design points, indicating high speed designs, tend to have lower weapon capability indices than the black design points representing lower speed design options.

The Multivariate Scatterplot also shows which variables are highly correlated. In this example, it is evident that the ship's beam is highly correlated with its volume, displacement, and stability characteristics.

To take this demonstration a step further, a top-down design tradeoff is shown in the Multivariate Scatterplot in Figure 3.14. In this scatterplot matrix, all of the design points having a speed below 30 knots have been hidden, so that we can better visualize where the designs with optimal speed characteristics lie in the other dimensions of the design space. Also, to eliminate any infeasible designs from consideration, all those design points having infeasible stability characteristics were also hidden, leaving about 40% of the design points remaining. Progressing further down the matrix to the weapons capability index, it becomes evident that none of the remaining design points possess a capability index greater than 7, meaning that there is a tradeoff to be made between speed and weapons capabilities.

At this point in the design process, the next logical step would be to take a closer look at those design points that most closely meet the objectives. Those design points with the highest capability index (of the remaining designs) have been colored blue to visualize where they lie in the other dimensions. If the designer were to infuse technologies to increase one or more capabilities, those technologies should be applied to one of the more optimal (or robust) existing designs in order to achieve the best outcome.

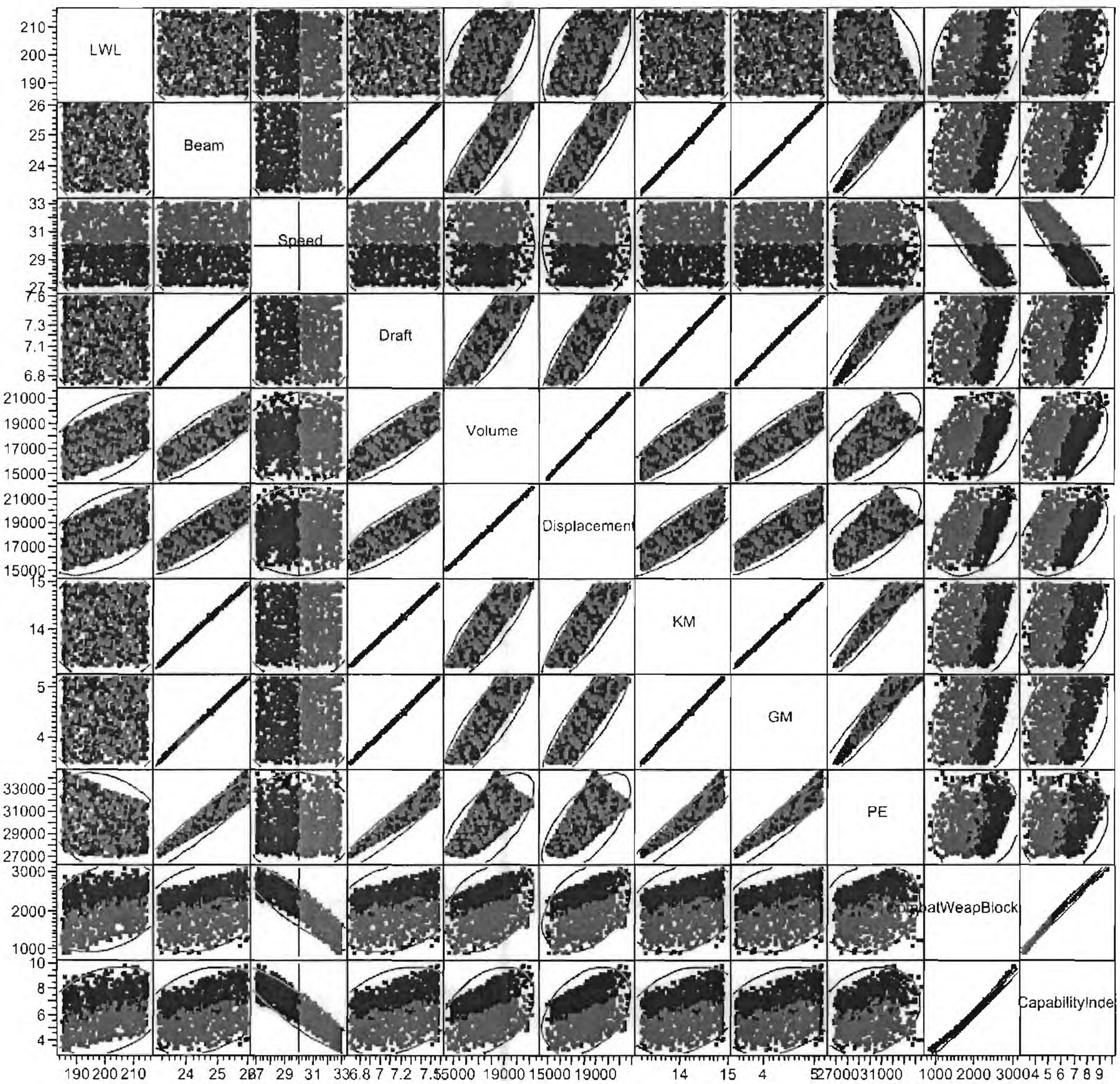

Figure 3.13 – Multivariate Scatterplot Matrix of 1000 Simulated Trials

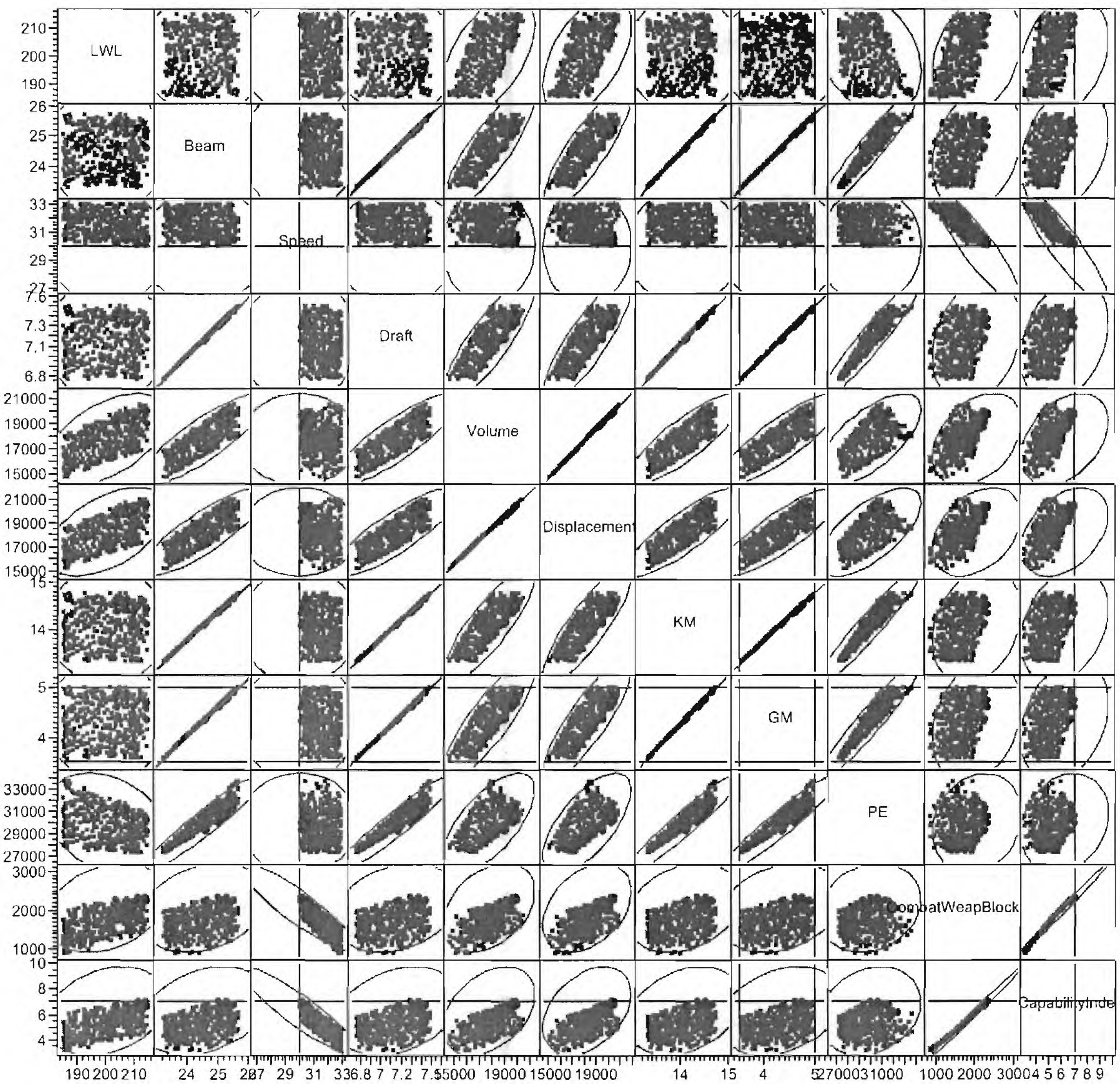

Figure 3.14 - Multivariate Scatterplot with Low-Speed Designs Hidden From View

4. EXTENSION OF PHASE I RESULTS TO A REAL SHIP DESIGN

Given the results presented in the previous section of this report, the project team believes that the next logical steps in the process of demonstrating the Advanced System-of-Systems Design Capability for the notional CG(X) in an air-defense scenario would be as follows:

