

Tools for Multi-Objective and Multi-Disciplinary Optimization in Naval Ship Design

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ABSTRACT

This thesis focuses on practical and quantitative methods for measuring effectiveness in naval ship design. An Overall Measure of Effectiveness (OMOE) model or function is an essential prerequisite for optimization and design trade-off. This effectiveness can be limited to individual ship missions or extend to missions within a task group or larger context. A method is presented that uses the Analytic Hierarchy Process combined with Multi-Attribute Value Theory to build an Overall Measure of Effectiveness and Overall Measure of Risk function to properly rank and approximately measure the relative mission effectiveness and risk of design alternatives, using trained expert opinion to replace complex analysis tools. A validation of this method is achieved through experimentation comparing ships ranked by the method with direct ranking of the ships through war gaming scenarios.

The second part of this thesis presents a mathematical ship synthesis model to be used in early concept development stages of the ship design process. Tools to simplify and introduce greater accuracy are described and developed. Response Surface Models and Design of Experiments simplify and speed up the process. Finite element codes such as MAESTRO improve the accuracy of the ship synthesis models which in turn lower costs later in the design process. A case study of an Advanced Logistics Delivery Ship (ALDV) is performed to assess the use of RSM and DOE methods to minimize computation time when using high-fidelity codes early in the naval ship design process.

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CHAPTER 1 INTRODUCTION

1.1 Motivation and Background

Naval ship concept design is traditionally an “ad hoc” process. Selection of design concepts for assessment is guided primarily by experience, design lanes, rules-of-thumb, and imagination. Communication and coordination between design disciplines (hull form, structures, resistance, etc.) require significant designer involvement and effort. Concept studies continue until resources or time runs out. Critical elements missing from this process are:

1. A consistent format and methodology for multi-objective decisions based on dissimilar objective attributes, specifically effectiveness, cost and risk. Mission effectiveness, cost and risk cannot logically be combined as in commercial decisions, where discounted cost can usually serve as a suitable single objective. Multiple objectives must be presented separately, but simultaneously, in a manageable format for trade-off and decision-making.
2. Practical and quantitative methods for measuring effectiveness. An Overall Measure of Effectiveness (OMOE) model or function is an essential prerequisite for optimization and design trade-off. This effectiveness can be limited to individual ship missions or extend to missions within a task group or larger context.
3. Practical and quantitative methods for measuring risk. Overall risk includes schedule, production, technology performance, and cost factors.
4. An accepted cost model sensitive to important producibility characteristics, but with a level of detail appropriate for concept exploration.
5. An efficient and robust method to search the design space for optimal concepts.
6. An effective framework for transitioning and refining concept development in a multidisciplinary design optimization (MDO).
7. A means of using the results of first-principle analysis codes at earlier stages of design.

This thesis focuses on the second and last of these critical elements.

There are a number of inputs which must be integrated when determining overall mission effectiveness in a naval ship: 1) defense policy and goals; 2) threat; 3) existing force structure; 4) mission need; 5) mission scenarios; 6) modeling and simulation or war gaming results; and 7) expert opinion. Ideally, all knowledge about the problem could be included in a master war-gaming model to predict resulting measures of effectiveness for a matrix of ship performance inputs in a series of probabilistic scenarios. Regression analysis could be applied to the results to define a mathematical relationship between input ship measures of performance (MOPs) and output effectiveness. The accuracy of such a simulation depends on modeling the detailed

interactions of a complex human and physical system and its response to a broad range of quantitative and qualitative variables and conditions including ship MOPs. Many of the inputs and responses are probabilistic so a statistically significant number of full simulations must be made for each set of discrete input variables. This extensive modeling capability does not yet exist for practical applications.

An alternative to modeling and simulation is to use expert opinion directly to integrate these diverse inputs, and assess the value or utility of ship MOPs in an OMOE function. Two methods for structuring these problems dominate the literature: Multi-Attribute Utility Theory and the Analytical Hierarchy Process. In the past, supporters of these theories have been critical of each other, but recently there have been efforts to identify similarities and blend the best of both for application in Multi-Attribute Value (MAV) functions. Brown [1] has adapted this combined approach to the ship concept design problem, but the use of this approach has never been validated.

As with effectiveness and risk, the multi-objective optimization requires a cost model that can generate lifecycle or total ownership cost for a specified design without direct user interaction. Cost models by their nature involve significant proprietary and sensitive data. Even within the Navy, organizations like NAVSEA 017 have resisted providing their models to the engineers. A practical and accepted cost model is required. This model must be sensitive to important producibility characteristics, but with a level of detail appropriate for concept exploration.

Once concept exploration has narrowed the design space, technologies have been selected, and major discrete design alternatives (e.g., type of propulsion, hull form, etc.) have been chosen from the full spectrum of design choices, optimization must continue as additional ship, system and subsystem details are added and more complete analysis is performed. This is a fully multidisciplinary problem that typically must employ an array of higher fidelity, discipline-specific computer codes to continue the optimization process while addressing the uncertainties inherent in the design. Higher fidelity codes are also required in concept exploration when significant departures are made from traditional design lanes to explore new technologies and new paradigms (high speed ships, automation, new materials).

The optimization quickly becomes computationally unmanageable when higher fidelity codes are used. Computational and optimization methods are required to minimize this computational burden.

1.1.1 Multi-Objective Optimization of Naval Ships

In this thesis, a multiple-objective genetic design optimization approach developed by Brown [2,3] is used to search the design space and perform trade-offs. This approach considers various combinations of hull form, hull materials, propulsion systems, combat systems and manning within the design space using mission effectiveness, risk and acquisition cost as objective attributes. A ship synthesis model is used to balance these parameters in total ship designs, to assess feasibility and to calculate cost, risk and effectiveness. The final design combinations are ranked by cost, risk and effectiveness, and presented as a series of non-dominated frontiers. A non-dominated frontier (NDF) represents ship designs in the design space that have the highest effectiveness for a given cost and risk compared to other designs in the design space. A non-dominated solution, for a given problem and constraints, is a feasible solution for which no other feasible solution exists that is better in one attribute and at least as good in all others. Concepts for further study and development are chosen from this frontier. The “best” design is determined by the customer’s preferences for effectiveness, cost and risk. Preferred designs must always be on the non-dominated frontier. This preference may be affected by the shape of the frontier and cannot be rationally determined a priori. Using a graphic similar to Figure 2, the full range of cost-risk-effectiveness possibilities can be presented to decision-makers, trade-off decisions can be made and specific concepts can be chosen for further analysis. “Knees in the curve” can be seen graphically as significant changes in the slope of the frontier.

Genetic algorithms (GAs) are used in this approach because they are able to explore a design space that is very non-linear, discontinuous, and bounded by a variety of constraints and thresholds. These attributes prevent application of mature gradient-based optimization techniques including Lagrange multipliers, steepest ascent methods, linear programming, non-linear programming and dynamic programming. GAs are also ideally-suited for multi-objective optimization since they develop a population of designs vice a single optimum. This population can be forced to spread-out over the non-dominated frontier.

The multi-objective optimization is implemented in Model Center (MC). Model Center is a computer-based design integration environment that includes tools for linking design model

components, visualizing the design space, performing trade studies and optimization, developing parametric models of the design space, and archiving results from multiple studies. By automating and simplifying these tasks, Model Center makes the design process more efficient, saves engineering time, and reduces the error in the design process [4].

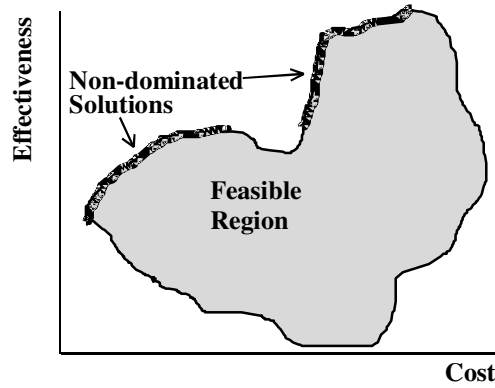


Figure 1 – Two Objective Attribute Space

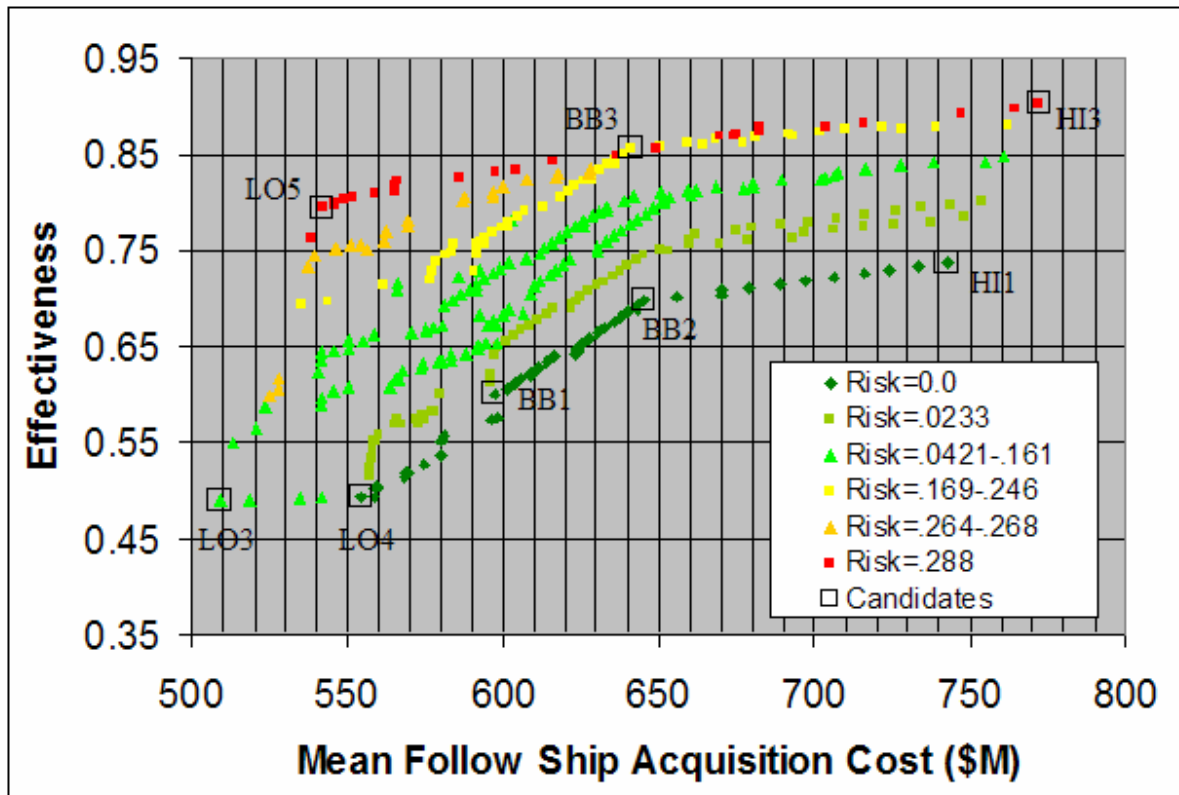


Figure 2 - Non-Dominated Frontiers

1.1.2 Overall Measure of Effectiveness

To perform the ship design optimization, quantitative objective functions are developed for each objective attribute. Effectiveness and risk are quantified using overall measures of effectiveness and risk.

The process for developing an OMOE objective function is shown in Figure 3. Important terminology used in describing this process includes:

- Overall Measure of Effectiveness (OMOE) - Single overall figure of merit index (0-1.0) describing ship effectiveness over all assigned missions or mission types
- Mission or Mission Type Measures of Effectiveness (MOEs) - Figure of merit index (0-1.0) for specific mission scenarios or mission types
- Measures of Performance (MOPs) - Specific ship or system performance metric independent of mission (speed, range, number of missiles)
- Value of Performance (VOP) - Figure of merit index (0-1.0) specifying the value of a specific MOP to a specific mission area for a specific mission type.

The process begins with the Mission Need Statement and mission description. Required operational capabilities (ROCs) are identified to perform the ship's mission(s) and measures of performance (MOPs) are specified for those capabilities that vary in the designs as a function of the ship design variables (DVs). Each MOP is assigned a threshold and goal value. Capability requirements and constraints applicable to all designs are also specified. An Overall Measure of Effectiveness (OMOE) hierarchy is developed from the MOPs using the Analytical Hierarchy Process (AHP) to calculate MOP weights and Multi-Attribute Value Theory (MAVT) to develop individual MOP value functions.

Figure 4 shows the simple OMOE Hierarchy used for the OMOE validation presented in this thesis. This OMOE represents the overall effectiveness of a notional destroyer to perform a specific mission as implemented in the HARPOON war game as described in Chapter 3. There are three MOP categories shown in this hierarchy: weapons, mobility and survivability. The MOP (metric) for weapons is number of VLS cells. Three cell capacities are considered under this MOP. Under mobility there are 2 MOPs: maximum speed and fuel capacity. Three speeds and three fuel capacities are considered under these MOPs in the study. Under survivability there are 2 MOPs: maximum sustainable damage and detection signature. Three hit limits and three detection signatures are considered under these MOPs. Each alternative under each MOP is

assigned a value of performance (0-1.0) using pairwise comparison as part of the AHP. This OMOE will be discussed in detail in Chapter 3.

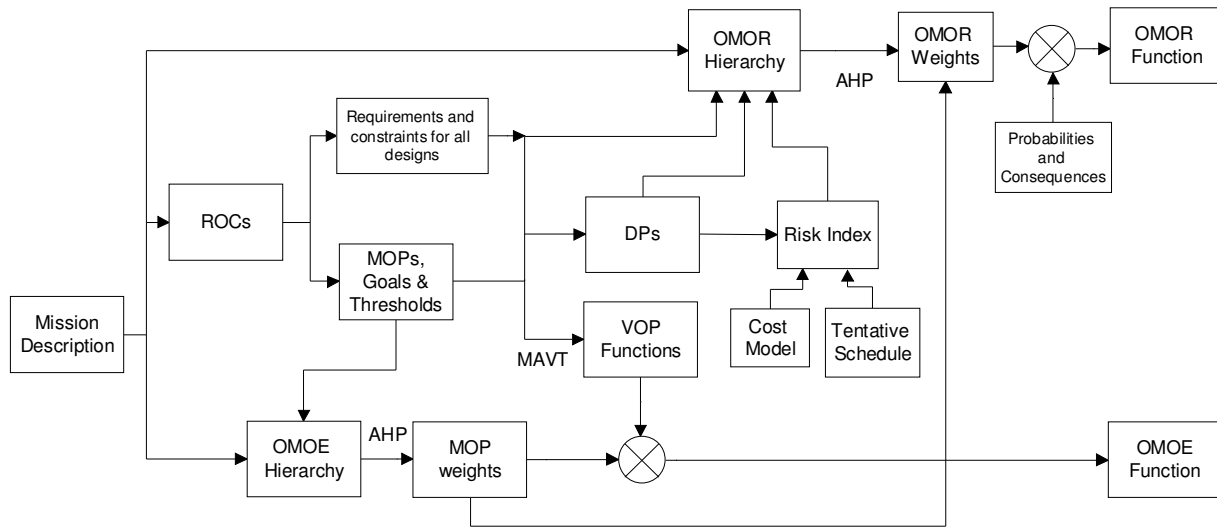


Figure 3 – OMOE and OMOR Development Process

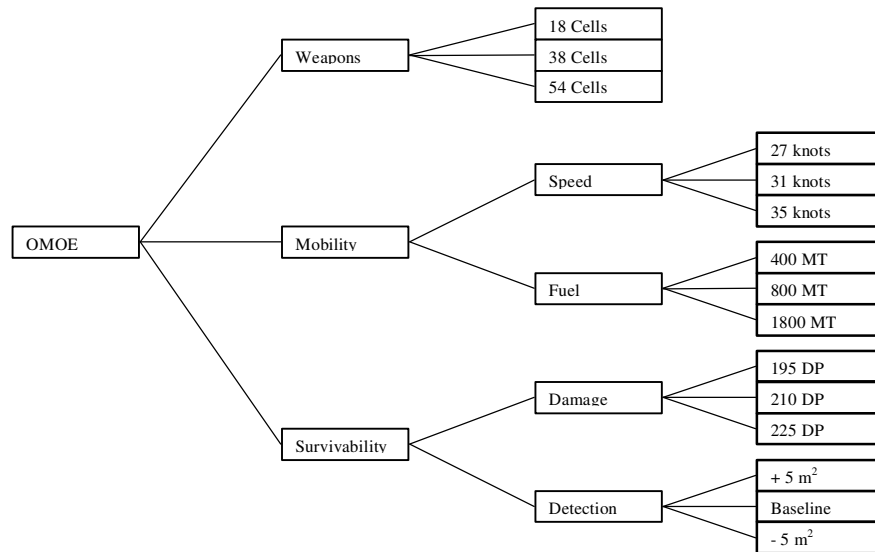


Figure 4 – HARPOON OMOE Hierarchy

In the AHP, pairwise comparison questionnaires are used to solicit expert and customer opinion, required to calculate AHP weights and value of performance (VOP). Value of Performance (VOP) functions (generally S-curves) are developed for each MOP and VOP values are calculated using these functions in the ship synthesis model. A particular VOP has a value of zero corresponding to the MOP threshold, and a value of 1.0 corresponding to the MOP goal. MOP weights and value functions are finally assembled in a single OMOE function:

$$OMOE = g[VOP_i (MOP_i)] = \sum w_i VOP_i (MOP_i) \quad (1)$$

Compare the relative IMPORTANCE with respect to: GOAL

1 = EQUAL 3 = MODERATE 5 = STRONG 7 = VERY STRONG 9 = EXTREME

| | | | | | | | | | | | | | | | | | | | |
|---|----------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|----------|
| 1 | Weapons | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Mobility |
| 2 | Weapons | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Survive |
| 3 | Mobility | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Survive |

| Abbreviation | Definition |
|--------------|---|
| Goal | Maximize DDG Overall Effectiveness |
| Weapons | Missile Vertical Launching System (VLS) |
| Mobility | Ship Movement |
| Survive | Survivability |

Figure 5 – Sample AHP Pairwise Comparison Questionnaire

1.1.3 Cost

As with effectiveness and risk, the multi-objective optimization requires a cost model that can generate lifecycle or total ownership cost for a specified design without direct user interaction. Cost models by their nature involve significant proprietary and sensitive data. Even within the Navy, organizations like NAVSEA 017 have resisted providing their models to the engineers.

A Virginia Tech naval combatant cost model adapted and expanded by Dr. Brown from a late-80's ASSET cost model (the ASSET cost module has since been removed) is the baseline cost model used in this thesis. This is a weight-based model supplemented with producibility and complexity adjustment factors.

1.1.4 Multi-Disciplinary Optimization

In early stage design, the design space (i.e., the number of possible combinations of the various design variables either continuous or discrete) is typically very large. Evaluating the performance of designs for even a small portion of this large design space can become prohibitive if the analyses are computationally expensive. Because of this, high-fidelity codes are typically not used in the early stages of the design process. As a result, major decisions regarding the basic elements of the design are already made before high-fidelity codes begin to be used. An important objective of this thesis is to identify methodologies that will enable high-fidelity codes to be used earlier in the design process. In this thesis, Response Surface Modeling and Design of Experiments techniques are used to generate a response surface approximation for ship bare hull structural weight.

1.2 Objectives

The primary objectives of this thesis are

- Validate the AHP/MAVT method for deriving a naval ship OMOE function.
- Assess the use of RSM and DOE methods for minimizing computational time when using high fidelity codes early in the naval ship design process. This is accomplished using a structural optimization case study.
- Integrate these techniques in a ship design case study.

1.3 Thesis Outline

Chapter 1 provides an introduction and motivation for the use of multi-objective and multi-disciplinary optimization of naval ships, the Overall Measure of Effectiveness of a ship design, and the ship cost model. The objectives of this thesis are described in Chapter 1.

Chapter 2 lays the foundation and background of the Analytical Hierarchy Process and Additive Utility Models. It describes the theory behind each and provides examples of them in use in other industries.

Chapter 3 validates the OMOE and use of the Analytical Hierarchy Process through experimentation. The experiment is conducted using a naval war gaming program called HARPOON and expert decision makers.

Chapter 4 discusses Model Center tools for trade studies, design space visualization, optimization of naval ship designs, and structural design optimization using Response Surface Models and MAESTRO.

Chapter 5 applies the tools addressed in the previous chapters to a high speed naval surface combatant design case study.

Chapter 6 is a summary and conclusion.

CHAPTER 2 AHP AND ADDITIVE UTILITY MODELS

2.1 Utility Theory

When making decisions, the various objective attributes, parameters and criteria may be very different and may have different metrics. Frequently scales or units can not easily be converted to make comparisons. Utility theory, based on the foundation of decision making, is an attempt to infer subjective value, or utility, from choices. Utility theory provides a way to establish a common scale of measuring values for very different attributes or criteria. This metric may also be used with non-linear relationships using a nonlinear utility function. Utility is defined as a measure of the desirability of an outcome, usually a function of cost, benefit, or risk. A utility function transforms an outcome into a numerical value and measures the worth of an outcome. The utility of an outcome may be negative or positive. This utility function may be a simple table, a linear function, or a more complex function.

Utility theory originated in the 18th century, but wasn't significantly developed until the 20th century. The earliest accounts of utility theory date to Daniel Bernoulli's essay on the solution of the St. Petersburg paradox. Bernoulli used a utility function to explain the probability of winning money by flipping a coin. The money paid out doubled every time tails were flipped until heads was flipped. Bernoulli hypothesized that the "utility" (subjective value) of an outcome (a prize in a lottery) was not directly proportional to the money value of the prize. Rather, he proposed there was a negatively accelerating diminishing utility function, such that the "amount" of utility was proportional to the logarithm of the objective dollar value. It wasn't until 1947 that utility theory was formally developed by von Neumann and Morgenstern in their book, *Theory of Games and Economic Behavior*. One of their goals in this book was to promote the development of methods to measure utilities on numerical scales. [5,6]

In order to build a utility function, several normative axioms are used. The axioms are rational and reasonable, but do not always reflect the choices of a decision maker. When utility theory is used you assume that rational people make choices based upon these axioms. The common metric used by utility functions is called the ordered metric. The upper and lower limits of the ordered metric scale are two arbitrary points defined by the worst and best outcomes ($U(X_{\text{worst}}) = 0$ and $U(X_{\text{best}}) = 1$). [7]

Utility functions may be developed using questionnaires completed by the experts or decision makers. Utility functions are difficult to build. Unless the expert has a background in statistics it is often difficult to grasp the concepts of the lottery method required to objectively answer the questionnaire. Even a simple utility function requires significant effort to develop.

Utility functions compare only two attributes or parameters at a time. Multiple-attribute decisions require more than one utility function. These must be combined in some overall function. Additive utility functions use a weighted sum of individual utility functions. The sums can then be compared for each alternative since utility functions are ordered metrics. The weighting of the attributes (utility functions) is left up to the expert. This assumes that the individual comparisons are independent which is an ideal assumption, and is rarely entirely valid.

2.2 Multi-Attribute Utility Theory

Multi-attribute utility theory (MAUT) is an extension of utility theory. It is a basis for finding utility between alternatives that are characterized by multiple attributes. It is based on the axiom that the utility function $U = U(g_1, g_2, \dots)$ is being maximized. The utility function is an equation of all the estimated values of the attributes, g_i . Multi-attribute utility theory has been widely used in situations where the decision making depends on multiple factors and the utility calculation of decision alternatives is based on multiple attributes. The multi-attribute utility functions are used more often than general single attribute utility functions in complex environments where a decision maker needs to evaluate the alternatives with different attributes.

MAUT allows for some interaction of attributes by decreasing the calculations within attributes. A two attribute MAU function is defined as:

$$U(X_1, X_2) = k_1U(X_1) + k_2U(X_2) + Kk_1k_2U(X_1)U(X_2) \quad (2)$$

K is a normalizing factor equal to $(1 - k_1 - k_2)/k_1k_2$, where k_i is the weight an attribute has relative to the objective ($\sum k_i = 1$), and U is the utility (scale of 0 to 1) [7]. Equation (2) calculates the total utility of an alternative which is equal to the sum of the utility of each individual attribute of the alternative times their respective weights plus any interaction of the attributes. When there is no interaction between attributes this equation becomes:

$$U(X) = \sum k_iU(X_i) \quad (3)$$

2.3 Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) was developed by Dr. Thomas Saaty in the late 1970's [8,9,10]. It is a type of decision theory. Decision theories were developed because the human mind has a limited capability to retain large amounts of information and therefore cannot always make decisions based on a thorough resolution of all the issues. Also since most complex decisions are based on a number of interacting factors having varying degrees of importance, decision theories provide a way of organizing them into a more manageable process without losing their influence on the decision. Most statistical techniques developed in the past to help make decisions fail in real-world application because of their inability to derive weights of factors based on importance. The AHP helps overcome this inability. The primary goal of the AHP is to select an alternative that best satisfies a given set of criteria out of a set of alternatives. According to Saaty, the purpose of the AHP is to evaluate and prioritize the influence alternatives have on satisfying the objective of the problem. The power of the AHP is that it can be applied in any type of decision problem. It can be considered an extension of our information processing capacity and our thought processes [8].

The advantage AHP has over other decision theories is that it better represents the way experts make decisions. It allows for relative judgments and uses the human tendency to organize attributes (criterion influencing the objective) and complex goals into a hierarchy structure (Figure 6). The hierarchy structure allows the decision maker to consider intangible attributes as well as tangible attributes by rank. This hierarchy also allows for attributes of the same class to be placed in weighted parent clusters and weighted within the parent cluster. Parent clusters are criteria that cannot be represented by a single attribute. There can be any number of parent clusters used to organize the problem, but only the final children define the alternatives. AHP is also effective when the scales of attributes conflict or if they are difficult to compare. AHP is particularly superior over other methods when a model is very unstructured.

AHP scales the weights of attributes at each level of the hierarchy with respect to a goal using the decision maker's (experts') experience and knowledge in a matrix of pairwise comparisons of the attributes. The usual application of AHP is to select the best alternative from a discrete set of alternatives. The application described in this thesis is unique because AHP is used to calculate the weights in an additive utility function that can be used as an objective function for an unlimited number of alternatives that may not be defined apriori. This method

also requires that value or utility functions be developed for each attribute to combine with the weights in the additive function.

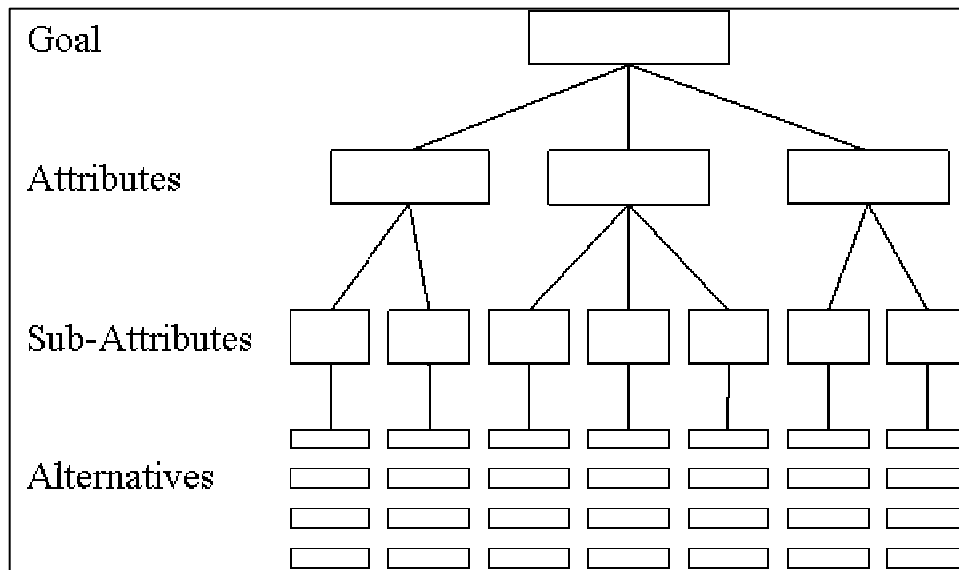


Figure 6 – Decision Hierarchy

The process begins by defining the goal and requirements of the problem. Then alternatives are identified that satisfy the requirements. Next the relative importance of each requirement to achieve the goal is assessed. Finally, the best alternative or set of alternatives is determined.

The pairwise comparison uses a 9 point ratio scale to convert relative magnitudes into ordered metrics. The 9 point scale uses an intensity scale, shown in Table 1, to compare alternatives. This scale assumes that the decision maker has knowledge about the relative importance of the attributes being compared, and that they can express the relative importance to the nearest integer with 9 being the highest and 1 being of equal importance. Zero is not included in the comparison so that reciprocals can be used in the comparison matrix.

Table 1 – Intensity scale of pairwise comparisons [9]

| Intensity of Importance | Definition | Explanation |
|-------------------------|-------------------------------------|---|
| 1 | Equal importance | Two activities contribute equally to the objective |
| 3 | Weak importance of one over another | Experience and judgment slightly favor one activity over another |
| 5 | Essential or strong importance | Experience and judgment strongly favor one activity over another |
| 7 | Demonstrated importance | An activity is strongly favored and its dominance demonstrated in practice |
| 9 | Absolute importance | The evidence favoring one activity over another is of the highest possible order of affirmation |
| 2,4,6,8 | Intermediate values | When compromise is needed |

Pairwise comparison is performed separately for branches (attributes) below each parent in the hierarchy. The objective is to produce a set of weights (w_i) for the branches below a parent, normalized so that the sum of these weights equals one. These weights are derived from the pairwise comparison preference matrix, but pairwise comparison may not be consistent (ie: $w_{13} \neq w_{12} w_{23}$). If A is preferred 4 times as much as B, and B is preferred twice as much as C, then A must be preferred 8 times as much as C to be consistent. When making judgments people are naturally inconsistent. This is often a result of thought and feeling. The AHP admits and measures inconsistencies of the decision maker that may reflect the quality of the decision maker's knowledge, the content of the judgments, and stability of the solution. This is accomplished by finding the best-fit eigenvector and eigenvalues. Multiple experts can also be used in AHP which may add more inconsistency. A level in the hierarchy can be added if the experts deserve different weights due to their expertise [8].