1. Obtain accurate data on the weight, center of gravity and cost versus performance for alternate sensor and weapons systems;
2. Develop surrogate models for these systems similar to the surrogate model discussed previously for the ship;
3. Connect the sensors and weapons systems performance to the ship model using the weight and CG from (2) above and the ship model as discussed in the previous sections; and
4. Obtain accurate cost information for the sensors, weapons and ship and parametrically include this data into the linked modeling system described in (3) above.

Once these steps have been completed, it would be possible to set up a complete design space visualization using existing ASDL technology. This visualization would permit users to analyze the various trade-offs, including cost and mission performance (rather than performance index), as discussed in Section 3.6.3 above.

5. PHASE I CONCLUSIONS AND RECOMMENDATIONS

Based on Phase I results discussed in the previous section of this report, we believe that the following conclusions and recommendations are valid:

1. The concept of using surrogate modeling to relate ship design parameters to a mission capability index has been demonstrated. When the input data is developed using a high-fidelity design process, such as *FlagShip Designer*, the resulting surrogate model can be used to rapidly explore the ship design space with a high degree of certainty;
2. *FlagShip Designer* is capable of rapidly creating a parent ship design and a large number of parametric variations to this parent design with sufficient detail and fidelity for meaningful modeling as discussed in (1) above. This tool can provide very accurate definition of the weight, volume and center of gravity available for mission-related systems as a function of hull characteristics. It can also be used to include ship performance parameters such as speed, endurance and seakeeping in the modeling process;
3. The project team has identified two areas where additional data is critical to the final System-of-System Design Process: (1) detailed data for incorporating mission systems performance modeling within the process; and (2) realistic cost information for mission systems and the ship. We have reached the conclusion that for mission system modeling, information required to model these systems as part of the design process is highly dependent on the individual mission systems, and for each candidate system, modeling must be based on data supplied by the Navy or the system vendor. Similarly, cost models must be supplied by the Navy or system vendors;
4. Although it has not been possible, for reasons discussed above, to include mission system performance or quantitative cost analysis during the Phase I effort, it is believed that these items can be readily incorporated into the process with input data from the Navy and mission system vendors. Therefore, achieving the overall objective of this project is possible, and it should be pursued by the Navy. In addition, with exception of incorporating these detailed sub-system models and accurate cost information, the technology to include the ship in a system-of-systems design process is now believed to be "existing technology"; and
5. Therefore, it is recommended that the Navy pursues development of the System-of-Systems Design Capability based on the findings of this Phase I effort, outside the context of the STTR Program. The capabilities required to model and visualize nested systems of systems, based on Navy or vendor supplied data, currently exists at ASDL and it would seem to be logical for Navy to fund this work directly for specific ship procurements. Similarly, *FlagShip Designer* has been proven to be a very useful tool for including the "ship system" in these efforts, and it is recommended that modification of this tool for seamless interface with ASDL proceed, again outside the context of the STTR Program. The project team believes that the most cost effective way to proceed would be to continue development of this methodology within an actual ship design project, where detailed mission systems performance models and cost models can be developed

based on an actual case. This approach would offer two advantages over continued funding through the STTR Program. These are: (1) actual (in some cases proprietary or classified) mission systems performance information could be included in the process; and (2) the resources applied to the effort would result in a realistic and immediately-useful tool for the subject ship design program, in addition to completing development required for general application to future programs.