To understand how AHP resolves inconsistency, it is useful to work backwards from a typical set of resulting weights (ex: w_1, w_2, w_3), noting how they were derived and the necessary requirements for their consistency. Consider a parent with three subordinate branches. Assume that a ratio scale is used for pairwise comparison. Given a final set of weights, (w_1, w_2, w_3), produced from a preference matrix W , Equation (4) shows how the elements in this matrix must be represented if it is a consistent preference matrix ($w_{ij} = w_i/w_j$). Its elements must follow the rules: $w_{ij} = w_{ji}^{-1}$ and $w_{ij} = w_{ik} w_{kj}$ for any values of i, j , and k .

$$W = \begin{bmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \frac{w_1}{w_3} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & \frac{w_2}{w_3} \\ \frac{w_3}{w_1} & \frac{w_3}{w_2} & \frac{w_3}{w_3} \end{bmatrix} \quad (4)$$

Since each row of W is a multiple of the first row, W has a rank of 1 and there is only one non-zero eigenvalue, q . Equation (4) takes the form:

$$W \cdot w = q \cdot w \quad (5)$$

where w is the eigenvector of W corresponding to the maximum eigenvalue, q , and the elements in w are the attribute weights.

To obtain this result which is characteristic of a consistent preference matrix, Saaty [11] assumes that we start with a potentially inconsistent pairwise comparison matrix, A , where the a_{ij} judgment values are only estimates of the consistent matrix, W , and the eigenvector, x , corresponding to the maximum eigenvalue (λ_{max}) of the inconsistent matrix A , is only close to w . Equation (6) represents the eigenvalue problem in the inconsistent case.

$$A \cdot x = \lambda_{max} \cdot x \quad (6)$$

He shows that for moderate inconsistency λ_{max} will be close to n (number of attributes) and all other λ 's will be close to zero. He also shows that the elements in x represent the best approximation to the attribute weights for the inconsistent preference matrix. The closer λ_{max} is to n , the more consistent the judgments are shown to be. Small perturbations in A only cause small perturbations in the eigenvalues. Inconsistency is measured as $(\lambda_{max} - n)/n$. The inconsistent case is generally considered valid when this inconsistency is less than 10%. [10]

Normalizing, the resulting weight of the i^{th} attribute is given by Equation (7).

$$w_i = x_i / \sum_{i=1}^n x_i \quad (7)$$

An example of the AHP estimates the relative distances of 6 cities to Philadelphia [8] using experience from air travel. The decision maker uses pairwise comparisons between cities determining how many times further one city is from Philadelphia than the other city is from Philadelphia. Table 2 shows the comparison matrix completed by the decision maker. Figure 7 shows this in the hierarchy form. Figure 8 shows the AHP analysis for this example.

Table 2 – Comparison of distances of cities from Philadelphia (w_{ij})

| City | Cairo | Tokyo | Chicago | San Francisco | London | Montreal |
|---------------|-------|-------|---------|---------------|--------|----------|
| Cairo | 1 | 1/3 | 8 | 3 | 3 | 7 |
| Tokyo | 3 | 1 | 9 | 3 | 3 | 9 |
| Chicago | 1/8 | 1/9 | 1 | 1/6 | 1/5 | 2 |
| San Francisco | 1/3 | 1/3 | 6 | 1 | 1/3 | 6 |
| London | 1/3 | 1/3 | 5 | 3 | 1 | 6 |
| Montreal | 1/7 | 1/9 | 1/2 | 1/6 | 1/6 | 1 |

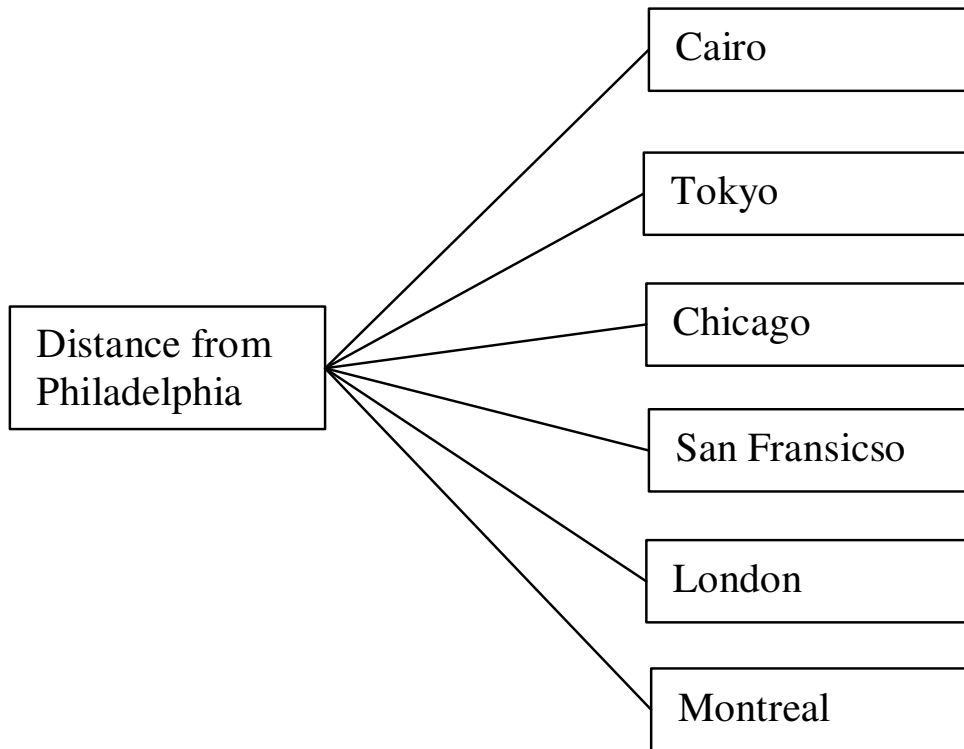


Figure 7 – Hierarchy of Distance Example

$$\begin{aligned}
A &:= \begin{pmatrix} 1 & \frac{1}{3} & 8 & 3 & 3 & 7 \\ 3 & 1 & 9 & 3 & 3 & 9 \\ \frac{1}{8} & \frac{1}{9} & 1 & \frac{1}{6} & \frac{1}{5} & 2 \\ \frac{1}{3} & \frac{1}{3} & 6 & 1 & \frac{1}{3} & 6 \\ \frac{1}{3} & \frac{1}{3} & 5 & 3 & 1 & 6 \\ \frac{1}{7} & \frac{1}{9} & \frac{1}{2} & \frac{1}{6} & \frac{1}{6} & 1 \end{pmatrix} & \lambda := \text{eigenvals}(A) & \lambda = \begin{pmatrix} 6.454 \\ 0.133 + 1.577i \\ 0.133 - 1.577i \\ -0.23 + 0.665i \\ -0.23 - 0.665i \\ -0.26 \end{pmatrix} & \lambda_{\max} := \lambda_1 & \lambda_{\max} = 6.454 \\
& n := 6 & & \text{inconsist} := \frac{\lambda_{\max} - n}{n} \\
& X := \text{eigenvecs}(A) & & \text{inconsist} = 0.076 \\
X &= \begin{pmatrix} 0.505 & 0.156 + 0.494i & 0.156 - 0.494i & -0.208 + 0.412i & -0.208 - 0.412i & -0.422 \\ 0.767 & 0.754 & 0.754 & 0.812 & 0.812 & 0.88 \\ 0.064 & -8.726 \times 10^{-3} - 0.044i & -8.726 \times 10^{-3} + 0.044i & -0.054 + 0.033i & -0.054 - 0.033i & 0.041 \\ 0.224 & -0.199 - 0.102i & -0.199 + 0.102i & 0.146 + 0.091i & 0.146 - 0.091i & -0.077 \\ 0.317 & -0.228 + 0.239i & -0.228 - 0.239i & -0.06 - 0.296i & -0.06 + 0.296i & 0.189 \\ 0.051 & 0.027 - 0.034i & 0.027 + 0.034i & -0.016 - 0.042i & -0.016 + 0.042i & -0.061 \end{pmatrix} \\
x_1 := X_{i,1} & x = \begin{pmatrix} 0.505 \\ 0.767 \\ 0.064 \\ 0.224 \\ 0.317 \\ 0.051 \end{pmatrix} & w := \frac{x}{\sum_{i=1}^6 x_i} & w = \begin{pmatrix} 0.262 \\ 0.397 \\ 0.033 \\ 0.116 \\ 0.164 \\ 0.027 \end{pmatrix}
\end{aligned}$$

Figure 8 – Calculating Hierarchy Weights for Inconsistent Comparison Matrix

Using the Intensity Scale, Table 1, and referring to Table 2, the questions asked in the comparison are: given city A (row) and city B (column), how much further is city A from Philadelphia than city B. Only the comparisons above the diagonal are made (the diagonal being 1 since A compared to A is equal) and the reciprocals fill in the rest of the comparison matrix. The matrix is then reduced to its eigenvector with each eigenvalue being the weight or relative distance of each city from Philadelphia. Table 3 shows a comparison of the eigenvector results from the AHP to the actual distances.

Table 3 – Real and Estimated Distances

| City | Distance from Philadelphia (miles) | Normalized Distance | Normalized Eigenvector |
|---------------|------------------------------------|---------------------|------------------------|
| Cairo | 5729 | 0.278 | 0.262 |
| Tokyo | 7449 | 0.361 | 0.397 |
| Chicago | 660 | 0.032 | 0.033 |
| San Francisco | 2732 | 0.132 | 0.116 |
| London | 3658 | 0.177 | 0.164 |
| Montreal | 400 | 0.019 | 0.027 |

2.4 Combination of AHP and MAUT

Once the relative importance weights of attributes are found using the AHP the overall measure of effectiveness can be defined using additive multi-attribute utility theory or multi-attribute value theory. Utility theory is really just a specific subset of value theory where the lottery method and a strict interval scale are used for the attribute value functions. More general multi-attribute value (MAV) functions can be used in place of utility functions to assess the relative value of alternatives or performance metrics for a particular attribute if explicit bounds or anchor points (goal and threshold) are established for the attribute values [12]. These value functions can then be developed using pairwise comparison of attribute values or the function can be shaped from inspection rather than using a lottery. A MAV function is defined as

$$V_i = \sum_j w_j x_{ij} \quad (8)$$

where:

V_i is the overall value of the i^{th} alternative

w_j is the weight or relative importance of the j^{th} criteria established from AHP

x_{ij} is the value (or score) of the i^{th} alternative for the j^{th} criteria (0-1)

The threshold represents the minimum value acceptable for a particular attribute. The goal represents a reasonable technology limit or a point beyond which further improvement has no additional value for the attribute. [12]

The following example of choosing the best car to buy shows the use of the AHP in conjunction with MAVT.

A customer wants to buy a new car based on price, power, and safety [13]. This example is restricted to 3 car options, a BMW, a Mercedes, and a Citroen. Criteria for the best possibility are chosen. The car needs to have airbags (Measure of Performance 1, MOP1) and anti-lock brakes (MOP2), be less than \$33,000 (MOP3), have a cylinder capacity greater than 2500 (MOP4), and have a nominal power greater than 130 (MOP5). Figure 1 shows the hierarchy tree and Table 4 gives the specifics of the three car alternatives.

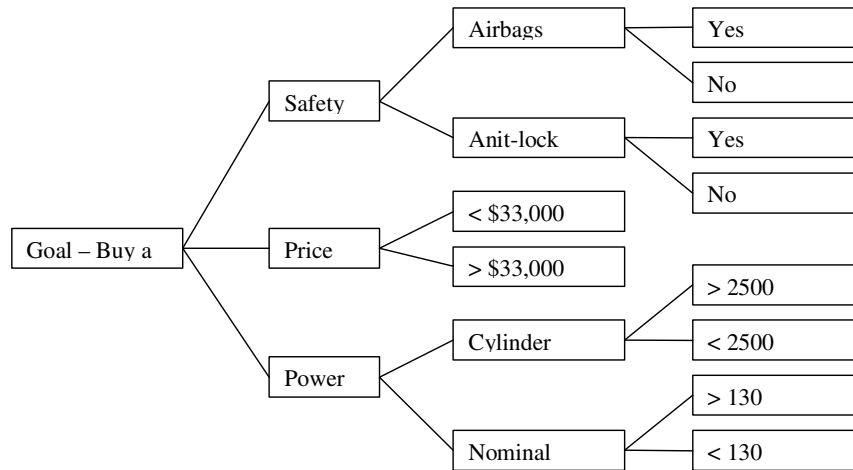


Figure 9 – Car Example Hierarchy

Table 4 – Car Specifics

| | BMW | Mercedes | Citroen |
|-------------------|------------|-----------------|----------------|
| Airbag | Yes | Yes | Yes |
| Anti-lock Brakes | Yes | Yes | No |
| Price | \$38,500 | \$46,500 | \$26,500 |
| Cylinder Capacity | 2495 | 2685 | 1749 |
| Nominal Power | 141 | 125 | 117 |

From the pairwise comparison completed by the customer the relative importance of safety, price, and power is 0.3, 0.4, and 0.3 respectively. In the safety cluster airbags and anti-lock brakes share equal relative importance (0.5 each). In the power cluster cylinder capacity has a relative importance of 0.4 and nominal power is 0.6. To keep this example simple the value of attribute performance (VOP) will simply be 1 if it is satisfied and 0 if it is not satisfied by the alternative. Table 5 shows the calculation of the overall measure of effectiveness (OMOE) for each alternative. It can be seen that by the criteria set by the customer the Citroen is the best alternative. The OMOE function for this analysis is:

$$\text{OMOE} = .3(.5*\text{VOP1}(\text{MOP1})+.5*\text{VOP2}(\text{MOP2}))+.4*\text{VOP3}(\text{MOP3})+.3*(.4*\text{VOP4}(\text{MOP4})+.6*\text{VOP5}(\text{MOP5}))$$

Table 5 – Car Example VOPs and OMOE

| | BMW | Mercedes | Citroen |
|---|------------|-----------------|----------------|
| Airbag VOP | 1 | 1 | 1 |
| Anti-lock Brakes VOP | 1 | 1 | 0 |
| Cylinder Capacity VOP | 0 | 1 | 0 |
| Nominal Power VOP | 1 | 0 | 0 |
| Safety VOP (0.5*Airbag + 0.5*Anti-lock Brakes) | 1 | 1 | 0.5 |
| Price VOP | 0 | 0 | 1 |
| Power VOP (0.4*Cylinder Capacity + 0.6*Nominal Power) | 0.6 | 0.4 | 0 |
| OMOE Goal – Buy the Car (0.3*Safety + 0.4*Price + 0.3*Power) | 0.48 | 0.42 | 0.55 |

2.5 Validation of AHP in other Applications

Validations of the AHP in other applications were researched to determine if there has been a validation or use of AHP similar to our OMOE application. Sections 2.5.1 to 2.5.5 describe examples that find weights of given alternatives with respect to a goal, which is similar to our application of finding weights to build an OMOE function. Each of the following examples are summaries from Rozann Saaty's *Validation Examples for the Analytical Hierarchy Process and the Analytical Network Process* [14].

2.5.1 Estimating Relative Areas using AHP

A simple AHP validation exercise is to estimate the relative areas of geometric shapes shown in Figure 10. The decision maker does not need any prior knowledge of the shapes. The job of the decision maker is to compare two of the shapes at a time (10 comparisons) estimating how many times larger the area of one shape is compared to the smaller shape using the fundamental scale of AHP. Figure 11 shows the hierarchy in Super Decisions, an AHP program. A comparison matrix completed by an arbitrary decision maker is shown in Figure 12.

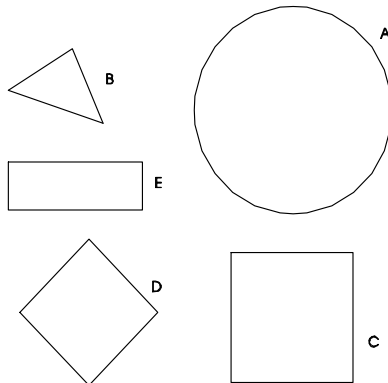


Figure 10 – Relative Areas Geometric Shapes [14]

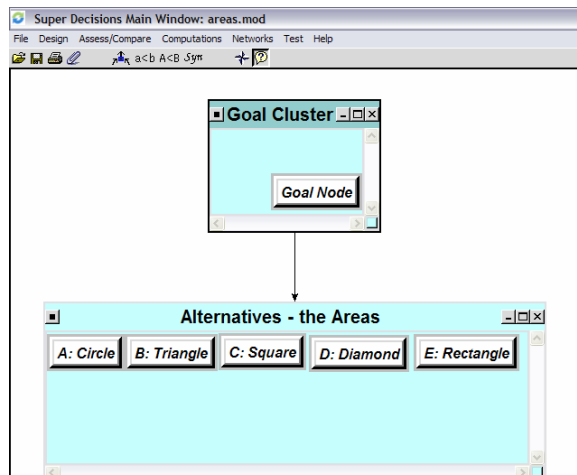


Figure 11 – Relative Area Hierarchy in Super Decisions

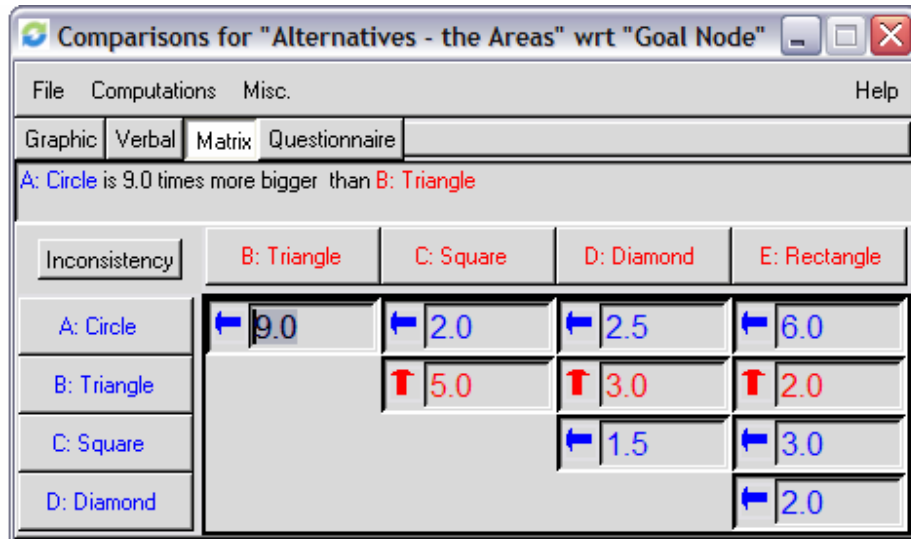


Figure 12 – Relative Area Comparison Matrix from Super Decisions

The results of this comparison are calculated by Super Decisions and are show below in Figure 13. Table 6 shows the comparison of the actual relative values vs. the ones found using the AHP.

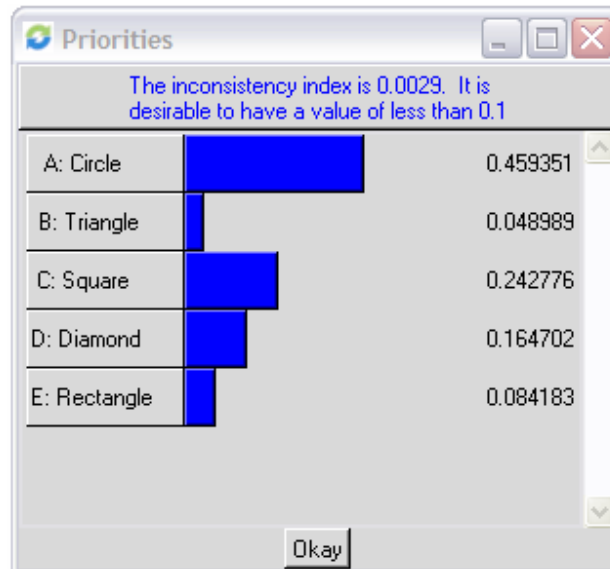


Figure 13 – Relative Area Results from Super Decisions

Table 6 – Relative Area AHP vs. Actual

| Figure | AHP Relative Area | Actual Relative Area |
|--------|-------------------|----------------------|
| A | 0.46 | 0.47 |
| B | 0.05 | 0.05 |
| C | 0.24 | 0.24 |
| D | 0.16 | 0.14 |
| E | 0.08 | 0.09 |

The results show that the order and weights of the figures derived from the Analytical Hierarchy Process are very close to the actual.

2.5.2 Estimating Relative Drink Consumption with AHP

This example shows that the relative scale works well on homogeneous elements of a real life problem. A matrix of paired comparison judgments is used to estimate relative beverage consumption in the United States. This exercise was done by a group of about 30 people who arrived at a consensus for each judgment. The types of beverages are listed on the left and at the top. The judgment is an estimate of how consumption of the drink on the left dominates that of the drink at the top. For example, when the judgment for coffee (row label) versus wine (column label) was made, it was thought that coffee is consumed extremely more and a 9 is entered in the first row and second column position. The value 1/9 is automatically entered in the second row and first column position. If the consumption of a drink on the left does not dominate that of a drink at the top, the reciprocal value is entered. For example in comparing coffee and water in the first row and eighth column position, water is consumed slightly more than coffee and a 1/2 is entered. Correspondingly, a value of 2 is entered in the eighth row and first column position. The bottom of Table 7 shows that the derived values obtained by computing the principal eigenvector of the matrix and normalizing it and the actual values obtained from the pages of the Statistical Abstract of the United States are similar.

Table 7 – AHP Drink Consumption Example [14]

*Which Drink is Consumed More in the U.S.?
An Example of Estimation Using Judgments*

| Drink Consumption in the U.S. | Coffee | Wine | Tea | Beer | Sodas | Milk | Water |
|--------------------------------------|--------|------|-----|------|-------|------|-------|
| Coffee | 1 | 9 | 3 | 1 | 1/2 | 1 | 1/2 |
| Wine | 1/9 | 1 | 1/3 | 1/9 | 1/9 | 1/9 | 1/9 |
| Tea | 1/3 | 3 | 1 | 1/4 | 1/5 | 1/4 | 1/5 |
| Beer | 1 | 9 | 4 | 1 | 1/2 | 1 | 1 |
| Sodas | 2 | 9 | 5 | 2 | 1 | 2 | 1 |
| Milk | 1 | 9 | 4 | 1 | 1/2 | 1 | 1/2 |
| Water | 2 | 9 | 5 | 1 | 1 | 2 | 1 |

The derived scale based on the judgments in the matrix with consistency .022 is:

| | | | | | | |
|--------|------|------|------|-------|------|-------|
| Coffee | Wine | Tea | Beer | Sodas | Milk | Water |
| .177 | .019 | .042 | .116 | .190 | .129 | .327 |

The actual consumption for the year 1998 (from Statistical Abstract of the United States, published in 2001) is:

| | | | | | | |
|------|------|------|------|------|------|------|
| .180 | .010 | .040 | .120 | .180 | .140 | .330 |
|------|------|------|------|------|------|------|

2.5.3 Airline Market Share Model with AHP

Another example of validation of the AHP is with the US Airline Market Share in 2000. The model was built using Super Decisions and the weighted results were compared to actual market results of the airlines in 2000. The hierarchy structure is shown in Figure 14. The models results are compared to the actual market in Table 8. To do a successful market estimation, the modeler must be very knowledgeable about that particular market, because making successful judgments depends on accumulated knowledge. Over the past several years, students have done dozens of market share models with remarkably good results. Students who know the business intimately without access to numerical information until after the exercise has been completed work this example and the following one in the classroom.

Table 8 – Airline Model Results vs. Actual Market Share

| Airline | Model Results | Actual Market (2000) |
|---------------|---------------|----------------------|
| American | 23.9 | 24 |
| United | 18.7 | 19.7 |
| Delta | 18.0 | 18.0 |
| Northwest | 11.4 | 12.4 |
| Continental | 9.3 | 10.0 |
| US Airways | 7.5 | 7.1 |
| Southwest | 5.9 | 6.4 |
| American West | 4.4 | 2.9 |

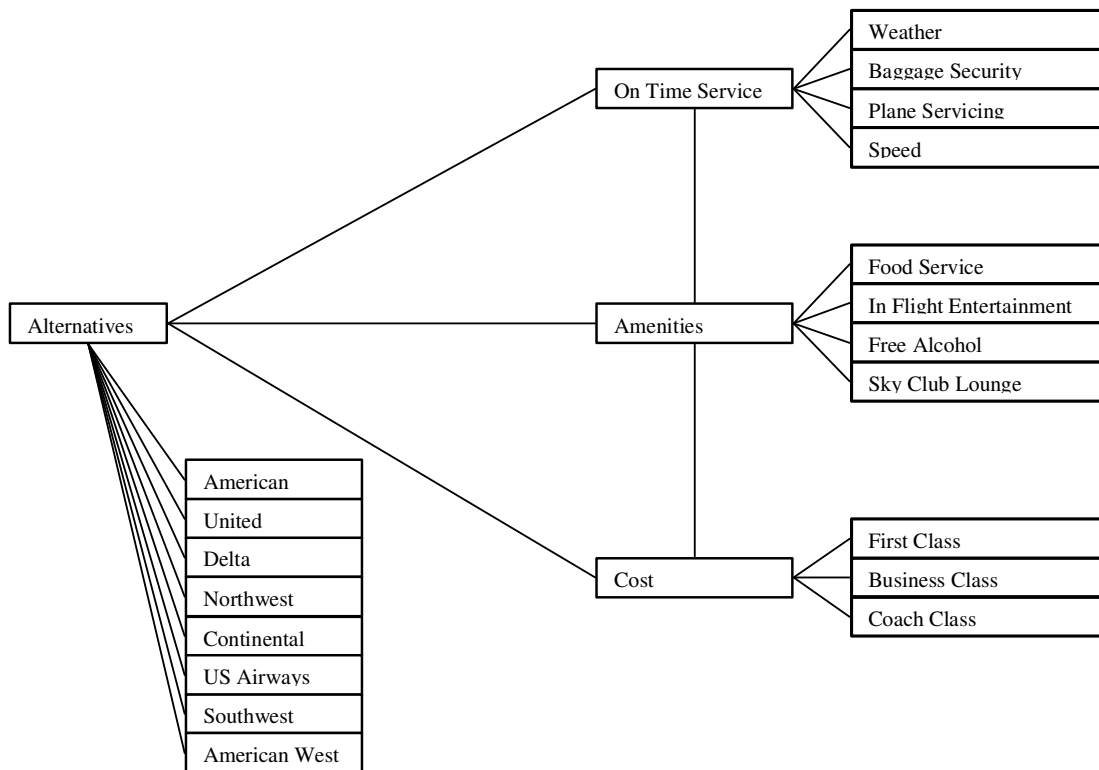


Figure 14 – Airline Model

2.5.4 Superstore Market Share Model with AHP

Another example of validation of the AHP is with the relative market share of the superstores, KMart, Target, and Walmart. The model was built using Super Decisions and the weighted results were compared to actual market results of the airlines in 2000. The hierarchy structure is shown in Figure 15. The first level is the 3 superstores. Each superstore is evaluated based on its advertising, location, customer groups, merchandise, and characteristics of the store. The model results are compared to the actual market share in Table 9.

Table 9 – Superstore Model Results vs. Actual Market Share

| Competitor | ANP Results | Actual Market Share |
|------------|-------------|---------------------|
| Walmart | 59.8 | 54.8 |
| Kmart | 24.8 | 25.9 |
| Target | 15.4 | 19.2 |

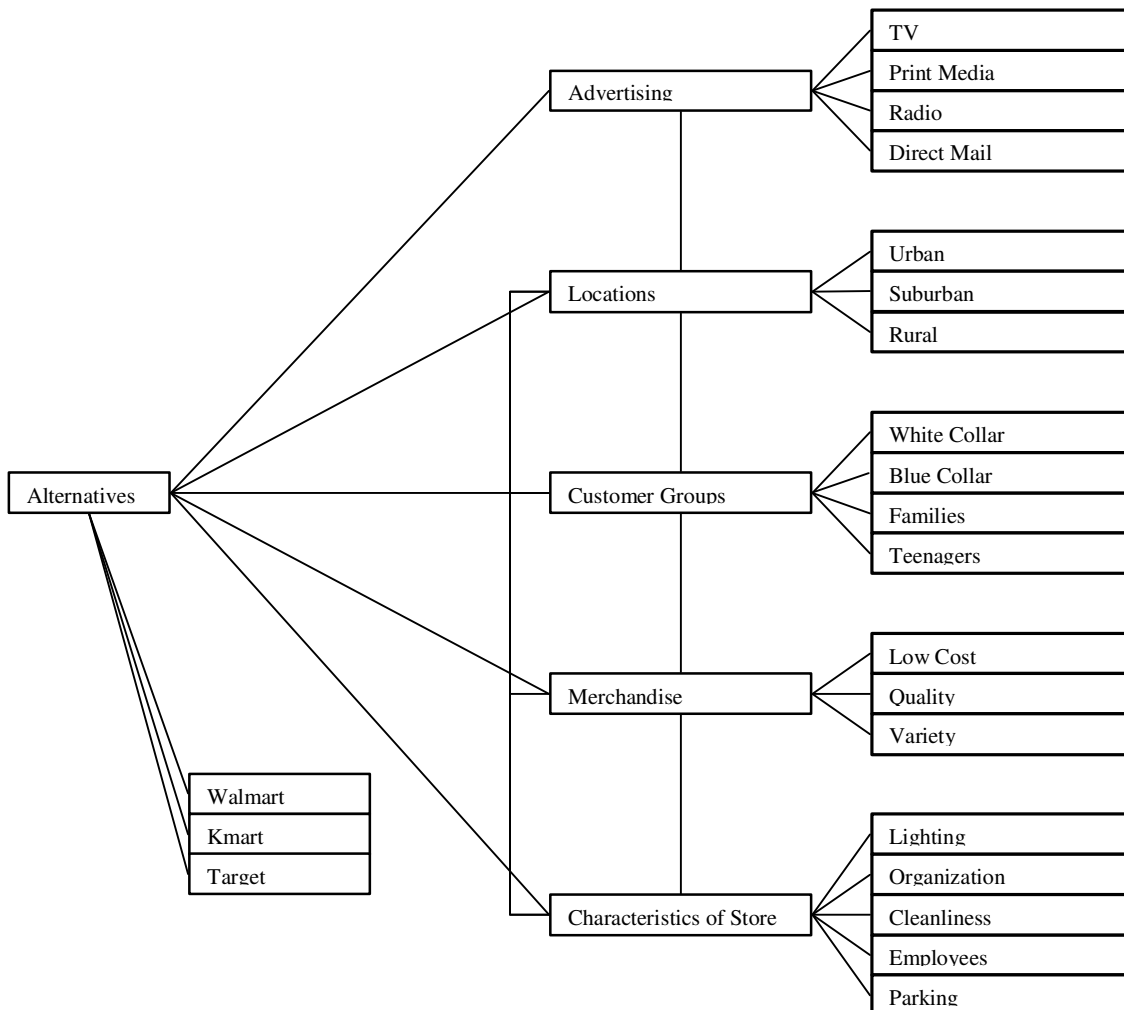


Figure 15 – Superstore Model Hierarchy

2.5.5 Predicting the winner of the 2003 World Series using AHP

This model was used to predict the winner of the 2003 Baseball World Series. At the beginning of the 2003 baseball playoffs Dan Rowlands [15] built an AHP model to predict the winners of each round of the playoffs. He collected data for each team in the playoffs based on the regular season statistics. These include starting pitching, defense, base running, hitting, hitting under pressure, home field advantage as well as a few others. Based upon his expertise of the game the criteria was weighted based upon: good pitching beating good hitting, and defense and base running win in the playoffs. Rowland also factored for the will to win, history of greatness, and overachievers.