6. WORK PLAN FOR PHASE II

The Chesapeake Marine Technology team believes that the capability that was originally proposed has been further developed and offers a viable opportunity to the Navy for the development of a System-of-Systems modeling, analysis and design capability. In fact, we believe that the technology to implement this process now exists, and the only missing components are: (1) detailed mission system performance models and (2) accurate cost modeling relationships for mission systems and the ship. This missing data is believed to be highly dependent on the specific ship design being considered. Therefore, we have recommended that further development of this capability is funded within a specific ship design program, where the necessary detailed information is available.

As a result, this team intends to continue to seek opportunities to develop and implement the Advanced System of Systems Design Capability, and will do so through channels other than the SBIR/STTR.

APPENDIX A – PHASE I DATA

Idendification		Independent Parameters			Dependent Parameters						Constants		Calculated Dependent Parameters		
Case	Design Point	LWL	Beam	Speed (kt)	Draft	Volume	Displacement	KM	GM	PE	KG	Cb	Combat-Weap Block Weight (1)	Combat-Weapon Block Capability Index (2)	Case
1	195m-demo-(L-5 B-0.5)	190.00	23.58	30.00	6.85	15420.00	15819.00	13.49	3.74	28700.00	9.75	0.50	1575	4.73	1
2	195m-demo-(L-5 B-1)	190.00	23.08	30.00	6.71	14770.00	15153.00	13.20	3.45	27739.00	9.75	0.50	1800	5.35	2
3	195m-demo-(L-5 B+0)	190.00	24.00	30.00	7.00	16083.00	16500.00	13.77	4.02	29687.00	9.75	0.50	1864	5.53	3
4	195m-demo-(L-5 B+1)	190.00	25.00	30.00	7.29	17456.00	17908.00	14.34	4.59	31743.00	9.75	0.50	2085	6.22	4
5	195m-demo-(L-5 B+2)	190.00	26.00	30.00	7.58	18887.00	19376.00	14.91	5.16	33909.00	9.75	0.50	2147	6.42	5
6	195m-demo-(L-10 B-0.5)	185.00	23.58	30.00	6.85	15014.00	15403.00	13.48	3.73	27562.00	9.75	0.50	1802	5.35	6
7	195m-demo-(L-10 B-1)	185.00	23.08	30.00	6.71	14382.00	14754.00	13.20	3.45	26610.00	9.75	0.50	1687	5.03	7
8	195m-demo-(L-10 B+0)	185.00	24.00	30.00	7.00	15660.00	16066.00	13.77	4.02	30252.00	9.75	0.50	1817	5.40	8
9	195m-demo-(L-10 B+1)	185.00	25.00	30.00	7.29	16996.00	17436.00	14.34	4.59	32412.00	9.75	0.50	1953	5.80	9
10	195m-demo-(L-10 B+2)	185.00	26.00	30.00	7.58	18389.00	18866.00	14.91	5.16	34691.00	9.75	0.50	2247	6.75	10
11	195m-demo-(L+0 B-0.5)	195.00	23.58	30.00	6.85	15826.00	16235.00	13.49	3.74	28292.00	9.75	0.50	1920	5.70	11
12	195m-demo-(L+0 B-1)	195.00	23.08	30.00	6.71	15159.00	15552.00	13.20	3.45	27372.00	9.75	0.50	1875	5.57	12
13	195m-demo-(L+0 B+0)	195.00	24.00	30.00	7.00	16506.00	16934.00	13.77	4.02	27583.00	9.75	0.50	1999	5.94	13
14	195m-demo-(L+0 B+1)	195.00	25.00	30.00	7.29	17915.00	18379.00	14.34	4.59	31207.00	9.75	0.50	2188	6.55	14
15	195m-demo-(L+0 B+2)	195.00	26.00	30.00	7.58	19383.00	19885.00	14.91	5.16	33278.00	9.75	0.50	2301	6.94	15
16	195m-demo-(L+10 B-0.5)	205.00	23.58	30.00	6.85	16637.00	17068.00	13.49	3.74	27744.00	9.75	0.50	2032	6.05	16