A partial hierarchy is shown in Figure 16. Since this model is large it will only be highlighted. The results of the model are shown in Figure 17. These results can then be used to figure out head to head series between two teams, for example New York (0.21) would win over Minnesota (0.11). From looking at the results it is figured that the Yankees would be in the final round while Oakland and Florida should also make it far.

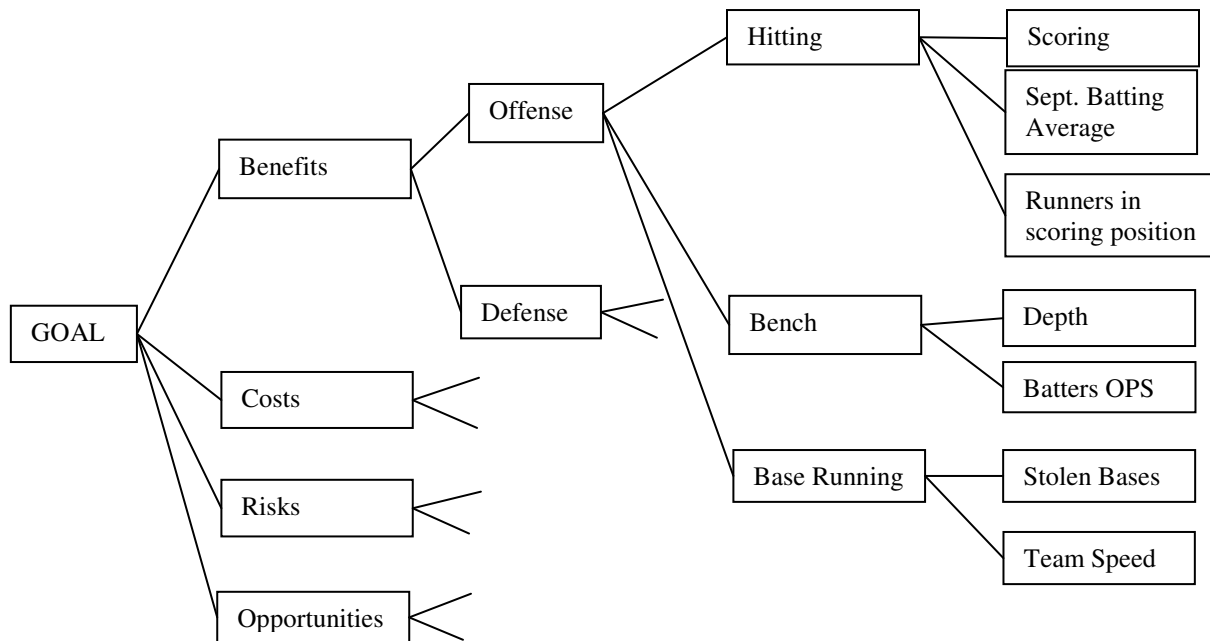


Figure 16 – Baseball Playoffs Model Hierarchy

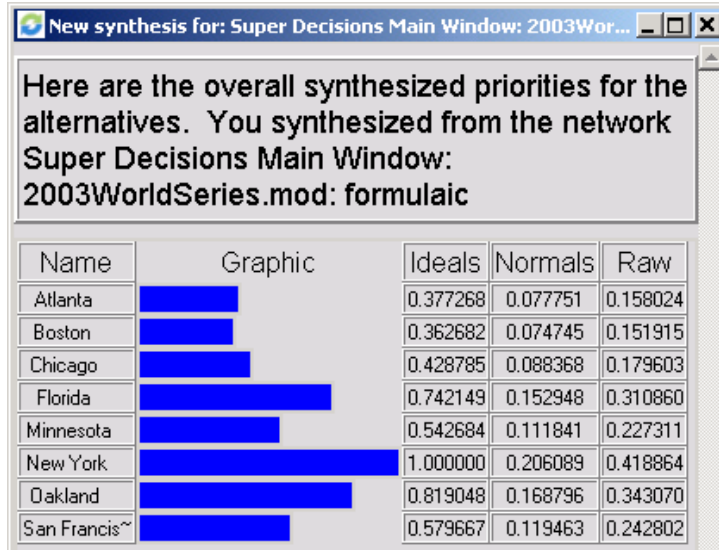


Figure 17 – Baseball Playoffs Model Results [14]

The following are the actual outcomes of the playoffs:

Divisional Playoffs

- New York (0.21) over Minnesota (0.11)
- Boston (0.07) over Oakland (0.17)
- Chicago (0.09) over Atlanta (0.08)
- Florida (0.15) over San Francisco (0.12)

League Championship Series

- New York (0.21) over Boston (0.07)
- Florida (0.15) over Chicago (0.09)

World Series

- Florida (0.15) over New York (0.21)

The model successfully predicted 5 of the 7 playoff series. The series of Boston vs. Oakland went to 5 games and the World Series went to 6 games. Although the World Series wasn't predicted correctly this is still very accurate.

2.6 Why are these validations not sufficient for our application?

These examples provide confidence in the AHP, but they do not prove that the AHP will be effective in an OMOE ship design application. For our application, we will use the AHP to calculate value function weights of attributes (MOPs), and also to define the value functions. The hierarchies of these examples are very similar to the OMOE hierarchy with attributes and

attribute weights that correspond to MOPs and MOP weights. In the typical implementation of the AHP only discrete variables and discrete numbers of alternatives are used, but when using a continuous value function many alternatives may be considered that are not known a priori.

In the previous examples the lowest level of the hierarchy has different characteristics all relating to the same group. For instance in the superstore example white collar, blue collar, families, and teenagers all relate to the customer groups. In the application using OMOE the lowest level of the hierarchy applies to different values of a given characteristic or MOP. For example 18 cells, 36 cells, and 54 cells are different weapon package values relating to the Vertical Launching System weapons characteristic of a ship design. By defining goals and thresholds it is possible to implement a zero to one value index for these MOPs and build value functions without needing to specify the designs that achieve a given level of performance in advance. In order to better validate this method, an experiment was devised that includes both weights and values functions in an OMOE function applied to a simple naval ship problem in a manner similar to how it would be used in naval ship design. This experiment is described in Chapter 3.

CHAPTER 3 OMOE EXPERIMENT

AHP and MAVT can be used to build an OMOE and OMOR function to properly rank and approximately measure the relative mission effectiveness and risk of design alternatives, using trained expert opinion to replace complex analysis tools. An experiment is performed to prove this hypothesis.

The experiment compares the ranking of 16 ships using two methods. The first method uses an OMOE and expert opinion to rank the ships, (experiment) and the second method uses the results of combat (war game) simulation to rank the ships (control). In the first method, experts are taught the relative importance of ship characteristics to achieve a specified ship mission using HARPOON, a ship and air combat simulator described in Section 3.1. The experts then answer an AHP pairwise comparison questionnaire to determine the weights and values (VOPs) of each MOP in the OMOE hierarchy with respect to the ship's HARPOON mission. This data is used to build an OMOE function for this mission. The OMOE function is used to rank 16 ships with different designs based on mission effectiveness. Next, the second method is used to rank the 16 ships using HARPOON to directly assess their mission effectiveness. A successful experiment should provide the same ranking with similar relative effectiveness. The detailed steps followed in this experiment were as follows:

1. Choose a naval ship class and mission types to be studied. The mission types must be realistic, not too complex, and within the capabilities of HARPOON.
2. Determine the required operational capabilities (ROCs) needed perform the mission. MOPs (ship measures of performance) are specified for each of the ROCs. Again, these must be simple enough for the experts to assess their value with a reasonable amount of training and experience (20 hours each).
3. Determine goal, threshold and baseline design characteristics for each measure of performance (MOP).
4. Create an OMOE hierarchy for the MOPs using the AHP.
5. Prepare a HARPOON naval war game/battle scenario with conditions of victory to reflect the ship's mission. These are the goal or success metrics for the mission.
6. Train the experts and provide battle experience using HARPOON in the specified scenario. Ten experts individually complete a HARPOON tutorial and then play this scenario in a series of 12 war games over 20 hours. Each time, the ships used in the scenario have different design characteristics consistent with the ROCs and MOPs they will be asked to compare. The designs are all variants of the baseline design with a single design characteristic changed to the goal or threshold value for one of the MOPs.

7. Assemble the expert opinion by having the experts complete a questionnaire for the OMOE hierarchy, making pairwise comparisons of the MOPs based on their experience playing the battle scenarios.
8. Use the questionnaire results to calculate the AHP eigenvalue weights and VOPs, and develop an OMOE function for the specified mission and design characteristics.
9. Use a Design of Experiments (DOE) method to define 16 different ships with various combinations of goal and threshold design characteristics spanning the design space.
10. Calculate an OMOE value for each of these ship designs using the OMOE function.
11. Rank the ships based on their OMOE value from most effective to least effective.
12. Select a single expert to “play” the scenario 10 times using the same 16 designs. Record the results for each design.
13. Rank the 16 designs from best to worst based on these results.
14. Compare the OMOE ranking to the direct ranking.

3.1 HARPOON Description

HARPOON III is an unclassified air and naval warfare simulator. Although originally marketed as a computer game, HARPOON has developed over time into a remarkably realistic, flexible, and capable warfare modeling tool. Contributions and improvements from an active user’s group, many with extensive naval experience, have consistently improved its realism, databases and usability. Most elements of a modern naval task force and likely battle scenarios can be modeled and exercised. HARPOON has been used extensively by various military activities around the world as a training and what-if simulation tool. [16] HARPOON includes databases for over 400 classes of ships from dozens of countries. It also uses databases of the weapon systems, munitions, propulsion systems, and fuels. The HARPOON II Admiral’s Edition includes 120 programmed scenarios, most of which are modeled after real battles. HARPOON was chosen for this experiment because of its flexibility to change ship characteristics and battle scenarios, its battle realism, and its extensive databases.

When playing HARPOON, the gamer has control of “battle pieces”. Battle pieces can be individual ships (the focus of this study), squadrons of ships that act as a single entity to carry out a mission, individual submarines, individual aircraft, aircraft squadrons, or land base facilities. Figure 18, Figure 19 and Figure 20 are examples of the HARPOON simulation environment. Having control over a battle piece allows the user to navigate, search for aircraft, land bases, surface ships, and submarines, and engage enemies with a range of weapons. The

objective (victory conditions) varies for each scenario and is stated at the beginning. An objective can have any number of victory conditions for destroying certain types and numbers of enemy ships or protecting friendly ships. Winning a scenario occurs when all victory conditions are met. Then end of a scenario occurs when a game is won or a set time period runs out (varies for each scenario).

In preparation for the experiment it was important to learn the capabilities and limitations of HARPOON. From HARPOON's tutorial and practice gaming, the following capabilities were identified and exercised:

- Control the navigation, speed, and mission of individual ships, aircraft, submarines, and squadrons.
- Use radar and sonar.
- Vary the speed, fuel capacity, armor thickness, sustainable damage, detection signatures, gun mounts, sensors, communication, air facilities, and weapons capacity of a ship.
- Change weather conditions, victory conditions and time duration of a scenario.
- Change difficulty settings and levels of computer help in navigation and aircraft control.

With limited time and resources only a subset of HARPOON's capabilities were used. The following sections describe the HARPOON features chosen for this experiment and the process for choosing them.

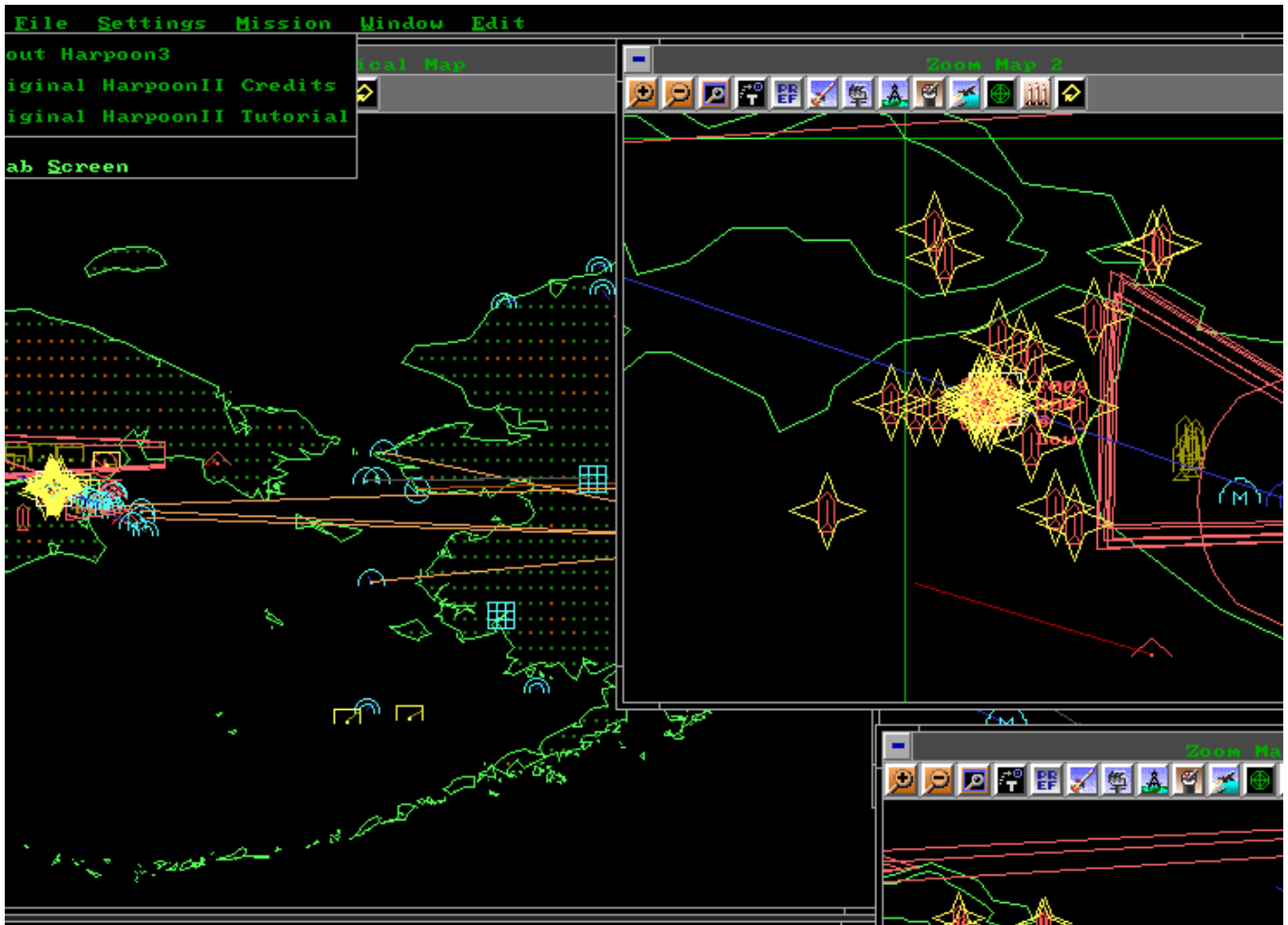


Figure 18 – HARPOON Screenshot 1

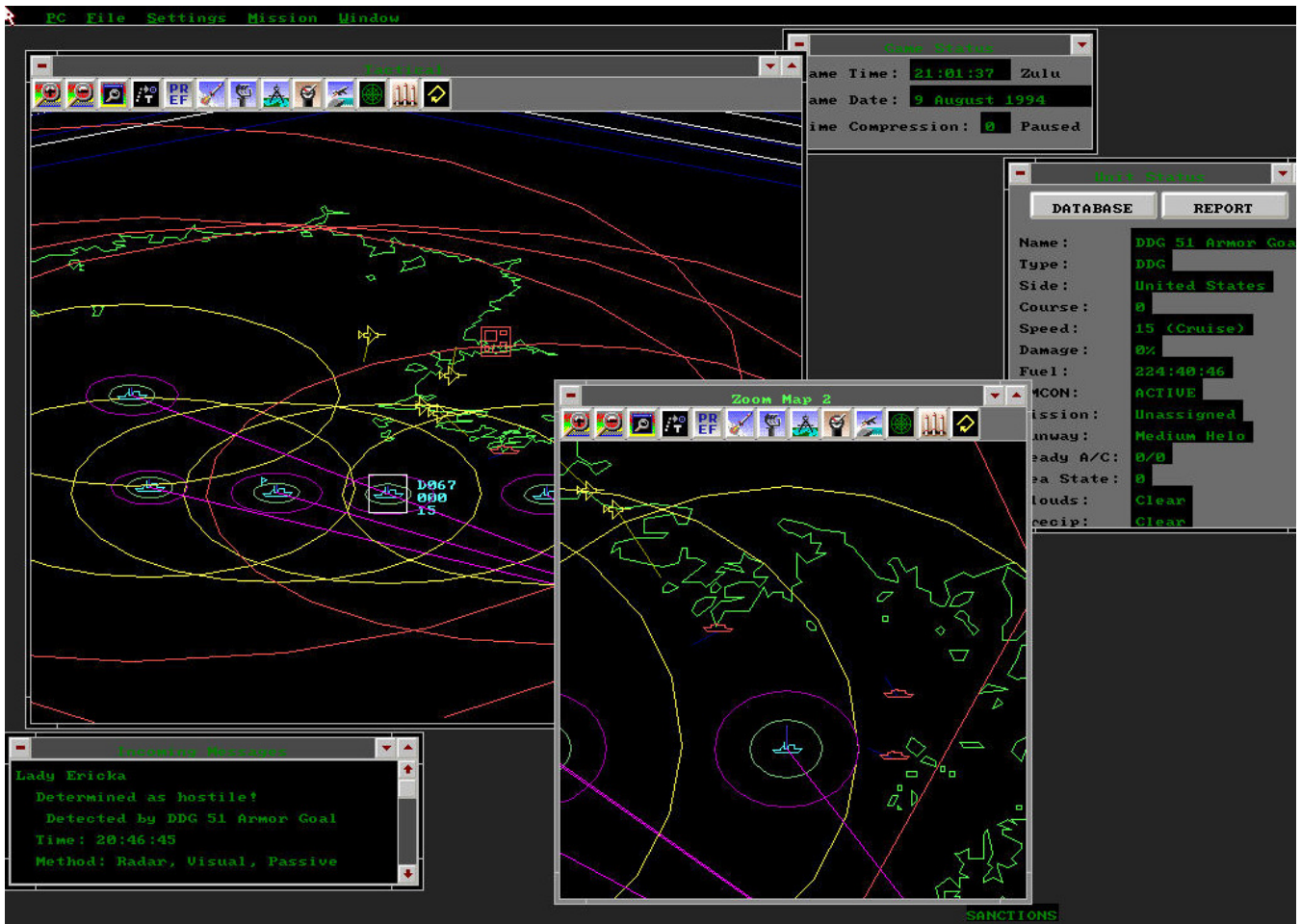


Figure 19 – HARPOON Screenshot 2

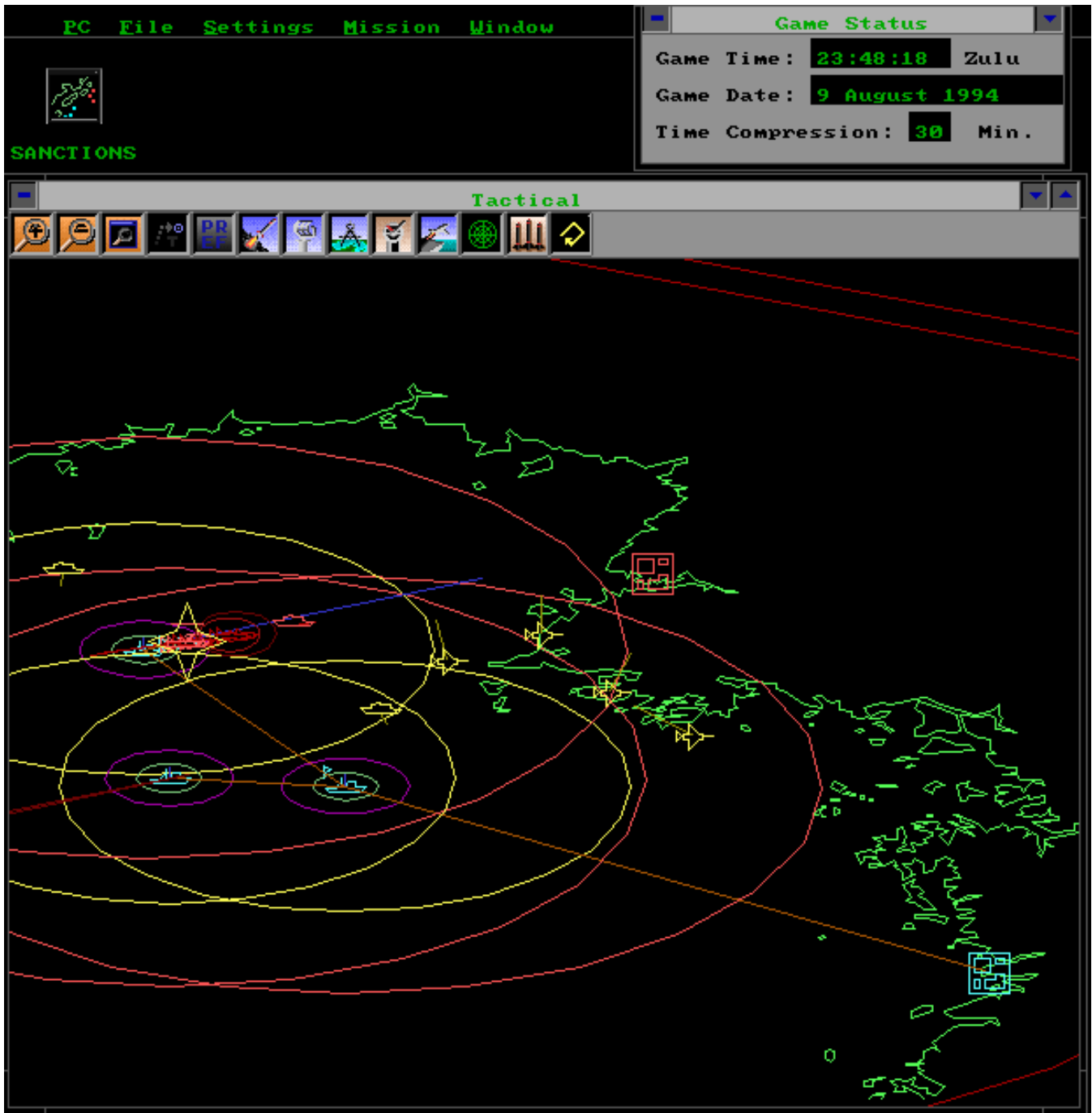


Figure 20 – HARPOON Screenshot 3

3.2 Preparing the Experiment (Steps 1-5)

3.2.1 HARPOON Ships and Mission Types

First the baseline ship class for this study was determined. This selection was limited to the classes included in HARPOON's database. Since this is a surface ship study, submarines were excluded. Ships carrying aircraft were also excluded to simplify the simulations and focus on the

characteristics of the ship. Four classes from HARPOON were considered that fit this study: CG47 Ticonderoga, DD 963 Spruance, DDG 51 Arleigh Burke, and FFG 7 Perry. Appendix A provides a brief description of these ships in HARPOON. From these, DDG 51 was selected because it is most representative of a modern surface combatant without the added capability and complexity of a cruiser.

According to the Military Analysis Network (FAS.org) [17] the Arleigh Burke Destroyers were designed to be used in high threat areas to conduct anti-air warfare (AAW), anti-submarine warfare (ASW), anti-surface warfare (ASUW), and strike warfare (STK). The first three warfighting capabilities were chosen to be included in the mission for this study.

3.2.2 HARPOON Mission Scenarios

HARPOON includes 120 programmed scenarios, most of which are modeled after real battles. Each scenario was studied to see who the players were (which countries), what “battle pieces” were used, and what type of opposition will be encountered (air, surface, and submarine threats). For this experiment only one scenario is needed, but it needs to use individual surface ships and span the three multi-mission warfighting areas listed in Section 3.2.1. The mission scenario must include encounters with air threats (AAW), submarine threats (ASW), and surface ship threats (ASUW). The 120 scenarios were narrowed down to 12 scenarios based on having at least one individual surface combatant as a “battle piece”. These were then further filtered down to 6 since some used coast guard cutters, not applicable to this study. The scenarios can be altered to add/delete/change “battle pieces”, change victory conditions, and change the time period allowed. Since these scenarios are proven as challenging and error free it is desired keep changes to a minimum. Descriptions of the 6 remaining scenarios are as follows:

Airplane Gambit

Good guys: US- 1 nuclear sub, 2 frigates

Enemies: Soviets

Mission: Protect Azores from surface, air, and submarine attacks.

Type of Threats Encountered: surface, air, submarine

Car Carrier Convoys

Good guys: US- 6 merchant ships, 3 destroyers, 2 frigates

Enemies: Soviets

Mission: Escort merchant vessels to Hiroshima with minimal losses.

Type of Treats Encountered: submarine

Sanctions

Good guys: US- 2 frigates, 2 destroyers, 1 cruiser

Enemies: North Korea, China

Mission: Blockade North Korean transport vessels and defend against Chinese naval units.

Type of Threats Encountered: surface, air, submarine

Yellow Surprise

Good guys: UK- 2 nuclear subs, 1 frigate, 5 surface vessels

Enemies: China

Mission: Defend shipping and shore based facilities and attack Chinese coastal targets.

Type of Threats Encountered: surface, air, submarine

The Eyes of Incheon

Good guys: US- 3 squadrons, 2 nuclear subs, 1 frigate

Enemies: North Korea

Mission: Show a strong naval force to discourage North Koreans from engaging in war.

Type of Threats Encountered: surface, air, submarine

The Great Satan

Good guys: US- 1 squadron, 1 nuclear sub, 1 cruiser

Enemies: Iran

Mission: Protect the straight of Hormuz from being closed.

Type of Threats Encountered: surface, air, submarine

The Sanctions Scenario was chosen because it uses 5 combat surface vessels, and because it encounters air, surface, and submarine threats. The scenario was modified to better fit the needs of this experiment by using 5 DDG51 destroyers, all with the same characteristics (example: 5 Damage Threshold ships) in place of 2 frigates, 2 destroyers and 1 cruiser. In the Sanctions scenario the main surface threat is small patrol boats. To make the scenario more challenging and better exercise the DDG required capabilities, two enemy destroyers were added as additional threats. In the experiment, this scenario is run 10 times with everything the same except for the DDG design characteristics which are varied to span the design space as discussed in Section 3.2.3.

The length of the scenario is limited to 3 hours. There are two victory conditions in Sanctions: 1) sink 5 patrol boats; 2) no US ships sunk. These are modified to three victory conditions based on the mission specified in Section 3.2.1: 1) sink 2 enemy destroyers, 2) sink 7 patrol boats, 3) no losses of US destroyers. To accomplish victory condition 3 anti-air and anti-surface operations are required. To win a scenario all three of these conditions must be met. Each victory condition is easy to accomplish on its own, but completing all 3 simultaneously is

difficult. This was done to push the experts to the limit to see which characteristics are most effective and in what combination.

3.2.3 ROCs, MOPs and Design Characteristics

To support the missions described in Section 3.2.1, the capabilities listed in Table 10 are required. The ship’s ability to perform these functional capabilities is measured by an explicit Measure of Performance (MOP).

Table 10 – Required Operational Capabilities and MOPs

| ROC | Description | MOP |
|---------|---|----------------------------|
| MOB 1 | Steam to design capacity in most fuel efficient manner | MOP2 – Speed |
| MOB 3 | Prevent and control damage | MOP3 – Fuel Capacity |
| MOB 5 | Maneuver in formation | MOP4 – Sustainable Damage |
| MOB 7 | Perform seamanship, airmanship and navigation tasks (navigate, anchor, mooring, scuttle, life boat/raft capacity, tow/be-towed) | MOP5 – Detection Signature |
| MOB 10 | Replenish at sea | Required for all designs |
| MOB 12 | Maintain health and well being of crew | Required for all designs |
| MOB 13 | Operate and sustain self as a forward deployed unit for an extended period of time during peace and war without shore-based support | MOP1 – Weapons Capacity |
| MOB 16 | Operate in day and night environments | MOP2 – Fuel Capacity |
| MOB 17 | Operate in heavy weather | Required for all designs |
| MOB 18 | Operate in full compliance of existing US and international pollution control laws and regulations | Required for all designs |
| AAW 1.2 | Provide unit self defense | MOP1 – Weapons Capacity |
| AAW 5 | Provide passive and softkill anti-air defense | Required for all designs |
| AAW 6 | Detect, identify and track air targets | Required for all designs |
| ASU 1 | Engage surface threats with anti-surface armaments | MOP1 – Weapons Capacity |
| ASU 4.1 | Detect and track a surface target with radar | Required for all designs |
| ASU 6 | Disengage, evade and avoid surface attack | MOP2 – Speed |
| ASW 1 | Engage submarines | MOP1 – Weapons Capacity |
| ASW 4 | Conduct airborne ASW/recon (LAMPS) | Required for all designs |
| CCC 3 | Provide own unit CCC | Required for all designs |
| CCC 4 | Maintain data link capability | Required for all designs |
| SEW 2 | Conduct sensor and ECM operations | Required for all designs |
| SEW 3 | Conduct sensor and ECCM operations | Required for all designs |
| INT 1 | Support/conduct intelligence collection | Required for all designs |
| INT 2 | Provide intelligence | Required for all designs |
| INT 3 | Conduct surveillance and reconnaissance | Required for all designs |
| NCO 3 | Provide upkeep and maintenance of own unit | Required for all designs |
| NCO 19 | Conduct maritime law enforcement operations | Required for all designs |
| LOG 1 | Conduct underway replenishment | Required for all designs |
| LOG 2 | Transfer/receive cargo and personnel | Required for all designs |

In HARPOON the characteristics and performance of ships in its database can be altered or entirely new ships can be created. There are 10 ship characteristics that can be changed in this game; armor thickness, sustainable damage (HARPOON calls this damage points), detection

signatures of the ship, gun mounts, propulsion systems, sensors, communication, fuel capacity, air facilities, and weapons capacity.

The armor thickness of the ship provides its ability to sustain damage without sinking or becoming inoperable. Armor thicknesses can be specified for four regions of the ship, general (main decks and belts), engineering (steering and propulsion spaces), bridge (command and control), and sensors (waveguides and antennas). Armor thickness is specified as either none, light (< 2" steel), medium (3"-5" steel), heavy (6"-11"), or special (>12"). If the ship takes a hit in a region of importance, for example steering, and does not have sufficient armor the ship will lose all mobility.

The amount of damage sustained is the amount of hits a ship can take before being sunk. HARPOON uses a metric called damage points specifying the amount of damage a ship can absorb before being destroyed. For example, typical damage points for a destroyer are about 200 while damage points for a patrol boat are about 30. This means that a destroyer can absorb about 7 times as many hits as a patrol boat can before being sunk.

The detection signatures of the ship refer to the cross sectional area seen by enemy sensors. It is broken down into the area seen by passive/ active sonar, visual, infra-red, and radar from the bow (straight on), side, stern. The areas can be increased or decreased to make the ship look larger or smaller to enemy sensors.

Gun mounts refer to the different guns, missile launchers, and decoy systems a ship has. There are over 800 different weapons and weapons packages available in HARPOON. Each mount's location and range of motion is specified.

The propulsion systems specified for a ship determine its speed. Different power plants can be used to change the speed or the characteristics of the power plants themselves can be altered to achieve desired speeds.

HARPOON has different sensor equipment alternatives which have different detection capabilities and ranges. It also has communication equipment alternatives which have different ranges.

A ship's fuel capacity is specified in metric tons (MT). This determines the endurance range of the ship. HARPOON brings realism by having different speeds consume the fuel faster or

slower. Fuel can be specified for the ship's propulsion and electrical, aviation, or weapons systems power.

The air facility characteristic determines what types of aircraft the ship can accommodate. It can be specified to accommodate for helicopters or fighter planes and the numbers of each.

The weapons capacity characteristic determines the amount of ammunition carried by the ship. Weapons can be specified by gun mount or packages of magazines.

Because of the limited time and resources in this study, only 5 of these characteristics are chosen to be design variables. These are sustainable damage, detection signature, propulsion system (speed), fuel capacity, and weapons capacity. In preliminary studies using HARPOON with the selected scenario, these characteristics were shown to have the greatest impact on mission effectiveness. The other 5 characteristics are kept constant for all design variants. The air facility was not used to place more emphasis on ship characteristics. Table 10 also shows the relationship between the required operational capabilities (ROCs) and the Measures of Performance (MOPS). During the AHP process MOP (or design) alternatives are assigned a Value of Performance (0.0-1.0) which are combined with the MOP weights to calculate the OMOE using Equation (1).

3.2.4 Goals, Thresholds, and Hierarchy

The 5 measures of performance (MOPs) are arranged into an overall measure of effectiveness (OMOE) hierarchy shown in Figure 4. The OMOE hierarchy is the basis for the pairwise comparison and the AHP calculation of MOP weights. There are three MOP categories shown in this hierarchy: weapons capacity, mobility and survivability. The MOP for weapons is number of VLS cells. Three cell capacities are considered under this MOP. Under mobility there are 2 MOPs: maximum speed and fuel capacity. Maximum speed is determined by the selection of a propulsion plant. Three speeds and three fuel capacities are considered under these MOPs. Under survivability there are 2 MOPs: maximum sustainable damage and detection signature. Three hit limits and three detection signatures are considered under these MOPs. Each alternative under each MOP is assigned a value of performance (0-1.0). Threshold MOP alternatives were determined in preliminary HARPOON exercises so that if a ship has a threshold value of a given characteristic the user has just enough of that characteristic to achieve the objectives in the battle scenario, the baseline value gives the user a little more than enough, and the goal value gives the

user more than enough to win the scenario. Table 11 lists the MOP alternatives. The “baseline” detection signatures are listed in Table 12 with cross sectional areas of the ship as seen from head on, the side, and the rear of the ship.

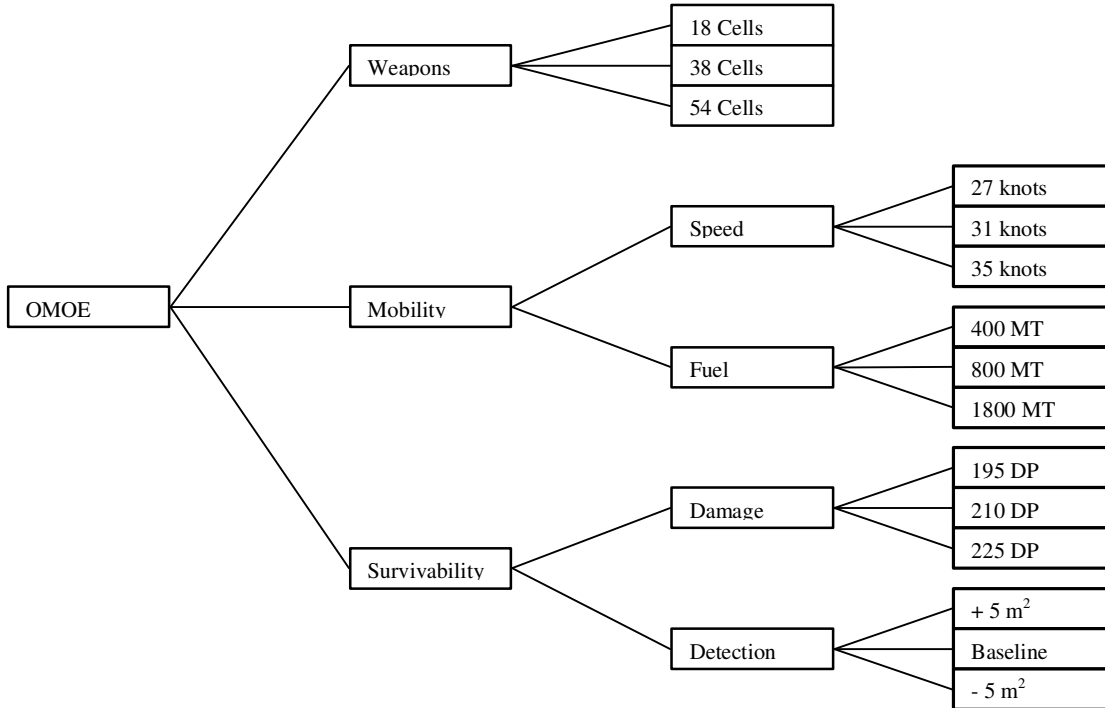


Figure 21 – Experiment OMOE Hierarchy

Table 11 – Summary of MOP Alternatives

| Design Parameter | Threshold | Baseline | Goal |
|---------------------|-------------------|-----------|-------------------|
| Damage Points | 195 | 210 | 225 |
| Detection Signature | +5 m ² | Baseline | -5 m ² |
| Fuel Range | 400 Mtons | 800 Mtons | 1800 Mtons |
| VLS | 18 cells | 36 cells | 54 cells |
| Max Speed | 27 knots | 31 knots | 35 knots |

Table 12 – Baseline Detection Signatures

| | Front | Side | Back |
|---------------|--------------------|--------------------|--------------------|
| Passive Sonar | 95 m ² | 95 m ² | 95 m ² |
| Active Sonar | 25 m ² | 40 m ² | 25 m ² |
| Visual | 240 m ² | 285 m ² | 240 m ² |
| Thermal | 140 m ² | 215 m ² | 170 m ² |
| Radar | 210 m ² | 255 m ² | 210 m ² |

Ten different DDG 51 variants were developed for training the experts in the value of individual MOPs. Each variant has the baseline value for 4 MOP (design) characteristics and either a threshold or goal value for the 5th characteristic. The ship is named after the 5th

characteristic and its value. For example damage threshold has a threshold sustainable damage of 195 DP, a baseline signature (described below), a baseline speed of 31 knots, a baseline fuel capacity of 800 MT, and a baseline weapons capacity of 36 VLS cells. Table 13 lists the design variants.

Table 13 – Ship Design Matrix

| Ship Variant | MOP1 Damage | MOP2 Signature | MOP3 Speed | MOP4 Fuel | MOP5 VLS |
|---------------------|----------------|-------------------|---------------|--------------|-------------|
| Damage Threshold | Threshold | Baseline | Baseline | Baseline | Baseline |
| Damage Goal | Goal | Baseline | Baseline | Baseline | Baseline |
| Signature Threshold | Baseline | Threshold | Baseline | Baseline | Baseline |
| Signature Goal | Baseline | Goal | Baseline | Baseline | Baseline |
| Speed Threshold | Baseline | Baseline | Threshold | Baseline | Baseline |
| Speed Goal | Baseline | Baseline | Goal | Baseline | Baseline |
| Fuel Threshold | Baseline | Baseline | Baseline | Threshold | Baseline |
| Fuel Goal | Baseline | Baseline | Baseline | Goal | Baseline |
| VLS Threshold | Baseline | Baseline | Baseline | Baseline | Threshold |
| VLS Goal | Baseline | Baseline | Baseline | Baseline | Goal |

3.3 Performing the Experiments (Step 6-7)

3.3.1 Experts

Experts are trained using a HARPOON tutorial (Section 3.3.2), and by playing the Sanctions Scenario with the 10 design variants listed in the design matrix (Table 13). Once trained, they complete the pairwise comparisons questionnaire (Section 3.3.4). Seven experts were chosen from ocean and aerospace engineering undergraduate students. These students did not have any prior knowledge of ship characteristics, military experience or experience with HARPOON. All their decisions were made from playing HARPOON in this study. Due to time constraints, the training was designed to take to about 20 hours to complete the 10 simulations.

3.3.2 HARPOON Tutorial

The first step in the expert’s training is to complete the HARPOON Tutorial provided with HARPOON. The tutorial consists of eight lessons; Orientation, Course and Speed, Using Sensors, Using Weapons, Submarine Operations, Air Operations, Using the Mission Editor, and Using the Formation Editor. Since this study doesn’t use submarines or aircraft the experts were instructed to skip Submarine Operations and Using the Formation Editor.

3.3.3 Scenario Runs/ Recording of Scenario Data

After completing the tutorial, each expert was assigned a random run order to complete the 10 simulations. The first two runs were repeated at the end to access a learning curve. The mission for the scenarios was explained as navigating the five destroyers, engaging any hostile units, and managing weapon and fuel supplies to complete the three victory conditions. After each run a summary of conclusions was recorded by each expert to aid them in the final questionnaires. The summary asks whether or not each victory condition was met, the time for completion, the percent damage each ship absorbed for both sides, and general observations on the performance of the ships. A sample summary form is provided in Appendix D.

3.3.4 Questionnaires

Once all runs were completed, the experts completed the pairwise comparison questionnaires. There is a questionnaire for each node of the hierarchy. The questionnaires asked the experts to compare two attributes on a relative importance scale of 1 – 9 with respect to completing the victory conditions. Three questionnaires, Table 14 to Table 16, are used to calculate MOP weights, and five questionnaires, Table 17 to Table 21, are used to calculate VOPs for individual MOP alternatives. Questionnaire results are provided in Appendix C – Questionnaire Data.

Table 14 – MOP Weight Questionnaire Node 0

| Node 0 | | | | | | | | | | | | | | | | | | | |
|---|----------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|----------|
| Compare the relative IMPORTANCE with respect to: GOAL | | | | | | | | | | | | | | | | | | | |
| 1 = EQUAL 3 = MODERATE 5 = STRONG 7 = VERY STRONG 9 = EXTREME | | | | | | | | | | | | | | | | | | | |
| 1 | Weapons | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Mobility |
| 2 | Weapons | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Survive |
| 3 | Mobility | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Survive |
| Abbreviation | | Definition | | | | | | | | | | | | | | | | | |
| Goal | | Maximize DDG Overall Effectiveness | | | | | | | | | | | | | | | | | |
| Weapons | | Missile Vertical Launching System (VLS) | | | | | | | | | | | | | | | | | |
| Mobility | | Ship Movement | | | | | | | | | | | | | | | | | |
| Survive | | Survivability | | | | | | | | | | | | | | | | | |

Table 15 - MOP Weight Questionnaire Node 20000

Node 20000

Compare the relative IMPORTANCE with respect to: Mobility < GOAL

1 = EQUAL 3 = MODERATE 5 = STRONG 7 = VERY STRONG 9 = EXTREME

| | | | | | | | | | | | | | | | | | | | |
|---|-------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|------|
| 1 | Speed | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Fuel |
|---|-------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|------|

| Abbreviation | Definition |
|--------------|------------------------------------|
| Goal | Maximize DDG Overall Effectiveness |
| Mobility | Ship Movement |
| Speed | Sustained Speed (knots) |
| Fuel | Ship Fuel Capacity (Range) |

Table 16 - MOP Weight Questionnaire Node 30000

Node 30000

Compare the relative IMPORTANCE with respect to: Survive < GOAL

1 = EQUAL 3 = MODERATE 5 = STRONG 7 = VERY STRONG 9 = EXTREME

| | | | | | | | | | | | | | | | | | | | |
|---|--------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|--------|
| 1 | Detect | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Damage |
|---|--------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|--------|

| Abbreviation | Definition |
|--------------|------------------------------------|
| Goal | Maximize DDG Overall Effectiveness |
| Survive | Survivability |
| Detect | Detection Signature |
| Damage | Damage Tolerance (Points) |

Table 17 – VOP Questionnaire Node 10000

Node 10000

Compare the relative IMPORTANCE with respect to: Weapons < GOAL

1 = EQUAL 3 = MODERATE 5 = STRONG 7 = VERY STRONG 9 = EXTREME

| | | | | | | | | | | | | | | | | | | | |
|---|----------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|----------|
| 1 | 18 cells | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 36 cells |
| 2 | 18 cells | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 54 cells |
| 3 | 36 cells | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 54 cells |

| Abbreviation | Definition |
|--------------|---|
| Goal | Maximize DDG Overall Effectiveness |
| Weapons | Missile Vertical Launching System (VLS) |
| 18 cells | Threshold (Low) – VLS w/ 18 missiles in 1 module |
| 36 cells | Baseline (Middle) – VLS w/ 36 missiles in 2 modules |
| 54 cells | Goal (High) – VLS w/ 54 missiles in 3 modules |

Table 18 - VOP Questionnaire Node 21000

| | | | | | | | | | | | | | | | | | | | |
|--|----------|------------------------------------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|----------|
| Node 21000 | | | | | | | | | | | | | | | | | | | |
| Compare the relative IMPORTANCE with respect to: Speed < Mobility < GOAL | | | | | | | | | | | | | | | | | | | |
| 1 = EQUAL 3 = MODERATE 5 = STRONG 7 = VERY STRONG 9 = EXTREME | | | | | | | | | | | | | | | | | | | |
| 1 | 27 knots | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 31 knots |
| 2 | 27 knots | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 35 knots |
| 3 | 31 knots | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 35 knots |
| Abbreviation | | Definition | | | | | | | | | | | | | | | | | |
| Goal | | Maximize DDG Overall Effectiveness | | | | | | | | | | | | | | | | | |
| Mobility | | Ship Movement | | | | | | | | | | | | | | | | | |
| Speed | | Sustained Speed (knots) | | | | | | | | | | | | | | | | | |
| 27 knots | | Speed Threshold (Low) | | | | | | | | | | | | | | | | | |
| 31 knots | | Speed Baseline (Middle) | | | | | | | | | | | | | | | | | |
| 35 knots | | Speed Goal (High) | | | | | | | | | | | | | | | | | |

Table 19 - VOP Questionnaire Node 22000

| | | | | | | | | | | | | | | | | | | | |
|---|--------|------------------------------------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---------|
| Node 22000 | | | | | | | | | | | | | | | | | | | |
| Compare the relative IMPORTANCE with respect to: Fuel < Mobility < GOAL | | | | | | | | | | | | | | | | | | | |
| 1 = EQUAL 3 = MODERATE 5 = STRONG 7 = VERY STRONG 9 = EXTREME | | | | | | | | | | | | | | | | | | | |
| 1 | 400 MT | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 800 MT |
| 2 | 400 MT | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 1800 MT |
| 3 | 800 MT | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 1800 MT |
| Abbreviation | | Definition | | | | | | | | | | | | | | | | | |
| Goal | | Maximize DDG Overall Effectiveness | | | | | | | | | | | | | | | | | |
| Mobility | | Ship Movement | | | | | | | | | | | | | | | | | |
| Fuel | | Ship Fuel Capacity (Range) | | | | | | | | | | | | | | | | | |
| 400 MT | | Fuel Threshold (Low) | | | | | | | | | | | | | | | | | |
| 800 MT | | Fuel Baseline (Middle) | | | | | | | | | | | | | | | | | |
| 1800 MT | | Fuel Goal (High) | | | | | | | | | | | | | | | | | |

Table 20 - VOP Questionnaire Node 31000

| | | | | | | | | | | | | | | | | | | | |
|--|-----------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|------------|
| Node 31000 | | | | | | | | | | | | | | | | | | | |
| Compare the relative IMPORTANCE with respect to: Detect < Survive < GOAL | | | | | | | | | | | | | | | | | | | |
| 1 = EQUAL 3 = MODERATE 5 = STRONG 7 = VERY STRONG 9 = EXTREME | | | | | | | | | | | | | | | | | | | |
| 1 | + 5 (Bad) | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Baseline |
| 2 | + 5 (Bad) | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | - 5 (Good) |
| 3 | Baseline | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | - 5 (Good) |
| Abbreviation | | Definition | | | | | | | | | | | | | | | | | |
| Goal | | Maximize DDG Overall Effectiveness | | | | | | | | | | | | | | | | | |
| Survive | | Survivability | | | | | | | | | | | | | | | | | |
| Detect | | Detection Signature | | | | | | | | | | | | | | | | | |
| + 5 (Bad) | | Detection Signature Threshold (m ²) | | | | | | | | | | | | | | | | | |
| Baseline | | Detection Signature Baseline (Middle) | | | | | | | | | | | | | | | | | |
| - 5 (Good) | | Detection Signature Goal (m ²) | | | | | | | | | | | | | | | | | |

Table 21 - VOP Questionnaire Node 32000

| | | | | | | | | | | | | | | | | | | | |
|---|----------|------------------------------------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|----------|
| Node 32000 | | | | | | | | | | | | | | | | | | | |
| Compare the relative IMPORTANCE with respect to: Damage < Survive < GOAL | | | | | | | | | | | | | | | | | | | |
| 1 = EQUAL 3 = MODERATE 5 = STRONG 7 = VERY STRONG 9 = EXTREME | | | | | | | | | | | | | | | | | | | |
| 1 | 195 Hits | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 210 Hits |
| 2 | 195 Hits | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 225 Hits |
| 3 | 210 Hits | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 225 Hits |
| Abbreviation | | Definition | | | | | | | | | | | | | | | | | |
| Goal | | Maximize DDG Overall Effectiveness | | | | | | | | | | | | | | | | | |
| Survive | | Survivability | | | | | | | | | | | | | | | | | |
| Damage | | Damage Tolerance (Points) | | | | | | | | | | | | | | | | | |
| 195 Hits | | Threshold Damage Tolerance (Low) | | | | | | | | | | | | | | | | | |
| 210 Hits | | Baseline Damage Tolerance (Middle) | | | | | | | | | | | | | | | | | |
| 225 Hits | | Goal Damage Tolerance (High) | | | | | | | | | | | | | | | | | |

3.4 Calculating OMOE Weights (Step 8-11)

3.4.1 Questionnaire Data Interpretation

The questionnaire is based on a relative scale from 9 to 1, with 1 as the neutral point. All the data collected was normalized to have 0 as the neutral point for calculation purposes. For example an answer of strength 9 on the right side was normalized to 8, an answer of strength 9 on the left side was normalized to -8, and a neutral strength 1 was normalized to 0. This was done so that when taking averages and standard deviations, regular mathematical equations could be used. Once the average was found it was converted back to the 9 to 1 strength scale. Appendix C – Questionnaire Data provides the data ranges and standard deviations of the questionnaire data.

3.4.2 OMOE Generator and Expert Choice

The hierarchy structure of this experiment was built in EXPERT CHOICE (EC). EXPERT CHOICE is a decision making program based on the principles of the Analytic Hierarchy Process. It allows the user to structure a decision into objectives and alternatives using a hierarchy tree (like the one in Section 3.2.4). EC uses pairwise comparison to rank the alternatives of an objective by weight. EC also has the capability to perform sensitivity analysis.

The 8 sets of VOP questionnaire data collected (one for each expert and an average) were entered into the questionnaire section of EC. This VOP data is shown in Table 22 and Table 23. MOP weights were calculated for each expert using the AHP. These MOP weights are listed in

Table 24. The questionnaire average was found by using the average questionnaire answers as an 8th set of inputs to calculate weights in EC.

Table 22 – VOPs from Questionnaires Part 1

| | N1 | N2 | N3 | N10001 | N10002 | N10003 | N20000 | N30000 | N21001 | N21002 | N21003 |
|---------|----|----|----|--------|--------|--------|--------|--------|--------|--------|--------|
| Expert1 | -2 | -4 | -3 | 7 | 9 | 5 | 7 | -5 | 4 | 9 | 4 |
| Expert2 | -5 | -7 | 3 | 7 | 9 | 3 | 1 | -5 | 3 | 5 | 1 |
| Expert3 | -7 | -6 | -2 | 7 | 9 | 7 | 4 | 3 | 3 | 5 | 2 |
| Expert4 | -8 | 1 | 5 | 4 | 9 | 4 | 1 | 4 | 1 | 3 | 1 |
| Expert5 | -5 | -7 | -3 | 5 | 7 | 5 | -5 | -3 | 3 | 5 | 3 |
| Expert6 | -7 | -3 | 3 | 5 | 9 | 5 | 1 | -5 | 5 | 9 | 5 |
| Expert7 | -6 | 3 | 2 | 3 | 7 | 5 | 3 | -3 | 2 | 4 | 3 |
| Ave. | -6 | -4 | 2 | 5 | 8 | 5 | 2 | -3 | 3 | 6 | 3 |

Table 23 – VOPs from Questionnaires Part 2

| | N22001 | N22002 | N22003 | N31001 | N31002 | N31003 | N32001 | N32002 | N32003 |
|---------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Expert1 | 9 | 9 | 9 | 5 | 9 | 3 | 7 | 5 | 2 |
| Expert2 | 1 | 1 | 1 | 7 | 9 | 5 | 7 | 7 | 1 |
| Expert3 | 3 | 7 | 4 | 1 | 3 | 1 | 1 | 3 | 1 |
| Expert4 | 1 | 1 | 1 | 2 | 6 | 2 | 5 | 8 | 5 |
| Expert5 | 3 | 5 | 3 | 5 | 7 | 5 | 3 | 5 | 3 |
| Expert6 | 5 | 9 | 5 | 3 | 6 | 3 | 1 | 4 | 1 |
| Expert7 | 4 | 7 | 4 | 6 | 9 | 6 | 4 | 7 | 5 |
| Ave. | 4 | 6 | 4 | 4 | 7 | 4 | 4 | 6 | 3 |

Table 24 – MOP WEIGHTS from Questionnaires

| | Weapons | Fuel | Damage | Detection | Speed | Consistency |
|------------------------|---------|------|--------|-----------|-------|-------------|
| Expert 1 | .558 | .280 | .021 | .100 | .041 | 0.14 |
| Expert 2 | .739 | .045 | .029 | .141 | .046 | 0.15 |
| Expert 3 | .760 | .115 | .072 | .024 | .029 | 0.13 |
| Expert 4 | .500 | .036 | .341 | .086 | .037 | 0.05 |
| Expert 5 | .731 | .031 | .021 | .060 | .157 | 0.10 |
| Expert 6 | .669 | .044 | .041 | .202 | .044 | 0.05 |
| Expert 7 | .360 | .093 | .129 | .388 | .030 | 0.33 |
| Mean Weights | .617 | .092 | .093 | .143 | .055 | |
| (Excluding Ques. Ave.) | | | | | | |
| Standard Deviation | .108 | .113 | .042 | .082 | .139 | |
| | | | | | | |
| Questionnaire Ave. | .701 | .071 | .048 | .145 | .035 | 0.06 |

3.5 Validation (Step 12-14)

To validate the OMOE method and prove the hypothesis, 16 ships are ranked based on the OMOE functions developed from expert opinion, and compared to the ranking of the same 16 ships using HARPOON directly. A design of experiments (DOE) was used to choose 16 representative ship designs from the 243 possible in the design space. The 16 designs are ranked

by effectiveness (OMOE) from the OMOE functions developed using the questionnaire average method and the mean OMOE method.

3.5.1 Design of Experiment (DOE)

With 5 ship characteristics and 3 possible values for each, there are 243 possible combinations of ship designs (3^5). Because of time and resource constraints, this was too many to assess directly in the simulation. It was manageable for only 20 or less ship designs to be evaluated. A design of experiments (DOE) was used to choose the designs. To ensure a sufficient representation of the design space, a $\frac{1}{2}$ fraction factorial DOE method was used to select the combinations of characteristics to use for the representative designs.

A factorial experiment is useful when several characteristics are of interest in a design. A full factorial experiment is a complete replication of the entire design space, all possible design combinations at all levels of the characteristics. The baseline level of each characteristic was omitted (ie. only threshold and goal characteristics were considered) to reduce the number of designs and limit the experiment time. This results in a 2^5 (32 designs) full factorial experiment. In a 2^5 experiment there are 31 degrees of freedom, 5 of which correspond to main effects, 10 correspond to two-factor interactions and 16 correspond to higher order interactions (three-factor interactions or more). A main effect is a change in response due to a change in level of a factor. Factor interactions occur when the change in response between two levels of one factor is not the same at all levels of the other factors. For example there is a response difference of 2 between the high and low levels of factor A while factor B is at its low level and a response difference of 3 between the high and low levels of factor A while factor B is at its high level). The higher order interactions are of no value in this experiment. Therefore a $\frac{1}{2}$ fraction factorial experiment can be used. [18]

A $\frac{1}{2}$ fraction factorial experiment uses half the designs from a full factorial experiment, 2^{5-1} (16 designs). Construction of a 2^{5-1} experiment starts from the full factorial experiment with the last (fifth) characteristic column removed. This is called the basic experiment, shown in Table 25. If a characteristic has a threshold value it receives a “-1”. If a characteristic has a goal value it receives a “1”. The value of the fifth characteristic is found by taking the product of the first 4 characteristics. If the product is positive, the 5th characteristic is given the goal value “1”. If the product is negative, the 5th characteristic is given the threshold value “-1”. All combinations with the fifth characteristic are not considered. This is a proven method in statistical design of

experiments to provide a full representation of the design space. Table 26 lists the characteristics and their values for the final 16 ship designs. A “-1” indicates that the design has a threshold value for the characteristic and a “1” indicates a goal value.

Table 25 – Basic Design of 2^{5-1}

| Ship # | Weapons | Fuel | Damage | Detection |
|--------|---------|------|--------|-----------|
| 1 | -1 | -1 | -1 | -1 |
| 2 | 1 | -1 | -1 | -1 |
| 3 | -1 | 1 | -1 | -1 |
| 4 | 1 | 1 | -1 | -1 |
| 5 | -1 | -1 | 1 | -1 |
| 6 | 1 | -1 | 1 | -1 |
| 7 | -1 | 1 | 1 | -1 |
| 8 | 1 | 1 | 1 | -1 |
| 9 | -1 | -1 | -1 | 1 |
| 10 | 1 | -1 | -1 | 1 |
| 11 | -1 | 1 | -1 | 1 |
| 12 | 1 | 1 | -1 | 1 |
| 13 | -1 | -1 | 1 | 1 |
| 14 | 1 | -1 | 1 | 1 |
| 15 | -1 | 1 | 1 | 1 |
| 16 | 1 | 1 | 1 | 1 |

Table 26 – Ship Design Characteristic Values for $\frac{1}{2}$ Fraction Factorial Design

| Ship # | Weapons | Fuel | Damage | Detection | Speed |
|--------|---------|------|--------|-----------|-------|
| 1 | -1 | -1 | -1 | -1 | 1 |
| 2 | 1 | -1 | -1 | -1 | -1 |
| 3 | -1 | 1 | -1 | -1 | -1 |
| 4 | 1 | 1 | -1 | -1 | 1 |
| 5 | -1 | -1 | 1 | -1 | -1 |
| 6 | 1 | -1 | 1 | -1 | 1 |
| 7 | -1 | 1 | 1 | -1 | 1 |
| 8 | 1 | 1 | 1 | -1 | -1 |
| 9 | -1 | -1 | -1 | 1 | -1 |
| 10 | 1 | -1 | -1 | 1 | 1 |
| 11 | -1 | 1 | -1 | 1 | 1 |
| 12 | 1 | 1 | -1 | 1 | -1 |
| 13 | -1 | -1 | 1 | 1 | 1 |
| 14 | 1 | -1 | 1 | 1 | -1 |
| 15 | -1 | 1 | 1 | 1 | -1 |
| 16 | 1 | 1 | 1 | 1 | 1 |

3.5.2 OMOE Calculation for Representative Ships Based on Expert Opinion

OMOE are calculated for each of the 16 ships using weights calculated individually for each expert, mean weights calculated from the individual expert weights, and weights calculated using the average preferences from the questionnaires, Table 24. OMOEs are then calculated using Equation 1. When calculating OMOEs, goal characteristics are given a value of performance

(VOP) of 1.0, and threshold characteristics are given a VOP of zero. A ship having all threshold values has an OMOE of 0.0, and a ship having all goal values has an OMOE of 1.0. Ships having combinations of goal and threshold characteristics have an OMOE between 0.0 and 1.0. For example, the Questionnaire Average OMOE for Ship Design 1 is:

$$(0 * 0.701) + (0 * 0.071) + (0 * 0.048) + (0 * 0.145) + (1 * 0.035) = 0.035$$

Next, the 16 ship designs are ranked based on their OMOE. In all there are 9 sets of ranks, 1 for each expert, 1 for the average of the questionnaires, and 1 for the mean weights from Expert Choice. OMOEs for each design calculated using the average of the questionnaires and using the mean weights are listed in Table 27 with their resulting ranks.