17	195m-demo-(L+10 B-1)	205.00	23.08	30.00	6.71	15936.00	16349.00	13.20	3.45	26904.00	9.75	0.50	1958	5.82	17
18	195m-demo-(L+10 B+0)	205.00	24.00	30.00	7.00	17353.00	17802.00	13.77	4.02	28619.00	9.75	0.50	2075	6.19	18
19	195m-demo-(L+10 B+1)	205.00	25.00	30.00	7.29	18834.00	19322.00	14.34	4.59	30453.00	9.75	0.50	2277	6.86	19
20	195m-demo-(L+10 B+2)	205.00	26.00	30.00	7.58	20377.00	20905.00	14.91	5.16	32378.00	9.75	0.50	2450	7.47	20
21	195m-demo-(L+20 B-0.5)	215.00	23.58	30.00	6.85	17449.00	17901.00	13.49	3.74	27556.00	9.75	0.50	2119	6.33	21
22	195m-demo-(L+20 B-1)	215.00	23.08	30.00	6.71	16714.00	17147.00	13.20	3.45	27101.00	9.75	0.50	2040	6.07	22
23	195m-demo-(L+20 B+0)	215.00	24.00	30.00	7.00	18199.00	18671.00	13.77	4.02	28323.00	9.75	0.50	2200	6.59	23
24	195m-demo-(L+20 B+1)	215.00	25.00	30.00	7.29	19753.00	20264.00	14.34	4.59	30018.00	9.75	0.50	2375	7.20	24
25	195m-demo-(L+20 B+2)	215.00	26.00	30.00	7.58	21371.00	21925.00	14.91	5.16	31840.00	9.75	0.50	2556	7.86	25
26	195m-demo-(L-5 B-0.5)	190.00	23.58	33.00	6.85	15420.00	15819.00	13.49	3.74	28700.00	9.75	0.50	679	2.83	26
27	195m-demo-(L-5 B-1)	190.00	23.08	33.00	6.71	14770.00	15153.00	13.20	3.45	27739.00	9.75	0.50	925	3.26	27
28	195m-demo-(L-5 B+0)	190.00	24.00	33.00	7.00	16083.00	16500.00	13.77	4.02	29687.00	9.75	0.50	937	3.28	28
29	195m-demo-(L-5 B+1)	190.00	25.00	33.00	7.29	17456.00	17908.00	14.34	4.59	31743.00	9.75	0.50	1039	3.48	29
30	195m-demo-(L-5 B+2)	190.00	26.00	33.00	7.58	18887.00	19376.00	14.91	5.16	33909.00	9.75	0.50	1022	3.45	30
31	195m-demo-(L-10 B-0.5)	185.00	23.58	33.00	6.85	15014.00	15403.00	13.48	3.73	27562.00	9.75	0.50	677	2.82	31
32	195m-demo-(L-10 B-1)	185.00	23.08	33.00	6.71	14382.00	14754.00	13.20	3.45	26610.00	9.75	0.50	803	3.04	32
33	195m-demo-(L-10 B+0)	185.00	24.00	33.00	7.00	15660.00	16066.00	13.77	4.02	30252.00	9.75	0.50	840	3.10	33
34	195m-demo-(L-10 B+1)	185.00	25.00	33.00	7.29	16996.00	17436.00	14.34	4.59	32412.00	9.75	0.50	878	3.17	34
35	195m-demo-(L-10 B+2)	185.00	26.00	33.00	7.58	18389.00	18866.00	14.91	5.16	34691.00	9.75	0.50	964	3.33	35
36	195m-demo-(L+0 B-0.5)	195.00	23.58	33.00	6.85	15826.00	16235.00	13.49	3.74	28292.00	9.75	0.50	1048	3.50	36
37	195m-demo-(L+0 B-1)	195.00	23.08	33.00	6.71	15159.00	15552.00	13.20	3.45	27372.00	9.75	0.50	1026	3.45	37
38	195m-demo-(L+0 B+0)	195.00	24.00	33.00	7.00	16506.00	16934.00	13.77	4.02	27583.00	9.75	0.50	1061	3.52	38
39	195m-demo-(L+0 B+1)	195.00	25.00	33.00	7.29	17915.00	18379.00	14.34	4.59	31207.00	9.75	0.50	1167	3.75	39
40	195m-demo-(L+0 B+2)	195.00	26.00	33.00	7.58	19383.00	19885.00	14.91	5.16	33278.00	9.75	0.50	1217	3.86	40
41	195m-demo-(L+10 B-0.5)	205.00	23.58	33.00	6.85	16637.00	17068.00	13.49	3.74	27744.00	9.75	0.50	1232	3.89	41
42	195m-demo-(L+10 B-1)	205.00	23.08	33.00	6.71	15936.00	16349.00	13.20	3.45	26904.00	9.75	0.50	1192	3.80	42
43	195m-demo-(L+10 B+0)	205.00	24.00	33.00	7.00	17353.00	17802.00	13.77	4.02	28619.00	9.75	0.50	1260	3.95	43
44	195m-demo-(L+10 B+1)	205.00	25.00	33.00	7.29	18834.00	19322.00	14.34	4.59	30453.00	9.75	0.50	1463	4.44	44