Table 27 – Ship Design Ranking by OMOE and Expert Opinion

| Ship # | OMOE from Questionnaire Average | Average Rank | OMOE from Mean Weights | Mean Rank |
|--------|---------------------------------|--------------|------------------------|-----------|
| 1 | 0.035 | 16 | 0.055 | 16 |
| 2 | 0.701 | 8 | 0.617 | 8 |
| 3 | 0.071 | 14 | 0.092 | 15 |
| 4 | 0.807 | 6 | 0.764 | 7 |
| 5 | 0.048 | 15 | 0.093 | 14 |
| 6 | 0.784 | 7 | 0.765 | 6 |
| 7 | 0.154 | 12 | 0.240 | 12 |
| 8 | 0.820 | 5 | 0.802 | 5 |
| 9 | 0.145 | 13 | 0.143 | 13 |
| 10 | 0.881 | 4 | 0.815 | 4 |
| 11 | 0.251 | 10 | 0.290 | 11 |
| 12 | 0.917 | 2 | 0.852 | 3 |
| 13 | 0.228 | 11 | 0.291 | 10 |
| 14 | 0.894 | 3 | 0.853 | 2 |
| 15 | 0.264 | 9 | 0.328 | 9 |
| 16 | 1.000 | 1 | 1.000 | 1 |

3.5.3 Ship Ranking from HARPOON

Next, the 16 ships are ranked directly using HARPOON and the Sanctions Scenario. The ships are ranked based on several metrics. A ship design receives 1 point for each victory condition completed. If a victory condition is only partially completed a fraction of a point is given. The point fractions for partial completions are summarized later in this section. Since there are 10 possible patrol boats to sink, for the patrol boat victory condition extra points are given if more than 7 (required to satisfy the victory condition) patrol boats are sunk. The total score for each ship design equals the sum of the points for the 3 victory conditions. Table 28

shows the HARPOON results for each ship design. Victory Condition 1 is to completely destroy 2 enemy destroyers, Victory Condition 2 is to destroy 7 patrol boats, and Victory Condition 3 is to prevent the loss of any US ships. For the first victory condition, 1 point is given if both enemy DDGs are destroyed, ½ point for one, and 0 points for zero enemy DDGs. In the second victory condition the number of patrol boats destroyed is divided by the required number (7) to calculate the points given. For the third victory condition 1 point is given if all US ships remained in tact and undamaged. For every ship sunken, 0.2 points are subtracted from 1. If a ship is damaged but not sunk, the percent damage is multiplied times 0.2 and subtracted from the total. The highest possible score is 3.43 points.

Table 28 – HARPOON Direct Comparison Results

| Ship # | Victory Condition 1 | Victory Condition 2 | Victory Condition 3 | Total |
|--------|---------------------|---------------------|---------------------|-------|
| 1 | 0.00 | 0.43 | 0.40 | 0.83 |
| 2 | 1.00 | 0.86 | 0.72 | 2.58 |
| 3 | 0.50 | 1.00 | 0.67 | 2.17 |
| 4 | 0.50 | 1.43 | 0.81 | 2.74 |
| 5 | 0.50 | 1.00 | 0.80 | 2.30 |
| 6 | 1.00 | 0.86 | 0.75 | 2.61 |
| 7 | 0.50 | 1.14 | 0.80 | 2.44 |
| 8 | 1.00 | 1.00 | 0.76 | 2.76 |
| 9 | 0.00 | 0.86 | 0.68 | 1.54 |
| 10 | 1.00 | 1.14 | 0.69 | 2.83 |
| 11 | 1.00 | 1.14 | 0.40 | 2.54 |
| 12 | 1.00 | 1.14 | 0.75 | 2.89 |
| 13 | 0.50 | 1.43 | 0.55 | 2.47 |
| 14 | 1.00 | 1.00 | 0.82 | 2.82 |
| 15 | 0.50 | 1.29 | 0.76 | 2.54 |
| 16 | 1.00 | 1.43 | 0.73 | 3.16 |

3.5.4 OMOE Results and Conclusions

Finally, the results from Table 28 are ranked by total points from highest to lowest, and compared to the predicted rankings from the Analytical Hierarchy Process and Overall Measure of Effectiveness calculations, Table 27. Table 29 shows the ship rankings using the different methods and the difference compared to the actual simulation rank. Figure 22 and Figure 23 graphically show the difference between the simulation rank and the rankings from the other methods. A horizontal line means there is no difference in rank for that ship.

Table 29, Figure 22, and Figure 23 show that the OMOE calculation method using the questionnaire averages most closely matches the direct simulation results. The OMOE mean rank method also provides a good match. Neither method provides a perfect match. In

conclusion, the questionnaire average OMOE function provides a reasonable prediction of direct simulation results, proving the hypothesis that it is an acceptable tool for ranking design alternatives in concept exploration ship optimization.

Table 29 – Rank and Rank Differences

| Ship # | Simulation Rank | OMOE Mean Rank | Sim. - Mean Difference | Questionnaire Average Rank | Sim. – Ave. Difference |
|--------|-----------------|--------------------|------------------------|----------------------------|------------------------|
| 16 | 1 | 1 | 0 | 1 | 0 |
| 12 | 2 | 3 | 1 | 2 | 0 |
| 10 | 3 | 4 | 1 | 4 | 1 |
| 14 | 4 | 2 | 2 | 3 | 1 |
| 8 | 5 | 5 | 0 | 5 | 0 |
| 4 | 6 | 7 | 1 | 6 | 0 |
| 6 | 7 | 6 | 1 | 7 | 0 |
| 2 | 8 | 8 | 0 | 8 | 0 |
| 15 | 9 | 9 | 0 | 9 | 0 |
| 11 | 10 | 11 | 1 | 10 | 0 |
| 13 | 11 | 10 | 1 | 11 | 0 |
| 7 | 12 | 12 | 0 | 12 | 0 |
| 5 | 13 | 14 | 1 | 15 | 2 |
| 3 | 14 | 15 | 1 | 14 | 0 |
| 9 | 15 | 13 | 2 | 13 | 2 |
| 1 | 16 | 16 | 0 | 16 | 0 |
| | | Total Diff. | 12 | Total Diff. | 6 |

Design Rank Comparison

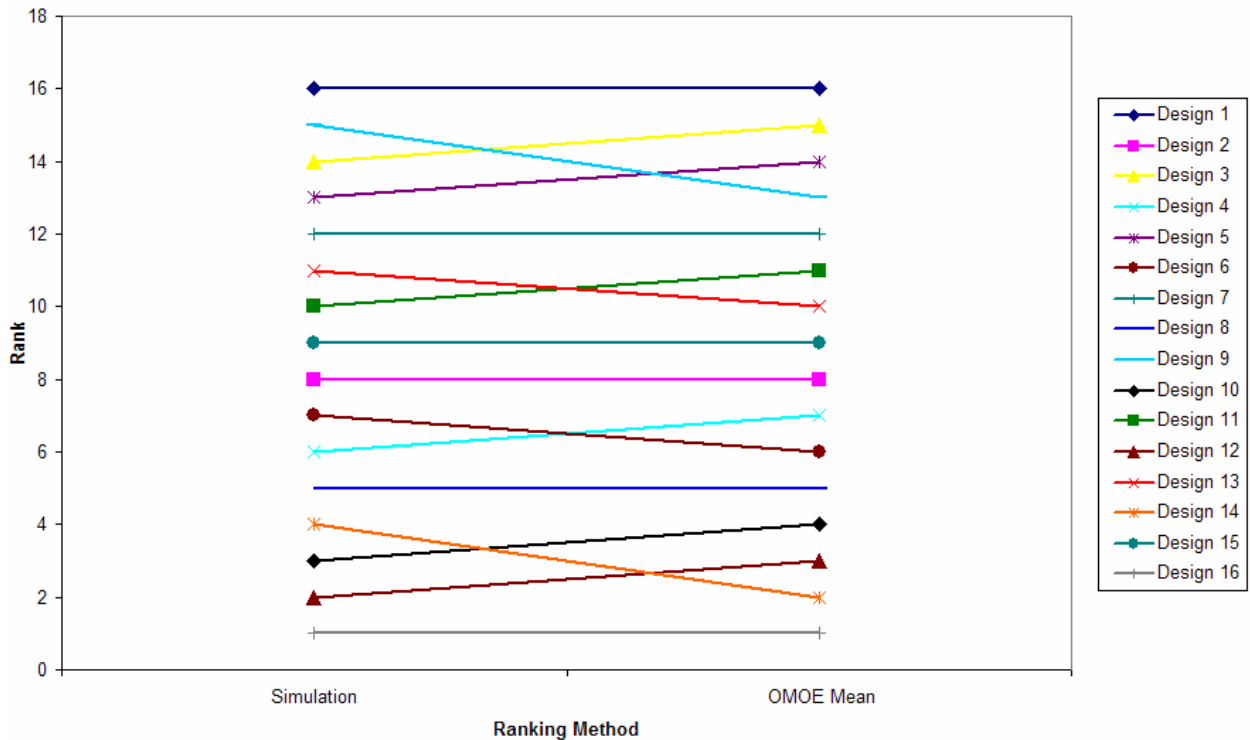


Figure 22 – Simulation Rank vs. OMOE Mean Rank

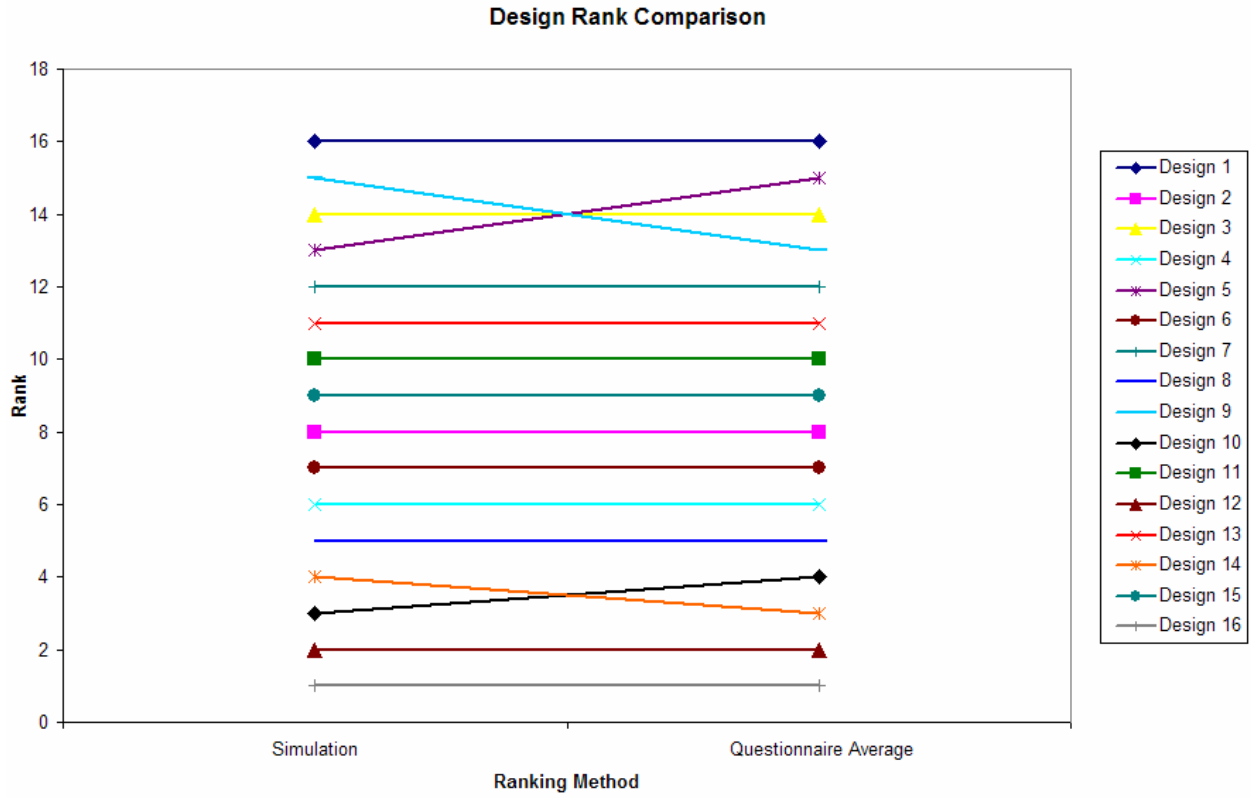


Figure 23 – Simulation Rank vs. Questionnaire Average Rank

CHAPTER 4 TOOLS FOR SHIP MULTI-DISCIPLINARY OPTIMIZATION

This chapter describes the methods, software, and software features used to search design space for non-dominated designs in concept exploration for a naval surface combatant. In early stage design, the design space (i.e., the possible combinations of the various design variables, both continuous and discrete) is typically very large. This is a fully multidisciplinary problem that typically must employ an array of higher fidelity, discipline-specific computer codes to perform the necessary assessment and analysis required for the optimization. Multidisciplinary in a ship design context means different disciplines such as hull form, structures, hydrodynamics, weights, stability, power, propulsion, etc. are required for analyses. Evaluating the performance of designs for even a small portion of this large design space can become prohibitive if these analyses are computationally expensive. Because of this, high-fidelity codes are typically not used in the early stages of the design process. As a result, major decisions regarding the basic elements of the design are already made before high-fidelity codes begin to be used. An important objective of this thesis is to identify methodologies that will enable high-fidelity codes to be used earlier in the design process. Response Surface Modeling and Design of Experiments techniques are used to generate a response surface approximation for the results or response of more complex and computer-intensive engineering models.

4.1 Ship Synthesis Model

4.1.1 Overview

As shown in Figure 24, the ship synthesis model is used to balance and assess designs selected by the multi-objective genetic optimizer (MOGO) in our Concept Exploration process. A flow chart for the synthesis model used in the case study for this thesis, and its interface with the MOGO in Model Center (MC) is shown in Figure 25. The case study is for an Advanced Logistics Delivery Ship (ALDV) described in Chapter 5. The synthesis model assesses the balance of the ship in terms of weight, displacement, volume, area and power. Values of Performance (VOPs), an Overall Measure of Effectiveness (OMOE), Overall Measure of Risk (OMOR), and life cycle cost are also calculated by the synthesis model. These characteristics determine a ship's feasibility and superiority or dominance relative to other ships in the design

space. Modules in the baseline synthesis model were developed using simple parametric equations written in FORTRAN, and are integrated and executed in Model Center. This thesis investigates an improvement to this model using a response surface model to calculate structural weight in the ALDV case study. The structural weight RSM uses MAESTRO (described in Section 4.5) to assess adequacy and calculate the bare hull structural weight of adequate designs.

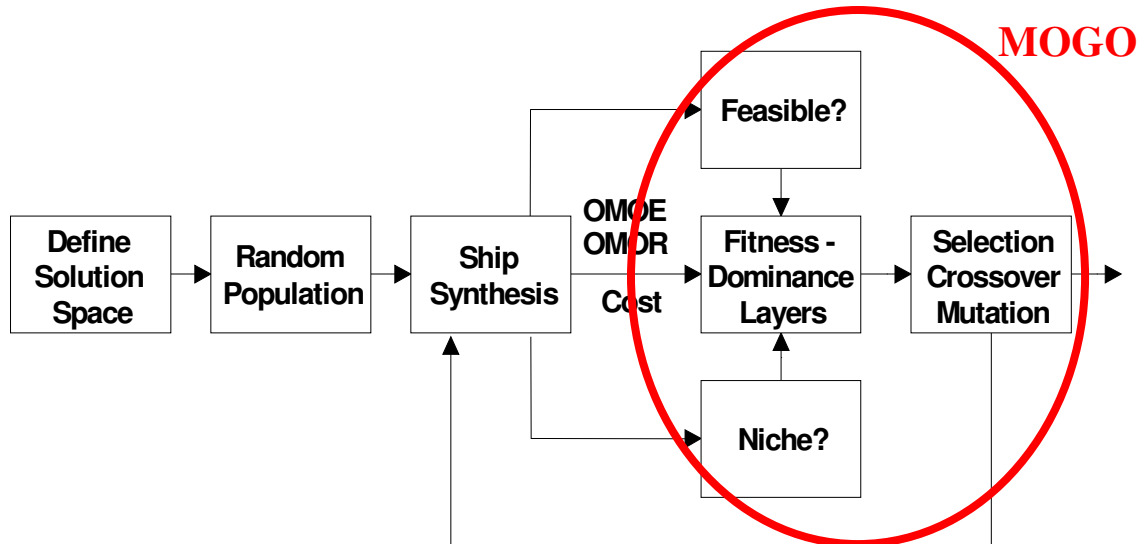


Figure 24 – Concept Exploration Process

4.1.2 Ship Synthesis Modules (for ALDV)

- Input Module - Inputs, decodes and processes the design variable vector and other design parameters that are constant for all designs. Provides this input to the other modules.
- ALDV Hull Form Module - Calculates hull form principal characteristics and supplies them to other modules. It scales the “parent” (baseline) characteristics to match the specified displacement and hull form type. It calculates the scaling factor, scales the parent hull characteristics to the daughter hull, adds appendage volumes, and calculates daughter hull characteristics including lengths, areas, and volumes.
- Combat Systems Module - Retrieves combat systems data from the Combat Systems Data Base as specified by the combat system design variables. Calculates payload SWBS weights, VCGs, areas and electric power requirements and assesses performance for the total combat system.
- Propulsion Module - Retrieves propulsion system data from the Propulsion System Data Base as specified by the propulsion system design variable. Database generated by modeling similar power plants in ASSET using single baseline design.

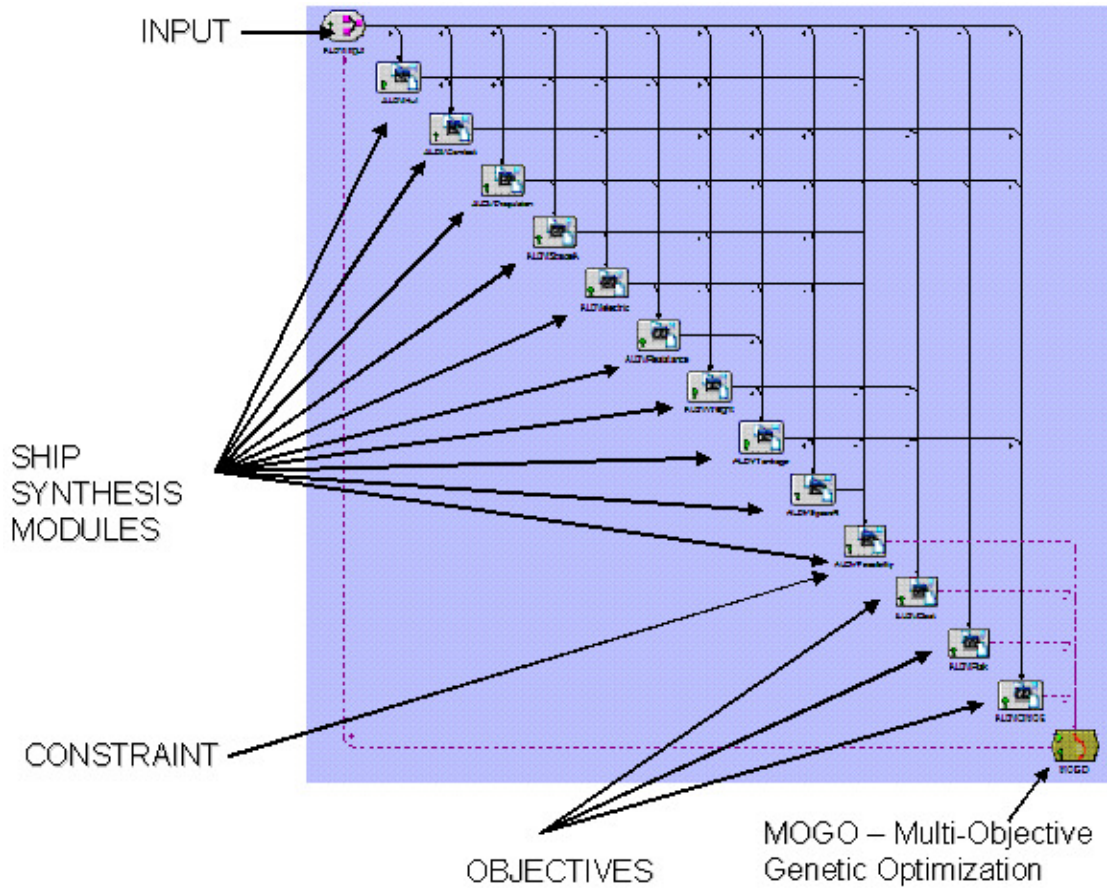


Figure 25 – Ship Synthesis Model

- Space Available Module - Calculates available volume and area, minimum depth required at amidships, cubic number, CN, and the height and volume of the machinery box.
- Electric Power Module - Calculates maximum functional electric load with margins (KW_{MFLM}), required generator power (KW_{GREQ}), required average 24-hour electric power (KW_{24AVG}), and required auxiliary machinery room volume (V_{AUX}). It estimates system power requirements using known values and parametric equations, sums and applies margins, assumes one ship service generator is unavailable, uses a power factor of 0.9, and uses the electric load analysis method from DDS 310-1.
- Resistance Module - Calculates hull resistance, sustained speed, and required shaft horsepower at endurance speed and sprint speed. The resistance is calculated using the Holtrop-Mennen regression-based method. It takes the input data of the individual side and center hulls and calculates the resistance for each. It adds the individual hull resistances with a 10% addition for hull interference. The module then calculates the effective bare hull power, appendage drag, and air drag. The propulsive coefficient is approximated. The sustained speed is calculated based on total BHP available with a 25% margin.

- Weight and Stability Module - Calculates single digit SWBS weights, total weight, fuel weight, and GM/B ratio using parametric equations and known weights. The module uses a combination of known weights and parametric equations to calculate the SWBS weights. KG is calculated from single digit weights and VCGs, estimated using parametric equations. The KM is calculated using geosim scaling of the parent hull KM.
- Tankage Module - Calculates tankage volume requirements based on required sprint and endurance range, and parametric equations. It uses a number of input variables including fluid specific volumes, ballast type, transmission efficiency, fuel weight, fuel consumption at sprint and endurance speeds, average generator engine fuel consumption, average electric load, sprint and endurance speed, total propulsion engine BHP, potable water weight, and lube oil weight. It uses parametric equations for various tank volumes and design data sheet DDS-200-1 for endurance fuel calculations. It outputs total required tankage volume, fuel tank volume, sprint range and endurance range.
- Space Required Module - Calculates deckhouse arrangeable area required and available, and total ship area required and available using parametric equations. Inputs include number and type of personnel, cubic number, known area requirements, hull and deckhouse volumes, large object volumes, average deck height, beam, and stores duration.
- Feasibility Module - Assesses the overall design feasibility of the ASC. It compares available to required characteristics including total arrangeable ship area, deckhouse area, sustained speed, electrical plant power, minimum and maximum GM/B ratios, endurance range, sprint range, and transom beam.
- Risk Module - Calculates a quantitative Overall Measure of Risk (OMOR) for a specific design taking into account performance risk, cost risk, and schedule risk.
- Cost Module - Calculates cost using the Naval Surface Warfare Center Carderock Small Fast Ship Cost Calculator. This calculator uses parametric equations for construction costs based on single digit (SWBS) weights, hull type, hull and deckhouse material, propulsion power type, propulsor type, and propulsion power. Fuel and personnel costs are added to calculate life cycle cost. It normalizes costs to the base year (2003) to find discounted life cycle cost. Other life cycle costs are assumed to be the same for all designs. It assumes a service life of 30 years with 3000 steaming hours underway per year. All recurring costs are excluded. The calculator assumes historical costs of modern surface combatants.
- Effectiveness Module - Calculates Values of Performance (VOPs) for sprint range, endurance range, provisions duration, sustained speed, draft, personnel, and RCS using their VOP functions. Inputs combat system VOPs from the combat system module. Calculates the OMOE using these VOPs and their associated weights. [19,20]

The weight module uses fuel as a slack variable: fuel weight = total weight – weight of everything else. Ship balancing of weight is therefore obtained without iteration. A design is

considered feasible if feasibility requirements assessed in the feasibility module and performance thresholds are satisfied simultaneously. If a design is feasible, the synthesis model continues to calculate cost, effectiveness and risk. These characteristics are the objective attributes for a Multi-Objective Genetic Optimization (MOGO) that is used to search the design space and identify non-dominated designs as described in section 1.1.1.

The MOGO is run in Model Center using a Darwin optimization plug-in (described in section 4.3), Figure 24 and Figure 25. The three objective attributes for the ALDV optimization are average follow ship acquisition cost, risk (technology performance, cost, and schedule risk), and overall effectiveness (OMOE). In the first design generation, the optimizer defines 200 balanced ships at random using the MC ship synthesis model to balance each design and quantify feasibility, cost, effectiveness, and risk. Each of the designs in this generation is ranked according to its fitness or dominance in the three objectives compared to the other designs in the population. When infeasibility or niching (bunching-up) in the design space occurs, penalties are assigned to the corresponding design. The second design generation of the optimization process is randomly selected from the first design generation, with higher probabilities of selection assigned to higher-fitness designs. Twenty-five percent of this second design generation is selected for crossover or swapping of design variable values. An even smaller percentage of randomly selected design variable values are then mutated or replaced with a new value at random. This process is repeated up to 300 times, and as each generation of ship designs is selected, the ship designs spread out and converge on the non-dominated frontier. Each ship design on the non-dominated frontier provides the highest effectiveness for a given cost and risk relative to other ship designs in the design space. The “best” design is determined by the customer’s preference in terms of effectiveness, cost, and risk. [19,20]

4.1.3 Interchanging Modules

Since the synthesis model is separated into different modules it is possible to replace certain modules or equations within a module with discipline-specific codes and Response Surface Models (RSM), described in Section 4.6. In this thesis a response surface model is used as a surrogate approximation for a computationally intensive mathematical analysis (MAESTRO). It is created using a set of data with inputs and their responses supplied from using a DOE. This moves the ship synthesis model from simple parametric equations (rough estimates) to more realistic estimates. Examples of discipline specific codes include MAESTRO for estimating

minimum adequate structural weight and SWAN for estimating sea keeping performance. Model Center has the ability to incorporate wrapped codes, integrating input and output variables of the codes with other modules. In the ALDV case study MAESTRO is run in Model Center prior to the optimization. Data is collected using a DOE to build a RSM which is added to the synthesis model to replace the simple parametric structural weight equation. This greatly reduces run time in the ship synthesis model assessment and analysis.

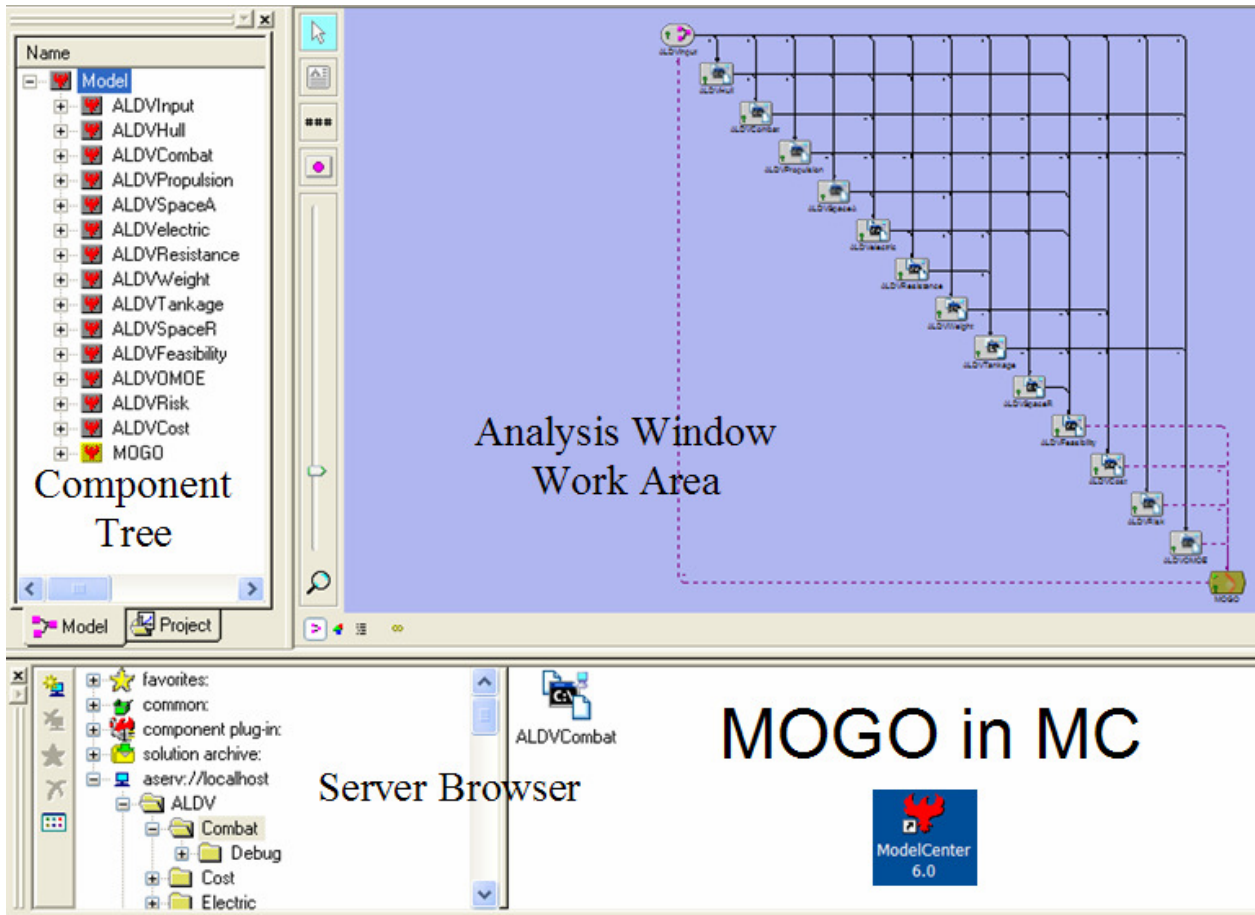


Figure 26 – Model Center Environment

4.2 Model Center Overview

The multi-objective optimization, design of experiments and response surface modeling are implemented in Model Center (MC). Model Center is a computer-based design integration environment that includes tools for linking design model components, wrapping analysis programs and running them in an automated fashion, visualizing the design space, performing trade studies and optimization, developing parametric models of the design space, and archiving results from multiple studies. By automating and simplifying these tasks, Model Center makes

the design process more efficient, saves engineering time, and reduces error in the design process. Figure 26 is an example of the Model Center environment.

4.3 Darwin Optimizer

Darwin is a genetic algorithm-based trade study tool designed specifically for solving "real world" engineering optimization problems. Genetic Algorithms (GAs) are probability-based algorithms that utilize processes analogous to natural selection to search for the best designs. Darwin is capable of solving design problems with both discrete and continuously valued design variables, and any number of constraints. Darwin is also able to perform Multi-Objective Genetic Optimization as described in Section 4.1.2. The algorithm is well suited for discontinuous, noisy, and/or multi-modal design spaces.

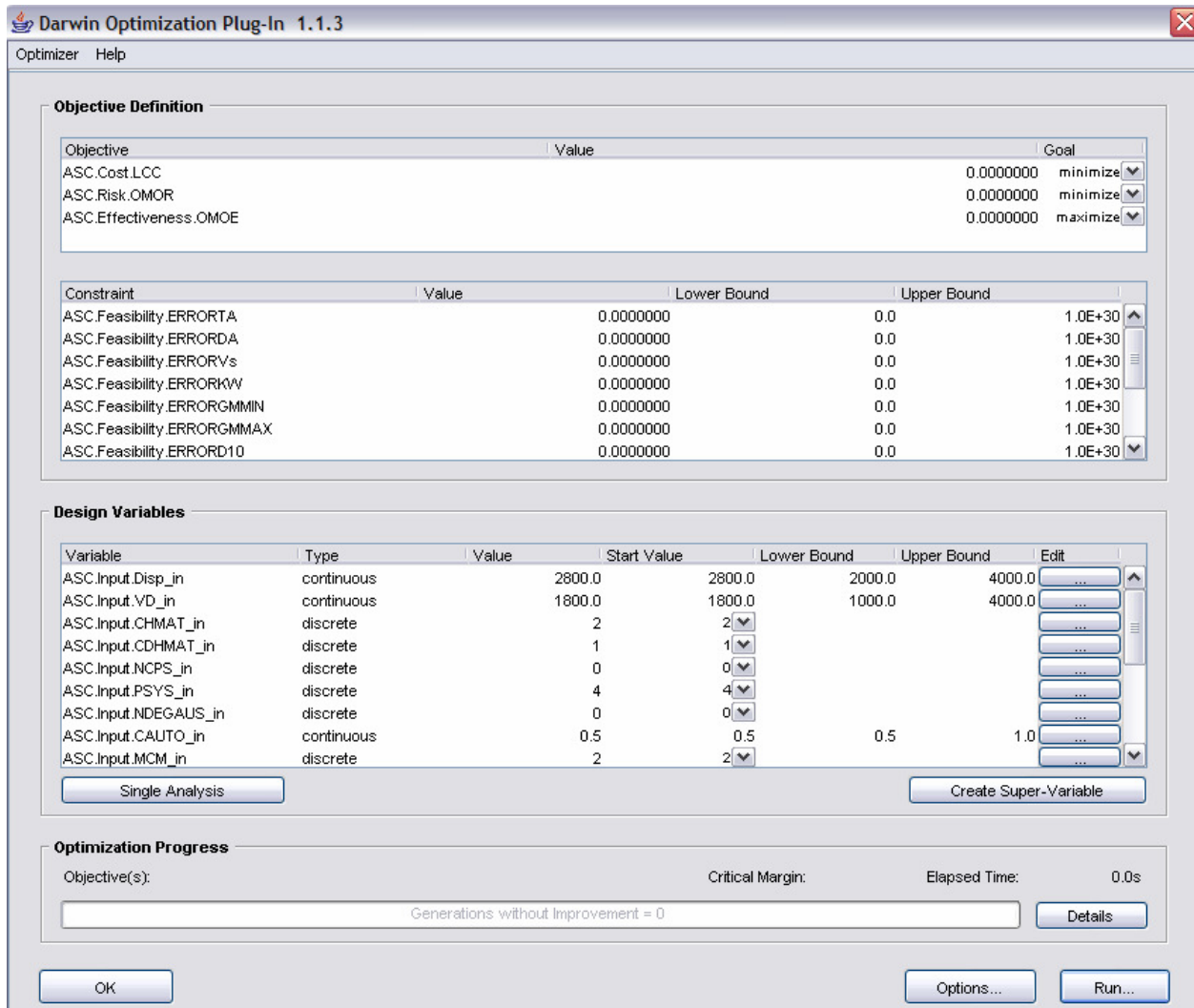


Figure 27 – Darwin Graphical User Interface

Darwin features an intuitive graphical user interface, shown in Figure 27, which allows the user to quickly define the optimization problem by dragging and dropping variables from Model Center's component tree, view optimization results in real time, and configure optimizer parameters (shown in Figure 28). [4]

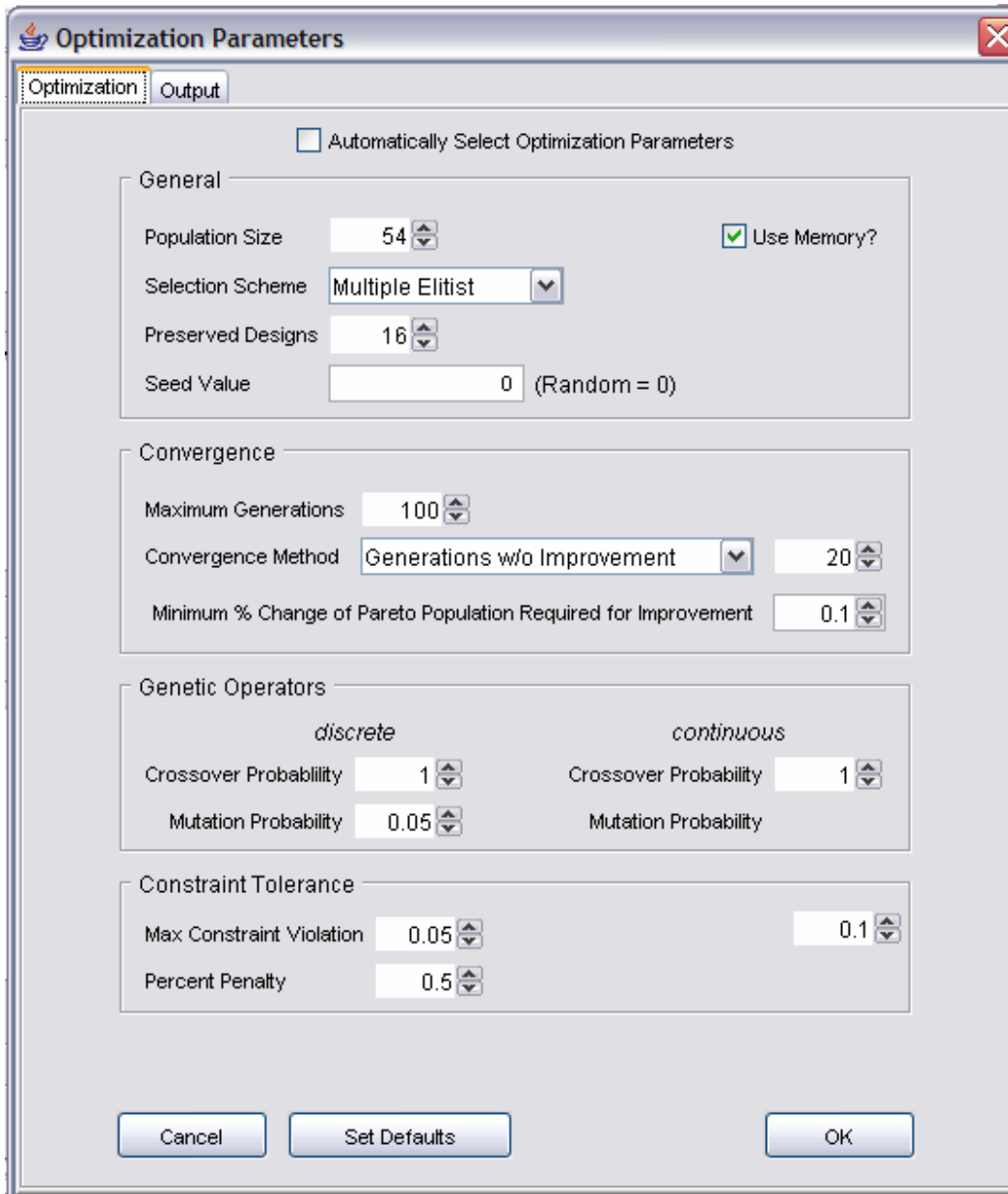


Figure 28 – Darwin Optimization Parameters Window

4.4 Design of Experiments Tool

The Design of Experiments (DOE) Tool in Model Center simplifies and structures the purposeful changing of inputs to a model to efficiently and effectively observe the corresponding changes in outputs (response variables). This is necessary to the building of a Response Surface

Model of the parent (more complex) model as will be discussed in Section 4.6. A set of valid values for each input variable constitutes a design point. The tool is used to efficiently select design points, and collect the responses of the model to these design points. Tools are provided to graphically set up and conduct this experiment. Figure 29 and Figure 30 show the DOE tool's graphical user interface. [4]

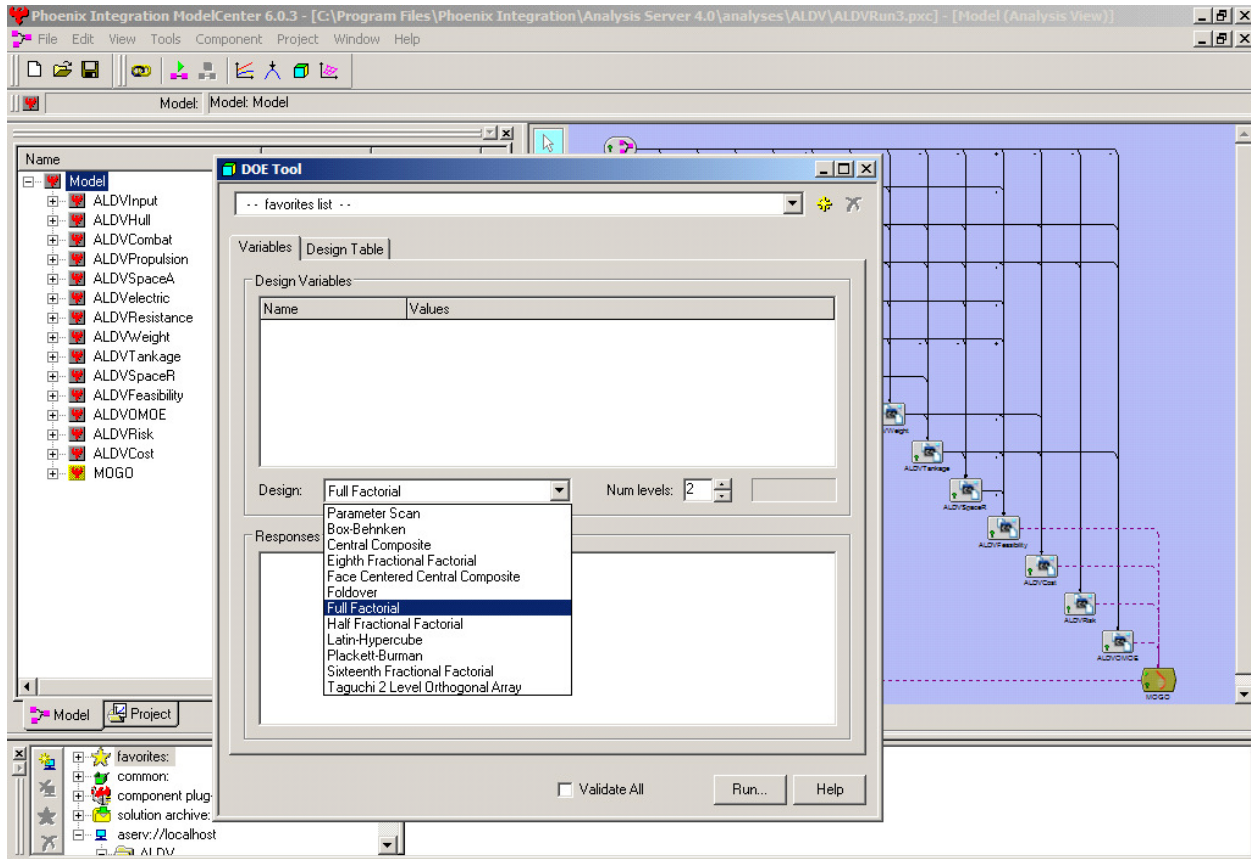


Figure 29 – DOE Graphical User Interface in Model Center

To perform a DOE, a set of input and response variables are selected with upper and lower boundary values for the input variables. An experiment design is a pre-defined set of design points selected using a DOE algorithm. Some DOE algorithms are selected to test a design for robustness (extent to which designs in the design space are feasible), other DOE algorithms are selected to quantify design variable's effect on each other, and other DOE algorithms are selected to screen a large number of design variables to isolate the most important ones. The following DOE algorithms are available in the Model Center DOE tool:

- Half Fractional Factorial
- Eighth Fractional Factorial
- Sixteenth Fractional Factorial

- Foldover
- Plackett-Burman
- Parameter Scan
- Full Factorial
- Latin-Hypercube
- Central Composite
- Face Centered Central Composite
- Box-Behnken

The half fractional factorial, eight fractional factorial, sixteenth fractional factorial, foldover, and Plackett-Burman designs are all screening experiments. Screening experiments are used as a pre-process to identify which variables are most active. These are most useful when many variables are present and therefore many design points.

The parameter scan and full factorial designs sample the whole design space. The parameter scan only allows two levels (high and low) of each variable to be tested while the full factorial allows two or more levels of each variable to be tested.

Phoenix Integration suggests the Latin-Hypercube design for our application since it takes a random sample of the design space. The Latin-Hypercube is similar to full factorial except that the internal space is divided into segments to achieve a more thorough investigation of the design space. The Latin-Hypercube allows the user to specify how many designs to sample within the design space. The specified number of designs determines how many segments a variable is broken into and how many random combinations of variables and segments are chosen.

When the DOE tool is run, it repeatedly sets the values for the design variables and then calculates each of the response variables. At each iteration, it stores the values in a Data Explorer, shown in Figure 31. The Data Explorer displays the inputs and outputs for each design point in a table which can be exported to Excel if desired. It also has the capability to generate graphs of responses vs. desired inputs, carpet and surface plots to display a response vs. two variables, or a main effects plot. The Main Effects Plot displays the sensitivity of the input variable to the response. A main effect is the difference between the average output of an input variable's upper and lower values. The input variable with the largest main effect has the greatest influence on the response variable.

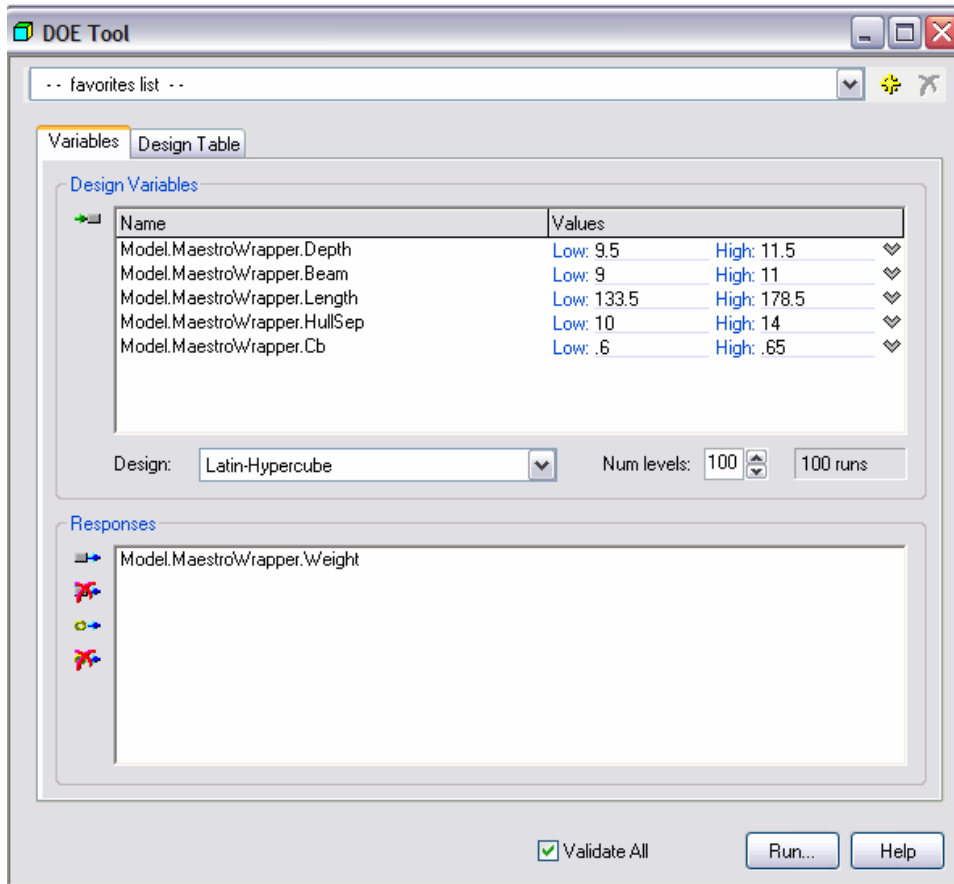


Figure 30 – DOE Graphical User Interface

Data Explorer : 4/6/2005, 15:10:52

Data Edit Page

Legend: input valid output invalid output modified value

| | 1 | 2 | 3 | 4 | |
|--|-------------|-------------|-------------|-------------|-----|
| design variable (Model.MaestroWrapper.Depth) | 9.77545 | 10.5343 | 10.1875 | 10.1272 | 9.9 |
| design variable (Model.MaestroWrapper.Beam) | 9.2768 | 10.2249 | 10.9017 | 9.87644 | 9.5 |
| design variable (Model.MaestroWrapper.Length) | 138.898 | 172.55 | 138.448 | 143.886 | 13 |
| design variable (Model.MaestroWrapper.HullSep) | 11.2647 | 11.9072 | 13.42 | 13.6978 | 10. |
| design variable (Model.MaestroWrapper.Cb) | 0.64024 | 0.62357 | 0.60376 | 0.61334 | 0.6 |
| response (Model.MaestroWrapper.Weight) | 1.6022e+006 | 2.1204e+006 | 1.8443e+006 | 1.8088e+006 | 1.6 |
| Model.MaestroWrapper.modnum | 2 | 2 | 2 | 2 | 2 |
| Model.MaestroWrapper.subnum | 3 | 3 | 3 | 3 | 3 |
| Model.MaestroWrapper.cycles | 1 | 1 | 1 | 1 | 1 |
| Model.MaestroWrapper.Depth | 9.77545 | 10.5343 | 10.1875 | 10.1272 | 9.9 |
| Model.MaestroWrapper.Beam | 9.2768 | 10.2249 | 10.9017 | 9.87644 | 9.5 |
| Model.MaestroWrapper.Length | 138.898 | 172.55 | 138.448 | 143.886 | 13 |
| Model.MaestroWrapper.HullSep | 11.2647 | 11.9072 | 13.42 | 13.6978 | 10. |
| Model.MaestroWrapper.Cb | 0.64024 | 0.62357 | 0.60376 | 0.61334 | 0.6 |
| Model.MaestroWrapper.Weight | 1.6022e+006 | 2.1204e+006 | 1.8443e+006 | 1.8088e+006 | 1.6 |

1 - Table

| | |
|--------------|-----------|
| \$17.00 | \$17.75 |
| 1.34e+007 | 1.34e+007 |
| 5 1/2 | 5 1/2 |
| 1.40235e+041 | 1.40235e+ |
| \$17.00 | \$17.75 |
| 5 1/2 | 5 1/2 |
| 5 23 | 5 23 |

2 - Weight

Add Page/Chart...

For Help, press F1

Figure 31 – Model Center's Data Explorer

4.5 MAESTRO [22]

The baseline ALDV ship synthesis model uses a very simple equation to estimate structural weight, sensitive only to displacement. To provide a more precise and robust estimate of structural weight sensitive to additional important global design variables, a response surface model for sufficient structural weight was developed using MAESTRO. A structural weight minimization was performed for each set of data collected to develop the RSM, a disciplinary optimization within a global ship optimization.

MAESTRO is a finite element analysis program for rationally-based analysis, evaluation, and structural optimization of ships. MAESTRO produces an optimum design based on any designer-specified measure of merit such as weight, cost, or any combination of these. The primary purpose of MAESTRO is for design, but it can be used to analyze an existing structure (or proposed design) using just the analysis and evaluation portions of the program and not the optimization portion. The program's underlying theory and a detailed description of its principal features are given in Hughes' *Ship Structural Design* [21], which constitutes the Theoretical Manual for the program.

The MAESTRO method of design is referred to as "rationally-based" because it includes, in each design cycle, all of the following:

- For the complete structure, a rapid, "design-oriented" finite element analysis which uses elements that are suited for preliminary design, as distinct from general purpose finite element programs which are more suited for analysis of details.
- An explicit evaluation of all limit states (ultimate strength and serviceability), at both levels (member level and "module", or multi-member level), for all load cases, thus establishing which limit states are currently critical (in the current design cycle) for each member, and by how much.
- Formulation of the linearized limit state equations, which utilize partial safety factors in order to achieve a consistent degree of structural reliability.
- Multi-objective optimization based on any combination of individual measures of merit (linear or nonlinear) such as structural weight, material cost, fabrication cost, and any other desired performance factors that are functions of the member size variables (plate thicknesses, web heights, flange breadths, etc.). Besides the limit state equations, the optimization can accommodate any number of designer-specified constraints, such as those relating to fabrication aspects or operational requirements.

The MAESTRO Optimization module uses sequential linear programming to redesign the structure. This optimization eliminates any structural inadequacies while achieving an optimum

design based on user specified objectives (goals), which may be weight or cost or both of these, in a weighted non-dimensional combination. In its optimization mode MAESTRO iterates the structure through design cycles in which it revises scantlings, reruns the finite element analysis, and reevaluates the structural adequacy of each member for all failure modes and load cases. This iterative process continues until the structure has converged to an optimum design that has no structural inadequacies. [22]

4.6 Response Surface Model (RSM)

Response surface models are often used as surrogate approximations for computationally intensive mathematical analyses or simulations. For example, you may have a numerical analysis that computes the critical displacements of a structural component as a function of several geometry parameters. If this analysis has to be run repeatedly, the computational expense may become prohibitive. [4]

Model Center's RSM plug-in can be used to construct computationally efficient response surface models that approximate the output of a simulation over a selected range of the input variables. The plug-in uses data collected from a DOE study (Phoenix Integration recommends using the Latin Hypercube DOE since this most effectively samples the design space). Once the study is complete the plug-in can be launched from the Data Collector. If sufficient data is provided (RSM tool shows an error if there is insufficient data), the response surface model can be created from some or all of the input and response variables from the DOE study. The response surface can be modeled using several polynomial model options including Quadratic Stepwise Regression, Cubic Stepwise Regression, Linear, Linear plus Quadratic Interaction Terms, Full Quadratic, Linear plus Quadratic and Cubic Interaction Terms, and Full Cubic. After creating a response surface, statistical details and graphs can be viewed. An example is shown in Figure 32. The statistical details describe how well the response surface fits the data provided. However, this does not necessarily mean the response surface describes the actual response of the parent model. It is only an approximation of the actual response, and the fit is only representative of the actual response if it is based on sufficient and precise data. The efficiency of the DOE algorithm and the number of samples determine the sufficiency of the data. Since the purpose of a RSM is to reduce computational time, large sample sizes are self-defeating. Therefore the DOE algorithm must be carefully chosen to sufficiently represent the design space.

A surface can be created using all the polynomial models and the best fit chosen. Once a response surface is chosen it can be returned to Model Center as a module or to replace a calculation in a module. This module can then be used in place of the parent disciplinary model (MAESTRO) for rapidly performing tasks such as parametric design studies or design optimization.

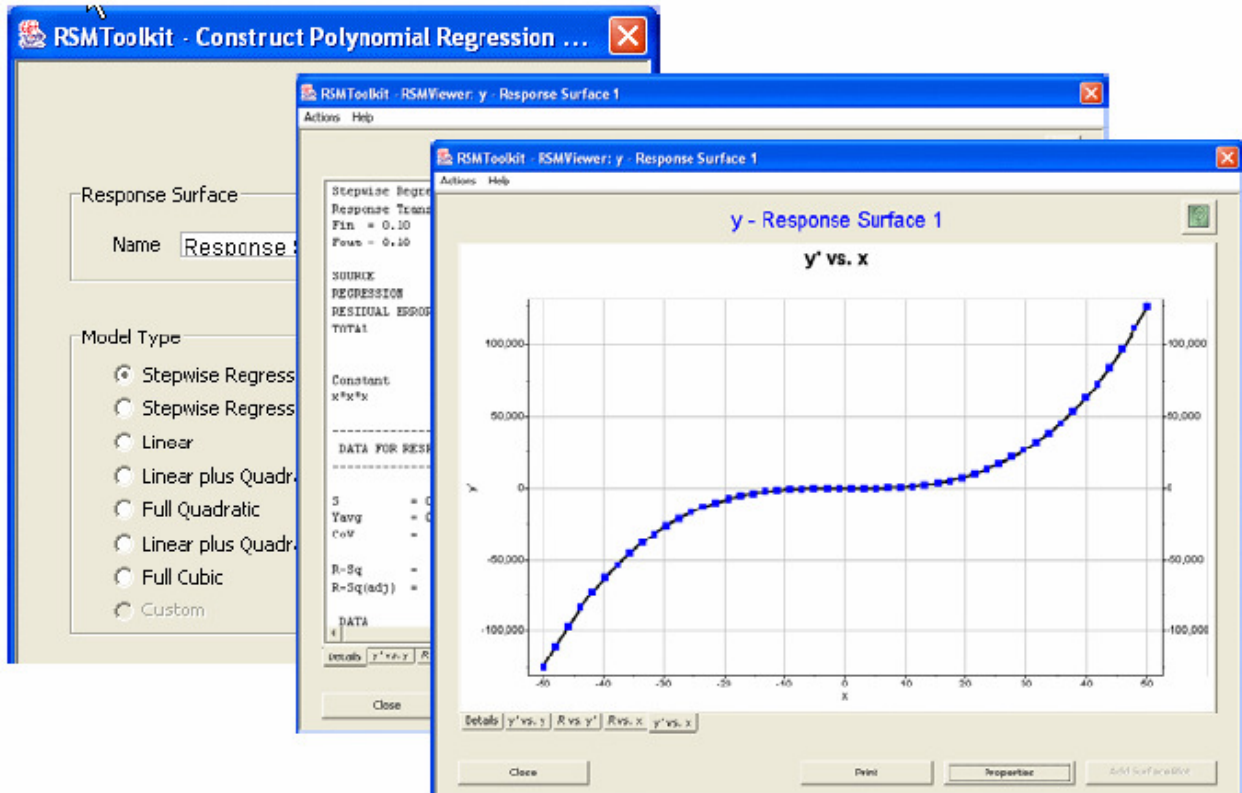


Figure 32 – RSM Details and Graph [4]

CHAPTER 5 ALDV CASE STUDY

In this chapter, a case study is described based on a concept exploration ship design from Virginia Tech’s 2005 senior ship design class. The ship is an Advanced Logistics Delivery Ship (ALDV). Its primary mission is to deliver logistics to marines ashore from a seabase using unmanned gliders. ALDV requires storage for the glider payloads and the aircraft. It must be high speed to travel from seabase to offshore, and it must be capable of launching the aircraft. Section 1.1 described the general multi-objective optimization and OMOE development process. The following sections describe the ALDV application of this process. The OMOE development process begins with the mission description and Mission Need Statement (Appendix E – ALDV Mission Need Statement).

5.1 ALDV OMOE

5.1.1 ALDV Mission

ALDV will transport and deliver marine logistics support from an off-shore seabase or shuttle ship (TAO, ADCX) to a dispersed, inland, Marine Expeditionary Brigade (MEB) using unmanned gliders, part of an Advanced Logistics Delivery Support System (ALDS). ALDV will also support the V-22 Osprey by providing at least one helicopter deck and refueling capabilities. ALDV may also support humanitarian missions by delivering supplies to victims of natural disasters. [23]

5.1.2 Mission Scenarios

A typical mission scenario for the primary ALDV mission is provided in Table 30. This mission scenario is used to establish the design requirements of the ship (e.g., speed, endurance, cargo capacity, etc.).

Table 30 - Military Mission Scenario [23]

| Day | ALDV Mission Description |
|-----------|--|
| 1 - 5 | Transit from CONUS to seabase |
| 6 | Refuel and restock supplies at seabase or shuttle ship |
| 7 | Transit from seabase to littoral zone |
| 8 – 11 | Deliver supplies to inland troops via unmanned glider |
| 12 | Return to seabase |
| 13 | Refuel and restock supplies at seabase or shuttle ship, perform maintenance |
| 14 | Transit from seabase to littoral zone |
| 15 - 175 | Continuously refuel and restock using seabase or shuttle ships and travel back and forth along littoral zone to deliver supplies to inland troops. Refuel V-22s. |
| 175 – 180 | Return to CONUS |

Required operational capabilities (ROCs) are identified to perform the ship’s missions, and measures of performance (MOPs) are specified for those capabilities that vary in the designs as a function of the ship design variables (DVs). Table 31 is a summary of ROCs with the corresponding MOPs and DVs for ALDV. Each MOP is assigned a threshold and goal value. Table 32 summarizes the MOP goals and thresholds. Capability requirements and constraints applicable to all designs are also specified.