45	195m-demo-(L+10 B+2)	205.00	26.00	33.00	7.58	20377.00	20905.00	14.91	5.16	32378.00	9.75	0.50	1463	4.44	45
46	195m-demo-(L+20 B-0.5)	215.00	23.58	33.00	6.85	17449.00	17901.00	13.49	3.74	27556.00	9.75	0.50	1388	4.25	46
47	195m-demo-(L+20 B-1)	215.00	23.08	33.00	6.71	16714.00	17147.00	13.20	3.45	27101.00	9.75	0.50	1320	4.09	47
48	195m-demo-(L+20 B+0)	215.00	24.00	33.00	7.00	18199.00	18671.00	13.77	4.02	28323.00	9.75	0.50	1442	4.39	48
49	195m-demo-(L+20 B+1)	215.00	25.00	33.00	7.29	19753.00	20264.00	14.34	4.59	30018.00	9.75	0.50	1551	4.66	49
50	195m-demo-(L+20 B+2)	215.00	26.00	33.00	7.58	21371.00	21925.00	14.91	5.16	31840.00	9.75	0.50	1667	4.97	50
51	195m-demo-(L-5 B-0.5)	190.00	23.58	27.00	6.85	15420.00	15819.00	13.49	3.74	28700.00	9.75	0.50	2115	6.31	51
52	195m-demo-(L-5 B-1)	190.00	23.08	27.00	6.71	14770.00	15153.00	13.20	3.45	27739.00	9.75	0.50	2332	7.05	52
53	195m-demo-(L-5 B+0)	190.00	24.00	27.00	7.00	16083.00	16500.00	13.77	4.02	29687.00	9.75	0.50	2420	7.36	53
54	195m-demo-(L-5 B+1)	190.00	25.00	27.00	7.29	17456.00	17908.00	14.34	4.59	31743.00	9.75	0.50	2694	8.39	54
55	195m-demo-(L-5 B+2)	190.00	26.00	27.00	7.58	18887.00	19376.00	14.91	5.16	33909.00	9.75	0.50	2789	8.76	55
56	195m-demo-(L-10 B-0.5)	185.00	23.58	27.00	6.85	15014.00	15403.00	13.48	3.73	27562.00	9.75	0.50	2373	7.19	56
57	195m-demo-(L-10 B-1)	185.00	23.08	27.00	6.71	14382.00	14754.00	13.20	3.45	26610.00	9.75	0.50	2227	6.69	57
58	195m-demo-(L-10 B+0)	185.00	24.00	27.00	7.00	15660.00	16066.00	13.77	4.02	30252.00	9.75	0.50	2401	7.29	58
59	195m-demo-(L-10 B+1)	185.00	25.00	27.00	7.29	16996.00	17436.00	14.34	4.59	32412.00	9.75	0.50	2582	7.96	59
60	195m-demo-(L-10 B+2)	185.00	26.00	27.00	7.58	18389.00	18866.00	14.91	5.16	34691.00	9.75	0.50	2956	9.45	60
61	195m-demo-(L+0 B-0.5)	195.00	23.58	27.00	6.85	15826.00	16235.00	13.49	3.74	28292.00	9.75	0.50	2450	7.47	61
62	195m-demo-(L+0 B-1)	195.00	23.08	27.00	6.71	15159.00	15552.00	13.20	3.45	27372.00	9.75	0.50	2393	7.26	62
63	195m-demo-(L+0 B+0)	195.00	24.00	27.00	7.00	16506.00	16934.00	13.77	4.02	27583.00	9.75	0.50	2556	7.86	63
64	195m-demo-(L+0 B+1)	195.00	25.00	27.00	7.29	17915.00	18379.00	14.34	4.59	31207.00	9.75	0.50	2783	8.74	64
65	195m-demo-(L+0 B+2)	195.00	26.00	27.00	7.58	19383.00	19885.00	14.91	5.16	33278.00	9.75	0.50	2925	9.32	65
66	195m-demo-(L+10 B-0.5)	205.00	23.58	27.00	6.85	16637.00	17068.00	13.49	3.74	27744.00	9.75	0.50	2532	7.77	66
67	195m-demo-(L+10 B-1)	205.00	23.08	27.00	6.71	15936.00	16349.00	13.20	3.45	26904.00	9.75	0.50	2443	7.44	67
68	195m-demo-(L+10 B+0)	205.00	24.00	27.00	7.00	17353.00	17802.00	13.77	4.02	28619.00	9.75	0.50	2582	7.96	68
69	195m-demo-(L+10 B+1)	205.00	25.00	27.00	7.29	18834.00	19322.00	14.34	4.59	30453.00	9.75	0.50	2703	8.42	69
70	195m-demo-(L+10 B+2)	205.00	26.00	27.00	7.58	20377.00	20905.00	14.91	5.16	32378.00	9.75	0.50	3030	9.77	70
71	195m-demo-(L+20 B-0.5)	215.00	23.58	27.00	6.85	17449.00	17901.00	13.49	3.74	27556.00	9.75	0.50	2606	8.05	71
72	195m-demo-(L+20 B-1)	215.00	23.08	27.00	6.71	16714.00	17147.00	13.20	3.45	27101.00	9.75	0.50	2513	7.70	72
73	195m-demo-(L+20 B+0)	215.00	24.00	27.00	7.00	18199.00	18671.00	13.77	4.02	28323.00	9.75	0.50	2690	8.37	73
74	195m-demo-(L+20 B+1)	215.00	25.00	27.00	7.29	19753.00	20264.00	14.34	4.59	30018.00	9.75	0.50	2893	9.19	74
75	195m-demo-(L+20 B+2)	215.00	26.00	27.00	7.58	21371.00	21925.00	14.91	5.16	31840.00	9.75	0.50	3105	10.09	75