An Overall Measure of Effectiveness (OMOE) hierarchy is developed from the MOPs using the Analytical Hierarchy Process (AHP) to calculate MOP weights and Multi-Attribute Value Theory (MAVT) to develop individual MOP value functions.

Table 31 - ROC/MOP/DV Summary [23]

| ROC | Primary MOP or Constraint | Threshold or Constraint | Goal | Related DV |
|--|---|--|--|---|
| MOB 1 - Steam to design capacity in most fuel efficient manner | MOP 6 – Sprint Range MOP 7 – Endurance Range MOP 9 – Sprint Speed | 250 nm 2500 nm 40 knots | 500 nm 3500 nm 50 knots | DV1 - Waterline Length DV 5 - Propulsion system alternative |
| MOB 3 - Prevent and control damage | MOP 13 – Personnel Vulnerability MOP 10 – RCS MOP 11 – Acoustic Signature MOP 12 – Magnetic Signature MOP 1 – MCM | 60 3000 ft3 Mechanical LM2500+ No Degaussing | 35 500 ft3 IPS ICR Degaussing | DV6 - Manning and automation factor DV2 - Deckhouse volume DV5 - Propulsion system alternative DV8 - Degaussing system |
| MOB 5 - Maneuver in formation | Required all designs | | | |
| MOB 7 - Perform seamanship, airmanship and navigation tasks (navigate, anchor, mooring, scuttle, life boat/raft capacity, tow/be-towed) | Required all designs | | | |
| MOB 10 - Replenish at sea | Required all designs | | | |
| MOB 12 - Maintain health and well being of crew | Required all designs | | | |
| MOB 13 - Operate and sustain self as a forward deployed unit for an extended period of time during peace and war without shore-based support | MOP 7 - Endurance Range MOP 8 - Provisions | 2500 nm 20 days | 3500 nm 45 days | DV1 - Waterline Length DV5 - Propulsion system alternative DV15 - Provisions duration |
| MOB 16 - Operate in day and night environments | Required all designs | | | |
| MOB 17 - Operate in heavy weather | Required all designs | | | |
| MOB 18 - Operate in full compliance of existing US and international pollution control laws and regulations | Required all designs | | | |
| AAW – Anti-Air Warfare Capabilities | MOP 5 – AAW | AAW = 4 | AAW = 1 | DV7 - AAW |
| ASUW – Anti-Surface Ship Attack Capabilities | MOP 3 – ASUW | ASUW = 3 LAMPS = 4 | ASUW = 1 LAMPS = 1 | DV8 - ASUW DV12 - LAMPS |
| ASW 4 - Conduct airborne ASW/recon (LAMPS) | MOP 4 – ASW MOP 2 – C4ISR | ASW = 2 LAMPS = 4 C4ISR = 2 | ASW = 1 LAMPS = 1 C4ISR = 1 | DV9 - ASW DV12 - LAMPS DV11 - C4ISR |
| ASW 5 – Support airborne ASW/recon | MOP 2 – C4ISR | LAMPS = 4 C4ISR = 2 | LAMPS = 1 C4ISR = 1 | DV12 - LAMPS DV11 - C4ISR |
| ASW 10 – Disengage, evade and avoid submarine attack by employing countermeasures and evasion techniques | MOP 4 – ASW MOP 9 – Sprint Speed MOP 6 – Sprint Range | ASW = 2 LAMPS = 4 40 knots 250 nm | ASW = 1 LAMPS = 1 50 knots 500 nm | DV9 - ASW DV12 - LAMPS DV5 - Propulsion System alternative |

| ROC | Primary MOP or Constraint | Threshold or Constraint | Goal | Related DV |
|--|---------------------------|-------------------------|-----------|------------------|
| CCC 1.6 – Provide a Helicopter Direction Center (HDC) | Required all designs | LAMPS = 4 | LAMPS = 1 | DV12 - LAMPS |
| CCC 3 - Provide own unit CCC | MOP 2 – C4ISR | C4ISR = 2 | C4ISR = 1 | DV11 - C4ISR |
| CCC 4 - Maintain data link capability | MOP 2 – C4ISR | C4ISR = 2 | C4ISR = 1 | DV11 - C4ISR |
| FSO 3 – Provide Support services to other units | Required all designs | LAMPS = 4 | LAMPS = 1 | DV12 - LAMPS |
| NCO 3 - Provide upkeep and maintenance of own unit | Required all designs | | | |
| LOG 2 – Transfer / Receive cargo and personnel | Required all designs | | | |
| LOG 3 – Seabase Docking Capability | Required all designs | | | |
| LOG 4 – Support land based personnel with logistics support via ALDV | MOP 15 - ALDV Cargo | 3 days | 8 days | DV6 - ALDV Cargo |
| AMW 6.1 – Conduct day helicopter, short/vertical takeoff and landing | Required all designs | LAMPS = 4 | LAMPS = 1 | DV12 - LAMPS |
| AMW 6.3 – Conduct all weather helicopter operation | Required all designs | LAMPS = 4 | LAMPS = 1 | DV12 - LAMPS |
| AMW 6.6 – Conduct helicopter refueling | Required all designs | LAMPS = 4 | LAMPS = 1 | DV12 - LAMPS |

Table 32 – ALDV Measures of Performance (MOPs) [23]

| Primary MOP or Constraint | Threshold or Constraint | Goal | Related DV |
|----------------------------------|-------------------------|-----------------------|---|
| MOP 1 - MCM | MCM = 2 | MCM = 1 | DV10 - MCM |
| MOP 2 - C4I | C4I = 2 | C4I = 1 | DV11 - C4I |
| MOP 3 - ASUW | ASUW = 3 LAMPS = 4 | ASUW = 1 LAMPS = 1 | DV8 - ASUW DV12 - LAMPS |
| MOP 4 - ASW | ASW = 2 LAMPS = 4 | ASW = 1 LAMPS = 1 | DV9 - ASW DV12 - LAMPS |
| MOP 5 – AAW | AAW = 4 | AAW = 1 | DV7 - AAW |
| MOP 6 - Sprint Range | 250 nm | 500 nm | DV1 - Waterline Length DV5 - Propulsion System alternative |
| MOP 7 - Endurance Range | 2500 nm | 3500 nm | DV1 - Waterline Length DV5 - Propulsion System alternative |
| MOP 8 - Provisions | 20 days | 45 days | DV15 - Provision Duration |
| MOP 9 - Sprint Speed | 40 knots | 50 knots | DV5 - Propulsion system alternative |
| MOP 10 - RCS | 3000 ft ³ | 500 ft ³ | DV3 - Deckhouse volume |
| MOP 11 - Acoustic Signature | Mechanical Drive | IPS | DV5 - Propulsion system alternative |
| MOP 12 - Magnetic Signature | No degaussing | Degaussing | DV8 - Degaussing system |
| MOP 13 - Personnel Vulnerability | 60 | 35 | DV6 - Manning and automation factor |
| MOP 14 - CBR | No CPS | Full CPS | DV14 - NCPS |
| MOP 15 - ALDV Cargo | 3 days | 8 days | DV16 - ALDV Days |

The ALDV OMOE hierarchy is shown in Figure 33. There are 15 ALDV MOPs. Each alternative or under each MOP or each MOP metric is assigned a value of performance (0-1.0) using pairwise comparison or value of performance function as part of the AHP.

In the AHP, pairwise comparison questionnaires are used to solicit expert and customer opinion, required to calculate AHP weights and value of performance (VOP). An example of the pairwise comparison used for ALDV is shown in Figure 34. Value of Performance (VOP) functions, generally S-curves for continuous MOPs like Figure 35 and discrete values between 0 and 1 for discrete MOPs, are developed for each MOP, and VOP values are calculated using these functions in the ship synthesis model. A particular VOP has a value of 0.0 corresponding

to the MOP threshold, and a value of 1.0 corresponding to the MOP goal. The MOP weights found for ALDV are shown in Figure 36 and Table 33. MOP weights and value functions are finally assembled in a single OMOE function:

$$OMOE = g[VOP_i(MOP_i)] = \sum w_i VOP_i(MOP_i) \quad (9)$$

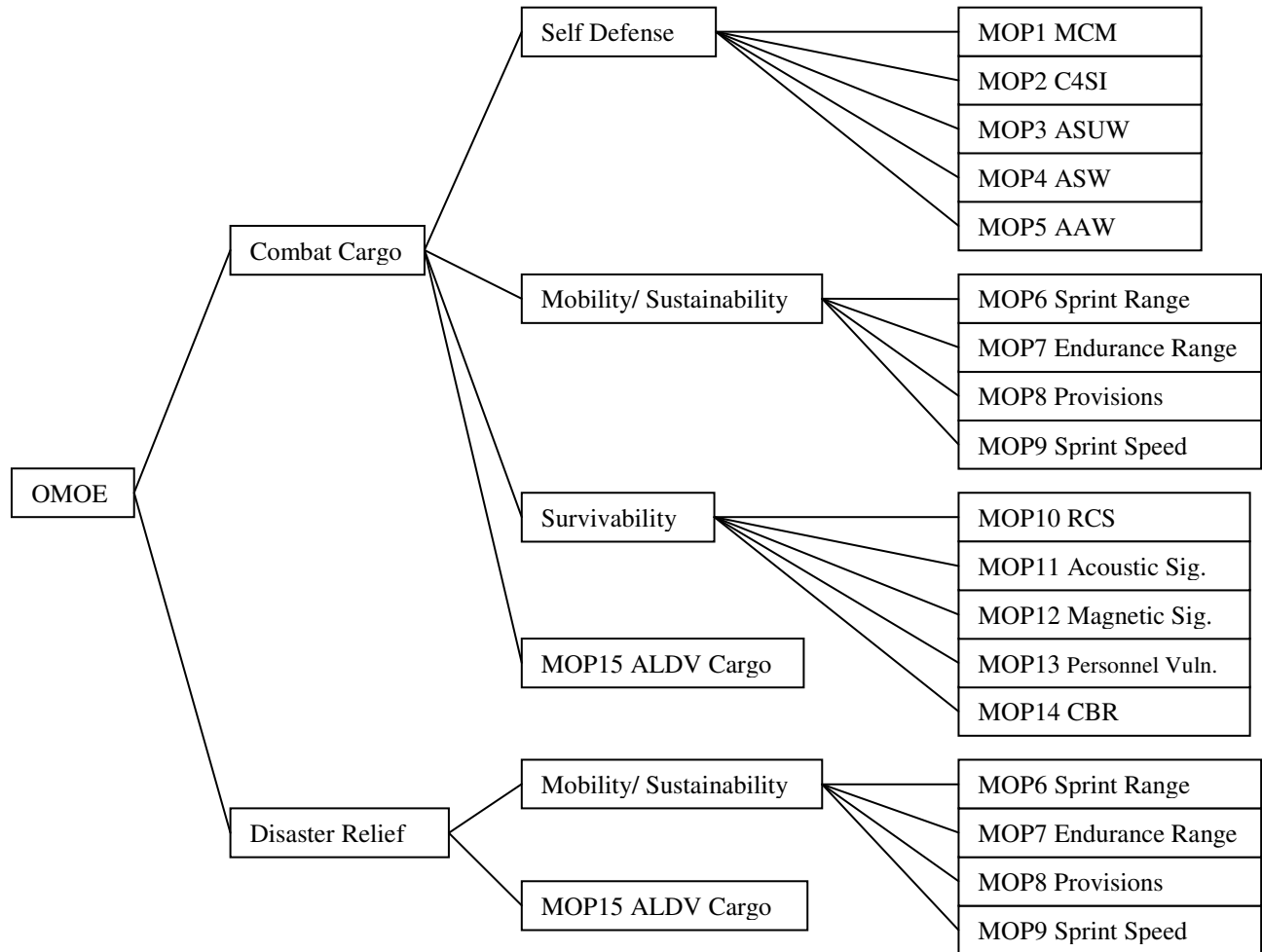


Figure 33 - ALDV OMOE Hierarchy

With respect to the Combat Cargo mission type, how do the following mission area categories compare?

1 = equal 3 = moderate 5 = strong 7 = very strong 9 = extreme

| | | | | | | | | | | | | | | | | | | |
|--------------------------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|--------------------------|
| Self Defense | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Mobility/ Sustainability |
| Self Defense | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Survivability |
| Self Defense | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | ALDS Cargo - MOP15 |
| Mobility/ Sustainability | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Survivability |
| Mobility/ Sustainability | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | ALDS Cargo - MOP15 |
| Survivability | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | ALDS Cargo - MOP15 |

Figure 34 - AHP Pairwise Comparison [23]

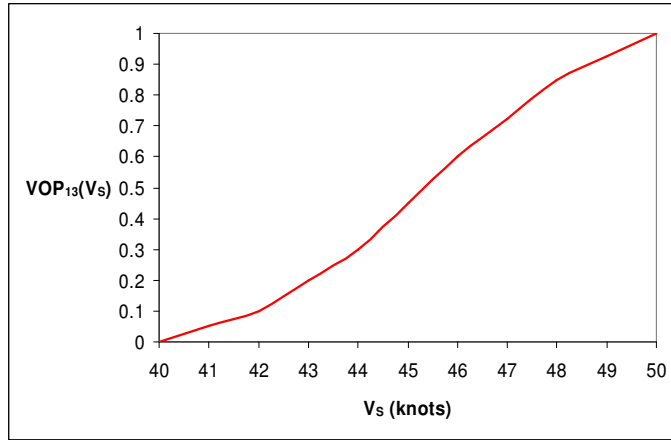


Figure 35 - S-shaped VOP Curve [23]

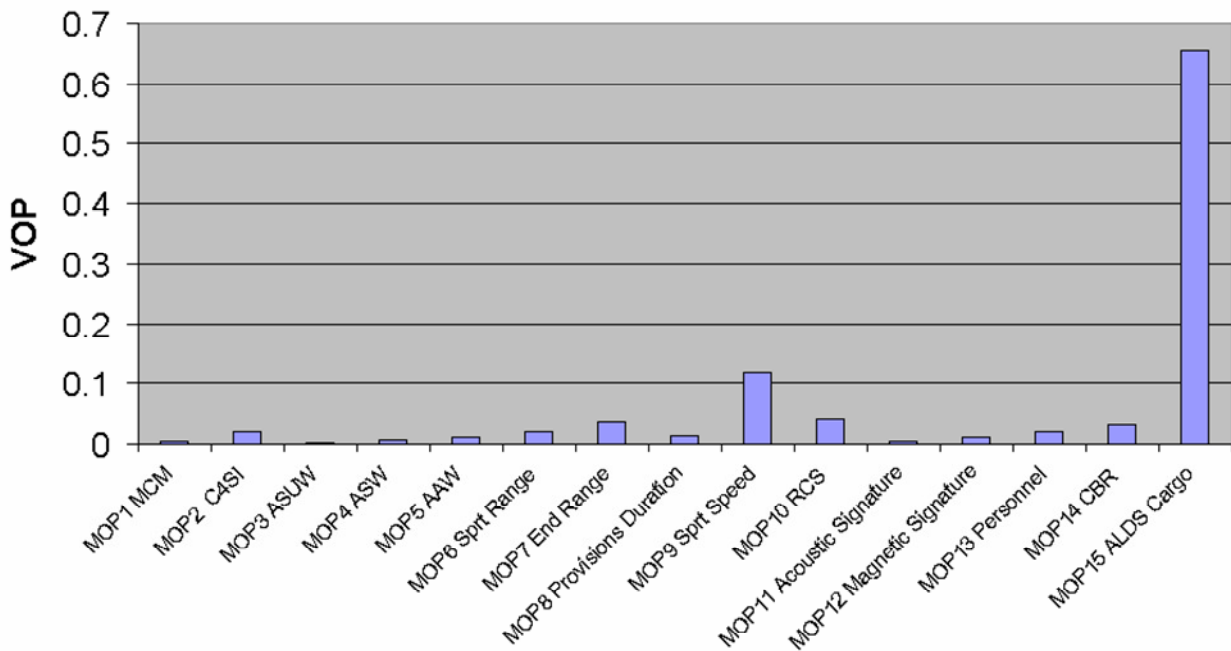


Figure 36 – MOP Weights [23]

Table 33 - MOP Weights [23]

| | |
|--------------------------|--------|
| MOP1 MCM | 0.0035 |
| MOP2 C4SI | 0.0214 |
| MOP3 ASUW | 0.002 |
| MOP4 ASW | 0.0069 |
| MOP5 AAW | 0.0108 |
| MOP6 Sprt Range | 0.021 |
| MOP7 End Range | 0.0364 |
| MOP8 Provisions Duration | 0.0132 |
| MOP9 Sprt Speed | 0.1193 |
| MOP10 RCS | 0.0409 |
| MOP11 Acoustic Signature | 0.0053 |
| MOP12 Magnetic Signature | 0.0123 |
| MOP13 Personnel | 0.0211 |
| MOP14 CBR | 0.0318 |
| MOP15 ALDS Cargo | 0.6541 |

5.2 ALDV Structural Design and RSM

5.2.1 Baseline Structural Design Example

In the concept exploration phase of the design process the ship synthesis model is used to balance and assess designs in the design space. ALDV has a trimaran hullform. A baseline hullform model was created in MAESTRO to be used as a “rubber ship” to estimate the structural weight of designs with different principle characteristics. The length, center hull beam, depth, and hull separation are varied in MAESTRO to reflect alternative designs in the ship synthesis model. Length is the ship length at the waterline, beam is the center hull beam at the waterline, depth is measured from the keel to the bottom of the cross structure at midships, and hull separation is measured from the centerline to the center of a side hull as shown in Figure 38. The scantlings of this new MAESTRO models are optimized and the structural weight is estimated. During the structural optimization and weight assessment the structure is treated as a non-floating structure. Longitudinal bending moments are applied to simulate a hogging wave case and a sagging wave case. The baseline MAESTRO model is shown in Figure 37 and its principle characteristics are shown in Figure 38.

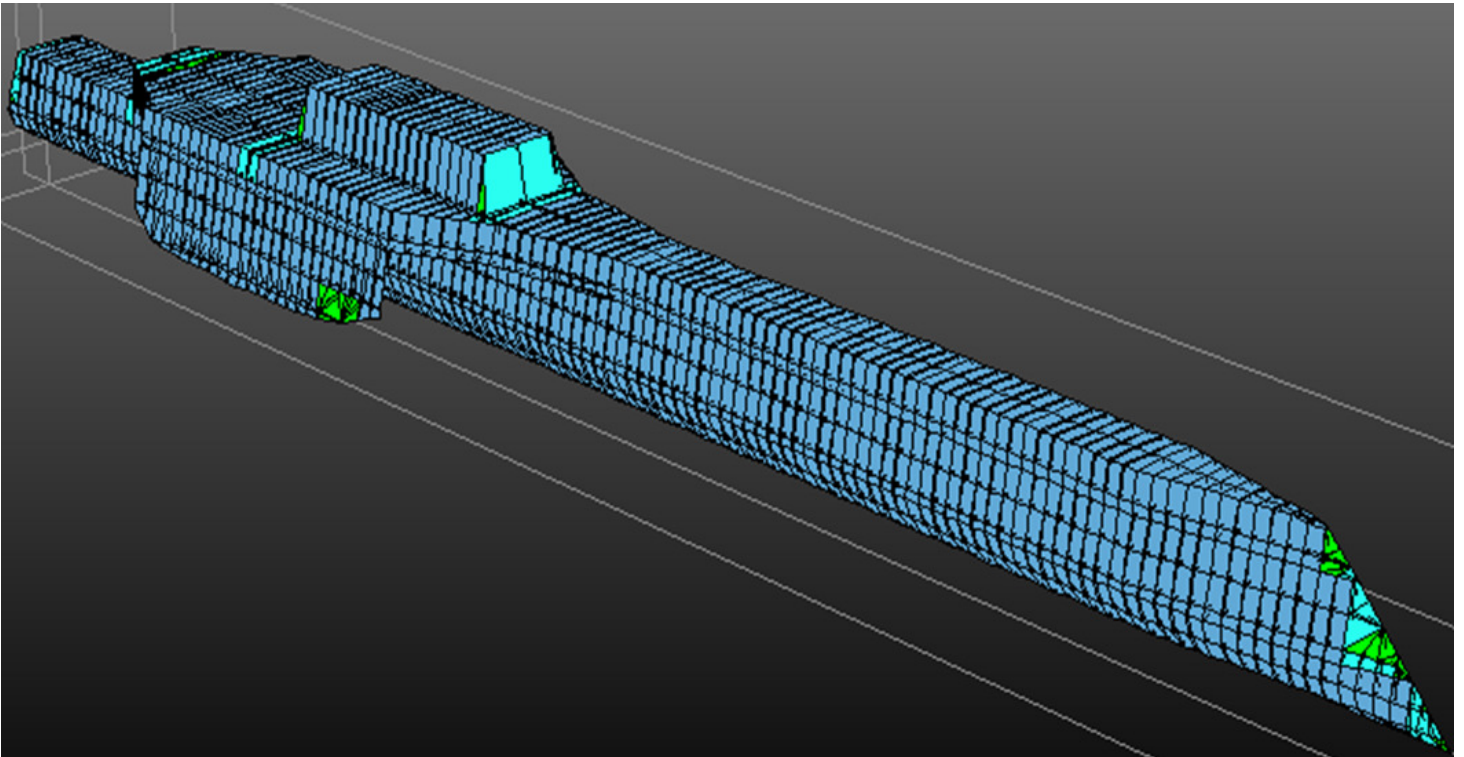
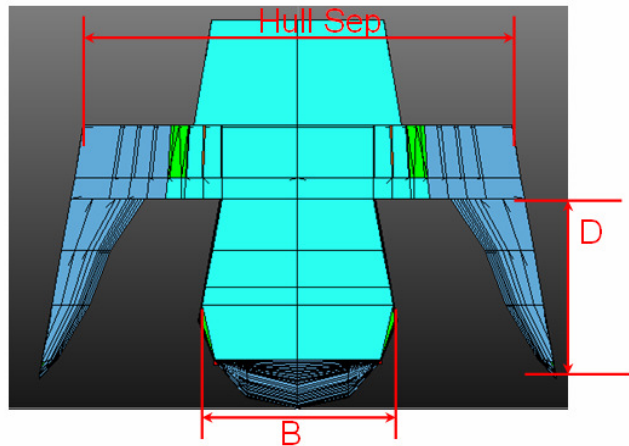


Figure 37 – Baseline MAESTRO Structure Model



Length: 178.5 meters
 Center Hull Beam: 9.5 meters
 Depth: 10 meters
 Hull Separation: 10.27

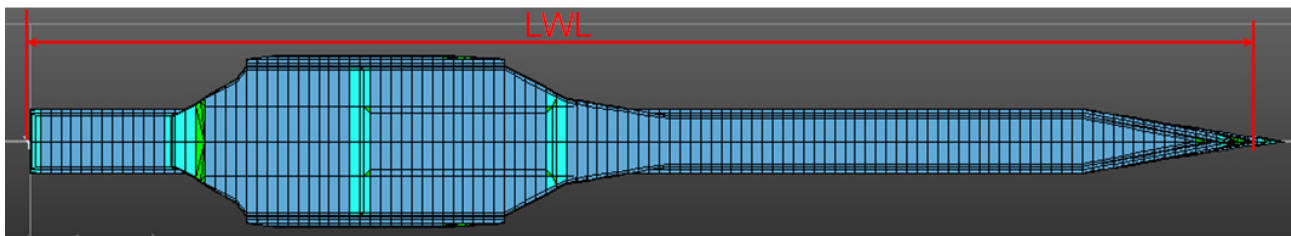


Figure 38 – Baseline Characteristics in Body Plan and Plan Views

5.2.2 Wrapping MAESTRO in Model Center

The current ship synthesis weights module uses a simple parametric model to estimate structural weight. It is desired to substitute a MAESTRO response surface model. The RSM is developed in Model Center (MC) using a “wrapper” for the MAESTRO structural assessment and optimization solver. A FORTRAN structural design interface (SDI) was also written to modify the MAESTRO baseline input file to the desired global ship principle characteristics. Model Center uses this program to perform a DOE and develop a RSM.

5.2.2.1 Modifying the Parent Hullform

The SDI reads and modifies the input file (.dat) for input to the MAESTRO solver. Length is changed by adding or subtracting parallel mid-body in the parent hull, shown in Figure 39, and changing the starting x coordinate of all modules affected by the added mid-body. Since the parent model uses a frame spacing of 1.5 meters, any input length is rounded to the nearest 1.5 meter increment. The SDI calculates the number of sections to be added to the mid-body module ($N_{SECTIONS} = (L_{NEW} - 178.5)/1.5$) and the change in length (D_X) to be added to all the modules following the expanded module.

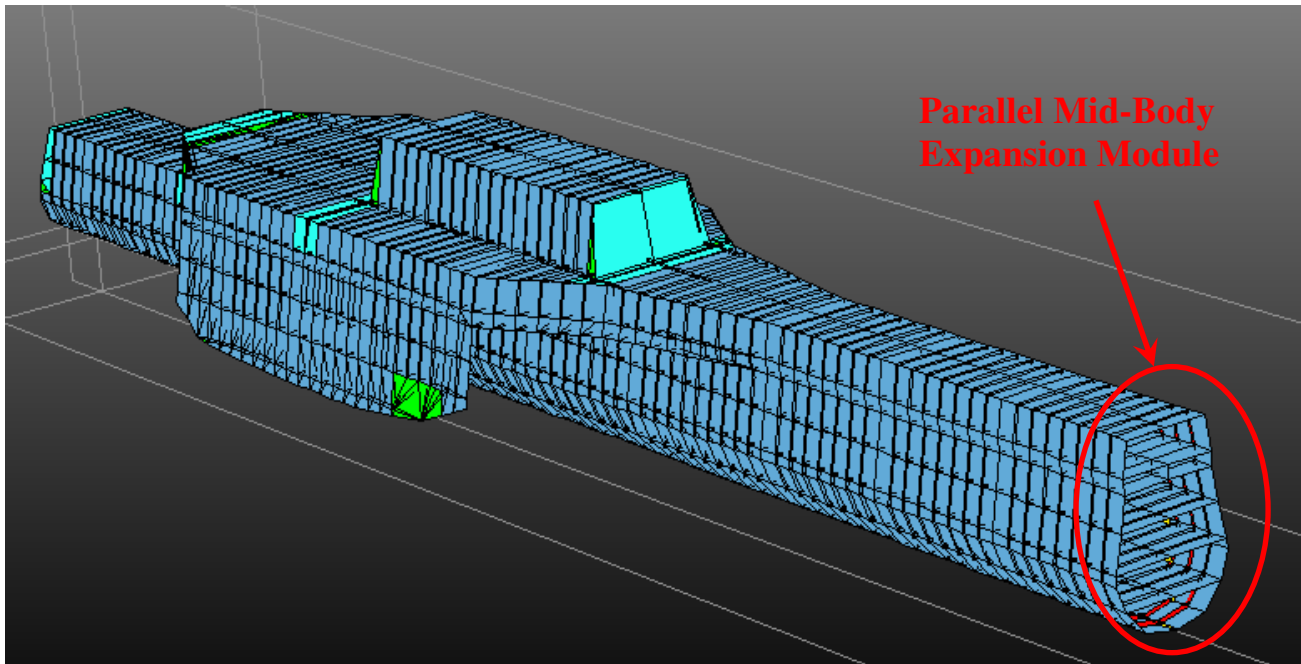


Figure 39 – Parent Hull Parallel Mid-Body Module

```

"Optimization"
VERSION 8.1.1
$JOB INFORMATION
DESIGN 7 0 0 0 0 0 0 0 0 0 0 0
$STRUCTURE PARAMETERS
2 0 1 3 , , , 1 1 , 0
REFERENCE 0 0 0 4.21
UNITS N m kg kg 1 1025.9 9.80665 "$"
CRITERIA default 1.5 1.25
$MATERIAL PROPERTY
ST4027 1 .205E+12 0.29 .353E+09 .565E+09 .353E+09 .785E+04 .785E+04 0.00 1.00
$COMPOSITE PANELS
NOBALANCE float PROCEED NOADJUST
$ SUBSTRUCTURE IDENTIFIER
SUBS 1
0 0 0 0 0 0
$ MODULE IDENTIFIER==>/top/sub1/mod1
MODULE 1 0 0 0 0 0 0
$ DATA GROUP 1-- GENERAL INFORMATION
4 0 1 22 0 11 , Y N 1
1.6 0 , , 1000 1 0 6.66666e-005 6.66666e-005
$ DATA GROUP 2 ENDPOINTS
2.300 0.000 2.300 0.000 0.000 0.000 !# 1
2.300 -3.963 2.300 -3.963 0.000 0.000 !# 2
4.168 4.651 4.168 4.651 0.000 0.000 !# 3
4.900 -4.584 4.900 -4.584 0.000 0.000 !# 4
7.500 -4.091 7.500 -4.091 0.000 0.000 !# 5

```

Number of sections added or subtracted for changed length

y and z node coordinates for scaling Depth and Beam

Figure 40 – MAESTRO .dat Sample File

To modify the .dat file for beam and depth, scaling factors multiply the nodes' beam (z) and depth (y) coordinates. For depth, all nodes' (y) coordinates are multiplied by D_{NEW}/D_{PARENT} . For beam, all nodes are multiplied by B_{NEW}/B_{PARENT} . Changes in hull separation can also

increase or decrease the overall beam. This is accomplished by changing the (z) coordinates of the outriggers where: $Z_{NEW} = [HullSep - (B_{NEW} / B_{PARENT} * 10.27)]$. HullSep is the desired hull separation (input) measured from the centerline to the center of an outrigger. Figure 40 is a sample of the MAESTRO .dat file showing where length, beam, and draft are modified.

5.2.2.2 Optimizing the New Hull Form in MAESTRO and Finding Structural Weight

Once the parent hull ship has been modified to reflect the current design's principle characteristics, scantlings are optimized for adequacy and minimum weight using MAESTRO's optimization function. Finally, the structural weight is calculated using the MAESTRO solver.