Maximum	10.0918
Minimum	2.8241

Notes:

1. Displacement - (SWBS400 + SWBS700)
2. From the formula:
   M = Q + (R*Wcbs) + (S*(Wcbs)^2)
   Where:
   Wcbs is the weight of the Combat-Weapon Block (sum of the weights of SWBS 400 and 700)
   M is the Combat-Weapon Block Capability Index, which is defined as varying between 3 and 10, where a higher score indicates increased combat-weapon capability

Q is a constant =	2.00000000000
R is a constant =	0.00083000000
S is a constant =	0.00000057200

3. Cases 1-25 are defined to be the baseline ships balanced to achieve 30 knots. In practice the machinery for power generation and motors to produce the necessary propulsion are step functions. Attempt has been to match the machinery to be within 30.0 to 30.4 knots.
4. Cases 26-50 have been designed to achieve a nominal speed 33 knots.
5. Cases 51-75 have been designed to achieve a nominal speed of 27 knots.
6. Cases where the GM is less than 3.5m or greater than 5m are considered to be non-feasible due to Dynamic Stability and Seakeeping issues.
7. Draft refer to the midships draft, and does not represent the navigational draft, which would include approximately 0.8m for the bow bulb protrusion below the baseline.
8. This table represents all the combinations, so is overconstrained from a "design of experiments" point of view.