Problems encountered when implementing this method included:

- The MAESTRO Optimizer only optimizes one module at a time.
- MAESTRO doesn't update the .dat file with the new scantlings.
- The Optimizer converges while there are still inadequate strakes.
- As scantlings vary, the weight changes and this changes the loads on a floating structure.

The SDI runs the MAESTRO optimizer for one module then updates the .dat input file to run MAESTRO again for the next module. However, this approach increases the run time from a few minutes to a non-desirable few hours. The SDI also searches the output file from the last MAESTRO module run for the new scantlings then reads and writes them back into the .dat file in the correct places. The module optimization order starts at the middle of the ship structure and works its way to the bow and stern, alternating sides. This order is performed because the middle of the ship has the greatest bending moments and affects the modules towards the bow and stern. The parent hullform has 25 modules broken into 5 substructures of 5 modules each. The program starts by optimizing module 3 of substructure 3 then module 2 of substructure 3, then module 4 of substructure 3, then module 1 of substructure 3 and so forth until module 1 of substructure 1 and module 5 of substructure 5 are optimized. The complete order is as follows:

1. Module 3 of Substructure 3
2. Module 2 of Substructure 3
3. Module 4 of Substructure 3
4. Module 1 of Substructure 3
5. Module 5 of Substructure 3
6. Module 5 of Substructure 2
7. Module 1 of Substructure 4
8. Module 4 of Substructure 2
9. Module 2 of Substructure 4

10. Module 3 of Substructure 2
11. Module 3 of Substructure 4
12. Module 2 of Substructure 2
13. Module 4 of Substructure 4
14. Module 1 of Substructure 2
15. Module 5 of Substructure 4
16. Module 5 of Substructure 1
17. Module 1 of Substructure 5
18. Module 4 of Substructure 1
19. Module 2 of Substructure 5
20. Module 3 of Substructure 1
21. Module 3 of Substructure 5
22. Module 2 of Substructure 1
23. Module 4 of Substructure 5
24. Module 1 of Substructure 1
25. Module 5 of Substructure 5

The problem of MAESTRO converging while there are inadequate strakes is because MAESTRO has the option of rounding scantlings to discrete numbers. This occurs after optimization takes place. During the rounding process, some strakes that were previously adequate from optimization become inadequate after rounding. To solve this, the discrete option was not used in optimizing the scantlings. The ability to use libraries of discretized stiffeners and plate thicknesses directly in the MAESTRO optimization, and the ability to perform a global ship optimization would be very valuable.

The problem of weight changes during optimization and resulting changes in draft and trim for hydrostatic balance in MAESTRO does not support the global ship optimization where displacement is an independent design variable and is fixed for a given structural optimization. MAESTRO would have to compensate for changes in structural weight with changes in loads which it is not able to do. This global algorithm will be reconsidered and possibly changed, but a temporary solution treats the ship as a non-floating structure without self weight. Bending moment curves are calculated using the ABS guide for high speed naval craft [24]. Equations (10) and (11) are longitudinal sagging and hogging maximum bending moment equations specific to trimaran hull forms.

$$\text{MaxM}_s = 110.0 * C_1 * \text{Length}^{**2} * (2 * \text{HullSep} + 2 * \text{SideBeam}) * (C_B + 0.7) \quad (10)$$

$$\text{MaxM}_h = -190.0 * C_1 * \text{Length}^{**2} * (2 * \text{HullSep} + 2 * \text{SideBeam}) * C_B \quad (11)$$

where $C_1 = 10.75 - ((300.0 - \text{Length})/100.0)^{**1.5}$.

These maximum bending moments are applied to the ship in accordance to Figure 41.

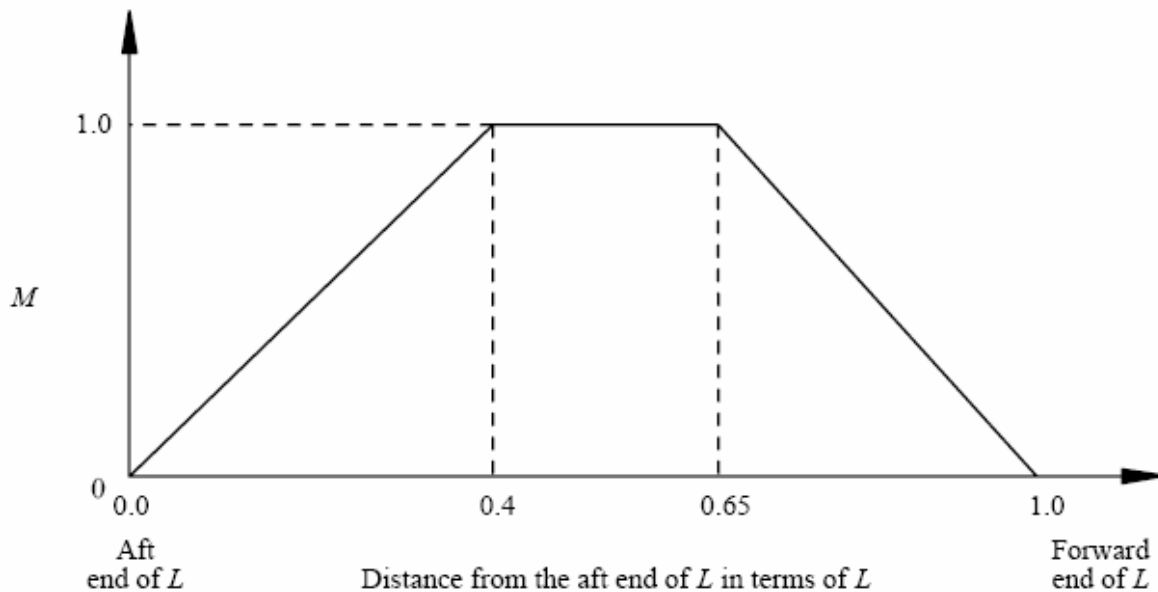


Figure 41 – Bending Moment Distribution [24]

This approach eliminates balancing. When each module is optimized it is treated as a cut structure including the module on either side with an external bending moment applied at the cuts in accordance with Figure 41. Once the entire ship is optimized, a final run is performed to calculate the structural weight. This is purely an analysis run for self weight. Gravity is turned on to allow MAESTRO to calculate total mass.

5.2.2.3 Model Center MAESTRO Wrapping Script

MAESTRO is “wrapped” using Analysis Server (AS) for use in Model Center (MC). The wrapper allows the MAESTRO optimization to be executed as a single component and linked to other components in MC. The particular wrapper for MAESTRO performs the following functions:

1. Reads the global design variable inputs from Model Center.
2. Writes an input file for modifying the .dat file.
3. Runs the SDI FORTRAN code that modifies the .dat file.
4. Runs the MAESTRO optimizer for the first module.
5. Runs the SDI updating the .dat file with new scantlings for the first module.
6. Repeats Steps 4 and 5 for all the modules.
7. Runs MAESTRO for the final analysis to find the optimized structural weight.
8. Retrieves the structural weight from the MAESTRO output.
9. Sends the structural weight back to Model Center.

Since this wrapper calls MAESTRO so many times, run time for one ship design can take up to a few hours.

5.2.2.4 Creating a Design of Experiments and Response Surface Model

The MAESTRO structural design interface component can be run in MC as a structural weight module in the ship synthesis model or a DOE can be performed to build a RSM for sufficient structural weight. Because of the long run time and efficiency of the RSM and DOE process, a RSM was created to replace the current ship synthesis model structural weight equation.

The first step in creating a RSM for structural weight is to generate a valid data set using a DOE. Each entry in the data set contains the input variables (length, beam, depth, hull separation, and block coefficient) and the output, structural weight. The DOE requires ranges for the input variables, and selection of the type of experiment. MC has a variety of experiment designs to choose from:

- Parameter Scan
- Box-Behnken
- Central Composite
- Eighth Fractional Factorial
- Face Centered Central Composite
- Foldover
- Full Factorial
- Half Fractional Factorial
- Latin-Hypercube
- Plackett-Burman
- Sixteenth Fractional Factorial

Phoenix Integration suggests the Latin-Hypercube design for this application since it takes a random sample of the design space. The Latin-Hypercube is similar to a Full Factorial design except that the design space is divided into discrete alternatives selected randomly to achieve a more thorough investigation of the design space. The Latin-Hypercube design allows the user to specify the number of alternatives to sample within the design space. Two Latin-Hypercube DOEs of 30 designs and 100 designs were performed to determine if additional designs significantly improved the response surface.

The run time for the 30 design DOE was about 2 days, and the run time for the 100 design DOE was about 1 week on our computer with a 3 GHz processor and 2 GHz of RAM. The data was collected in MC, input into the RSM tool, and response surfaces were created. The RSM tool has several different polynomial model types as described in Section 4.6. A response surface is created for every type of polynomial and compared to determine which has the best fit

to the data set. The 30 design data set did not have sufficient points to create surfaces with the full cubic and linear with cubic terms models. The 100 design data set did. There are 4 statistical checks to assess how well a polynomial response surface fits the data. The smaller the standard error, S, and the closer the coefficient of variation, CoV, is to 0%, the better the fit. There is also a better fit if the ratio of the regression sum of squares to the total sum of squares, R-Sq, is closer to 100%, and if the adjusted R-Sq is closer to R-Sq. By comparing S, CoV, R-Sq, and adjusted R-Sq for all the polynomial surface models, both 30 designs and 100 designs, it was determined that the 100 design full cubic response surface had the best and sufficient fit to the data. The statistical data comparing the 30 and 100 design runs is shown in Table 34. It can be seen that the CoV and the difference between R-SQ and adjusted R-SQ is smaller for 100 designs. No runs of more than 100 designs were run since the differences between 30 and 100 designs are so small it is unlikely to get closer results. The equation of this response surface model is then inserted in the structural bare hull weight calculation in the ship synthesis model.

This equation takes the form as follows:

| | |
|-------------------------|-----------|
| Depth | -1.47E+07 |
| Beam | 3.82E+06 |
| Length | 1.16E+06 |
| HullSep | -2.33E+06 |
| Cb | -1.04E+09 |
| Depth*Depth | 1.16E+06 |
| Beam*Beam | 6.43E+05 |
| Length*Length | -1.80E+03 |
| HullSep*HullSep | 2.17E+05 |
| Cb*Cb | 2.35E+09 |
| Depth*Beam | -1.27E+05 |
| Depth*Length | 2.09E+04 |
| Depth*HullSep | -6.83E+04 |
| Depth*Cb | 5.94E+06 |
| Beam*Length | -9.70E+03 |
| Beam*HullSep | 1.77E+05 |
| Beam*Cb | -3.16E+07 |
| Length*HullSep | 1.89E+04 |
| Length*Cb | -3.40E+06 |
| HullSep*Cb | -6.90E+06 |
| Depth*Depth*Depth | 9.80E+02 |
| Beam*Beam*Beam | -4.20E+04 |
| Length*Length*Length | 1.61E+00 |
| HullSep*HullSep*HullSep | -4.89E+02 |
| Cb*Cb*Cb | -1.48E+09 |
| Depth*Depth*Beam | -5.27E+04 |
| Depth*Depth*Length | -4.67E+01 |
| Depth*Depth*HullSep | -1.54E+04 |
| Depth*Depth*Cb | -7.32E+05 |
| Depth*Beam*Beam | 5.52E+04 |
| Depth*Beam*Length | -4.72E+02 |
| Depth*Beam*HullSep | 3.55E+03 |
| Depth*Beam*Cb | 2.38E+05 |
| Depth*Length*Length | -4.81E+01 |
| Depth*Length*HullSep | -4.95E+02 |
| Depth*Length*Cb | 7.65E+03 |
| Depth*HullSep*HullSep | 8.48E+03 |
| Depth*HullSep*Cb | 3.64E+05 |
| Depth*Cb*Cb | 1.61E+06 |
| Beam*Beam*Length | -1.33E+03 |

| | |
|------------------------|-----------|
| Beam*Beam*HullSep | 5.33E+02 |
| Beam*Beam*Cb | 3.88E+05 |
| Beam*Length*Length | 3.75E+00 |
| Beam*Length*HullSep | 1.66E+02 |
| Beam*Length*Cb | 6.21E+04 |
| Beam*HullSep*HullSep | -8.52E+03 |
| Beam*HullSep*Cb | -8.05E+04 |
| Beam*Cb*Cb | 1.04E+07 |
| Length*Length*HullSep | -1.28E+01 |
| Length*Length*Cb | 2.75E+03 |
| Length*HullSep*HullSep | -5.16E+02 |
| Length*HullSep*Cb | 2.88E+03 |
| Length*Cb*Cb | 1.47E+06 |
| HullSep*HullSep*Cb | -1.94E+05 |
| HullSep*Cb*Cb | 6.27E+06 |

where: Structural Weight = $2.05 \times 10^8 + (\text{constant in column 2}) * (\text{variable in column 1})$

Table 34 – 30 and 100 Design Run Statistical Data

| Number of Design Samples | Standard Error, S | Average Response | Coefficient of Variation, CoV | R-SQ | Adjusted R-SQ |
|--------------------------|---------------------|---------------------|-------------------------------|--------|---------------|
| 30 | 2.038×10^4 | 1.790×10^6 | 1.14% | 99.76% | 99.22% |
| 100 | 1.959×10^4 | 1.791×10^6 | 1.09% | 99.65% | 99.21% |

5.3 ALDV Ship Synthesis Model Design Space

In the ALDV case study each ship design is described using 16 design variables summarized in Table 35. The DV values for a design are selected by the MOGO from the range indicated and input into the ship synthesis model described in Section 4.1.2. The designs are balanced, assessed for feasibility, and objective attributes are calculated.

Table 35 - ALDV Design Variables (DVs)

| | Description | Lower Bound | Upper Bound | Discrete/Continuous |
|----|---|--------------------|---------------------------|---------------------|
| 1 | LWL Waterline Length | 156 m | 195 m | Continuous |
| 2 | VD Deckhouse Volume | 100 m ³ | 1200 m ³ | Continuous |
| 3 | CDHMAT Deckhouse Material | 1=steel | 2=aluminum | Discrete |
| 4 | BALtype Type of Fuel/Ballast Tanks | 0=clean ballast | 1=compensated fuel system | Discrete |
| 5 | PSYS Propulsion System | 1 | 9 | Discrete |
| 6 | Cman Manning Factor | 0.5 | 1 | Continuous |
| 7 | AAW Anti-Air Warfare System | 1 | 4 | Discrete |
| 8 | ASUW Anti-Surface Warfare System | 1 | 3 | Discrete |
| 9 | ASW Anti-Submarine Warfare System | 1 | 2 | Discrete |
| 10 | MCM Mine Counter Measures | 1 | 2 | Discrete |
| 11 | C4I Command, Control, Communication, Computer, Intelligence | 1 | 2 | Discrete |
| 12 | LAMPS | 1 | 4 | Discrete |

| | LAMPS Combat System | | | |
|----|--------------------------------------|---------|---------------------|----------|
| 13 | Ndegaus Degaussing | 0=none | 1=degaussing system | Discrete |
| 14 | Ncps Collective Protection System | 0=none | 2=full | Discrete |
| 15 | Ts Stores Duration | 20 days | 45 days | Discrete |
| 16 | TALDS Days of MEB Support | 3 days | 8 days | Discrete |

5.4 ALDV Optimization

The objective of optimization in the concept exploration phase of ship design is to identify non-dominated designs in the feasible design space. This is accomplished using a multi-objective genetic optimization in Model Center as described in Section 1.1.1. Through test runs it was discovered that the MOGO tends to locally optimize around certain discrete design variable values, particularly when the resolution for continuous variables is very fine and there are hundreds of continuous variable values being considered, and only a few values of discrete variables. This is very undesirable, so several possible solutions were tried. One solution is to have a single optimization run for each value of each discrete design variable and integrate the results. This is very computationally expensive. It was found that if the resolution of the continuous variables is kept as coarse as possible, and the mutation rate for discrete variables is much higher than for continuous variables, the problem is minimized. A two-part optimization process was devised. Part I is a broad multi-objective optimization created to select the discrete variable values and only roughly select continuous variable values. Part II fixes the discrete variable values based on preferred designs selected from the Part I non-dominated frontier, and optimizes the continuous variables with a much finer resolution. This also allows better use of Model Center's visualization tools which are intended primarily for exploring the relationship of continuous variables.

5.4.1 MOGO Optimization Part I

The MC MOGO is configured using the Darwin optimizer interface described in Section 4.3 and shown in Figure 27. In the MOGO interface window the objectives are specified as maximizing effectiveness (OMOE) while minimizing risk (OMOR) and cost (Average Follow Ship Acquisition Cost). The input (DVs) and their ranges from Table 35 are specified, and the following feasibility constraints are applied:

- Total arrangeable area required ratio must be > 0 .

- Deckhouse area required ratio must be > 0 .
- Sustained speed required ratio must be > 0 .
- Generator power required ratio must be > 0 .
- Minimum GM/B required ratio for stability and safety must be > 0 .
- Maximum GM/B required ratio to limit accelerations must be > 0 .
- Depth at station 10 required ratio must be > 0 .
- Endurance range required ratio must be > 0 .
- Sprint range required ratio must be > 0 .
- Transom width required ratio must be > 0 .
- Maximum total manning required ratio must be > 0 .

Next the optimization parameters, Figure 28, are specified for Part I. The population size for each generation is specified as 200. The selection scheme is selected for elitist. Elitist selection takes the worst design from the child population and replaces it with the best design from the parent population [4]. The optimizer is set to stop after 50 generations without improvement or a maximum of 150 generations. This convergence criteria requires a minimum 0.1 % change of the population to be considered an improved generation. The mutation probability for discrete variables is increased from 0.05 to 0.2. Other genetic operator parameters are maintained at their default values.

5.4.2 Part I Results

Figure 42 shows the effectiveness-cost-risk frontier generated by the genetic optimization. Each point in Figure 42 represents objective attribute values for a feasible non-dominated ship design. A 2D representation of the non-dominated frontier is shown in Figure 43. Non-dominated frontiers for different levels of risk (OMORs) are represented by different colors on the cost and OMOE plot. “Knees” in the curve are distinct irregularities at the top of steep slopes where substantial effectiveness improvement occurs for a small increase in cost. The “knees” are labeled as candidate designs for discussion. These designs are often the preferred possibilities for the customer.

The figures show that as cost and risk increase, effectiveness increases. The OMOE value is mainly driven by the ALDS mission cargo duration (T_{ALDS}). Increasing T_{ALDS} greatly increases the OMOE. However, increasing T_{ALDS} also increases the weight and size of the ship, which leads to a higher cost.

For this case study the discrete variable values of non-dominated Design #23 are chosen to be used in Part II. This design is chosen because it is a distinct “knee” on the curve. It has an OMOR of 0.2953 and an OMOE of 0.3434 with a follow ship cost of \$572.27 million. Table 36 summarizes the design variable values for Design #23.

Table 36 - Design Variables Summary

| Design Variable | Description | Trade-off Range | Design 23 Values |
|-----------------|------------------------------|---|--------------------|
| LWL | Waterline Length | 156 m – 195 m | 187 m |
| VD | Deckhouse Volume | 100 m ³ – 1200 m ³ | 600 m ³ |
| CDHMAT | Deckhouse Material | 1 = steel, 2 = aluminum | 1 = steel |
| BALtype | Type of Ballast | 0 = clean ballast, 1 = compensated fuel system | 0 = clean ballast |
| PSYS | Propulsion System | 9 Options | Option 3 |
| Cman | Manning Coefficient | 0.5 – 1.0 | 0.8985 |
| AAW | Anti-Air Warfare | 4 Options | Option 4 |
| ASUW | Anti-Surface Warfare | 3 Options | Option 2 |
| ASW | Anti-Submarine Warfare | 2 Options | Option 2 |
| MCM | Mine Counter Measures | 2 Options | Option 2 |
| C4I | Control Systems | 2 Options | Option 2 |
| LAMPS | LAMPS | 4 Options | Option 4 |
| Ndegaus | Degaussing System | 0 = none, 1 = degaussing system | 0 = none |
| Ncps | Collective Protection System | 0 = none, 2 = full | 2 = full |
| Ts | Number of stores days | 20 days – 45 days | 34 days |
| Talds | ALDS cargo duration | 2 days – 8 days | 5 days |

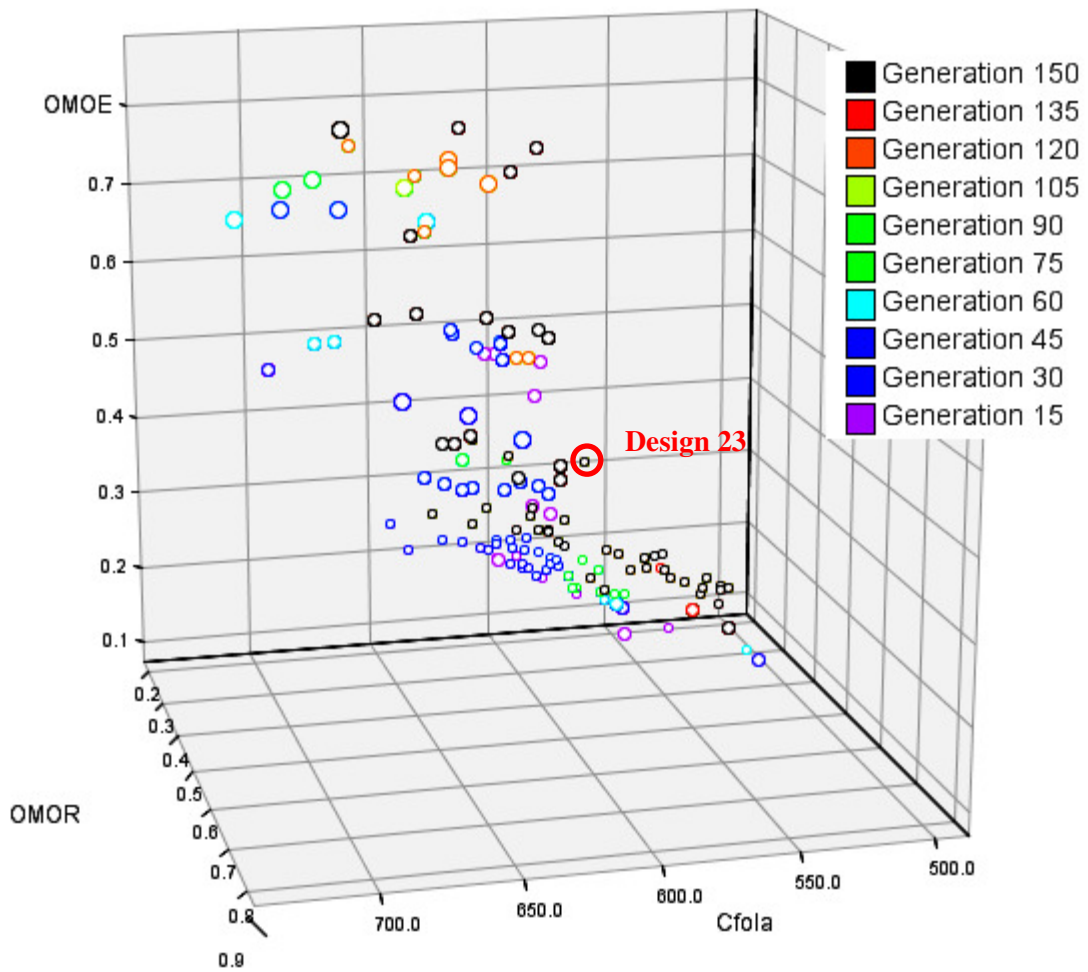


Figure 42 – 3-D Non-Dominated Frontier Part I

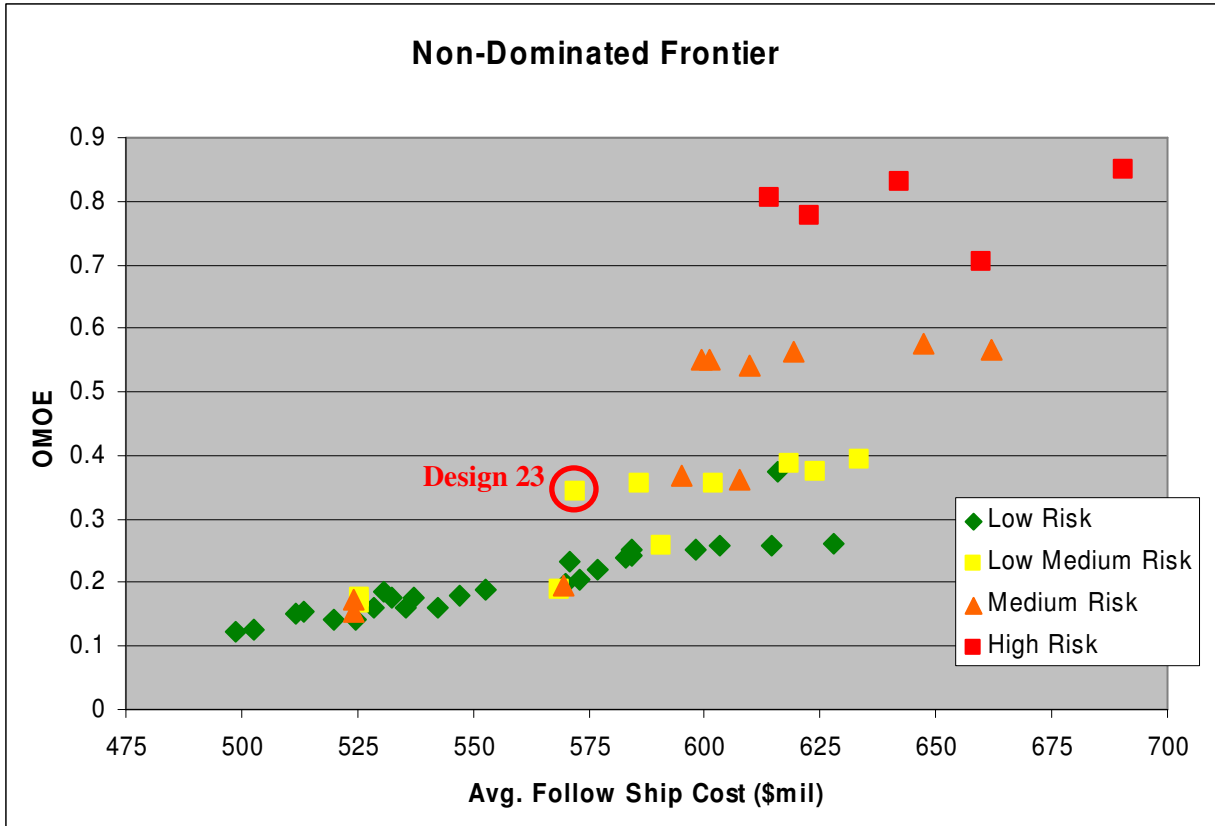


Figure 43 – 2-D Non-Dominated Frontier Part I

5.4.3 MOGO Optimization Part II

Part II of the MOGO optimization is configured in the same manner as Part I. The main difference being the design variables used. All discrete variable values are fixed at the Design #23 values, Table 37. Risk is not used as an objective since the only continuous variable risk depends on is the manning and automation factor which is also fixed at its Design #23 value. This leaves only two continuous variables to optimize in Part II. Since ALDS mission cargo duration (T_{ALDS}) is such an important design variable, it is converted to a continuous variable, its resolution is increased, and it is also included as an optimization variable.

To add greater flexibility and higher resolution the hull model is changed from a simple geosim to allow the lengths, beams, and drafts to change independently of each other. In Part I only the LWL is varied and all other principle characteristics are scaled based on the ratio: LWL_{input}/LWL_{parent} . Now LWL, CHB (beam of the center hull), D10 (depth at station 10), and HullSep (distance from the centerline to center of an outrigger) are varied independently and all other principle characteristics are calculated using separate length, beam, and depth scaling factors. Table 38 summarizes these ranges and resolutions.

Table 37 – Discrete Values for Design #23

| Design Variable | Design 23 Values |
|-----------------|-------------------|
| CDHMAT | 1 = steel |
| BALtype | 0 = clean ballast |
| PSYS | Option 3 |
| Cman | 0.8985 |
| AAW | Option 4 |
| ASUW | Option 2 |
| ASW | Option 2 |
| MCM | Option 2 |
| C4I | Option 2 |
| LAMPS | Option 4 |
| Ndegaus | 0 = none |
| Ncps | 2 = full |
| Ts | 34 days |

Table 38 – Design Variable Ranges Part II

| Design Variable | Lower Bound | Upper Bound | Resolution |
|-----------------|--------------------|---------------------|-------------------|
| LWL | 156 m | 195 m | 0.1 m |
| CHB | 9.0 m | 12.5 m | 0.1 m |
| D10 | 9.5 m | 13.0 m | 0.1 m |
| HullSep | 11 m | 15 m | 0.1 m |
| VD | 100 m ³ | 1200 m ³ | 10 m ³ |
| TALDS | 2 days | 8 days | 0.1 days |

5.4.4 Part II Results and Conclusions

Figure 44 shows the results of Part II in a 2-D plot since risk is not involved. The limiting factor in this case is TALDS. Effectiveness is increased mainly with increasing the number of TALDS days. The space required for increased TALDS days is limited by the size of the ship. The ship size is limited by the propulsion system. Since the propulsion system is fixed in Part II the size is limited to satisfy the sustained speed threshold.

The high end Design #13 has an OMOE of 0.4982 with the same risk as Design #23 of Part I and a cost of \$550.3 million, \$22 million less than Design #23. Another point of interest is Design #8 with an OMOE of 0.3355 and cost of \$539.7 million. This cost about \$32.4 million less than the baseline Design #23 and has only slightly less effectiveness. Other significant knees in the Part II curve occur at design points 1, 3, 5, and 12. Table 39 shows a comparison of these significant designs. From Table 39 it can be seen that TALDS, which was established in Part I to affect OMOE the most, is closely related to length and center hull beam. Plotting these designs on the Part I 2-D Non-Dominated Frontier shows they have significantly higher effectiveness for the associated cost and risk, Figure 45.

Since the ship is no longer a geosim the length, beam, depth, and hull separation can vary independently allowing for principle characteristics which maximize speed and volume required for TALDS. This greater flexibility from having more independent variables leads to the more refined optimization noted in the previous paragraph. In Table 39 the geosim values corresponding to a particular LWL are shown in parenthesis. The actual values have a significant departure from the geosim values particularly with depth. Speed and TALDS can now be optimized with less dependence. Therefore allowing the variables to be independent of a geosim proves to be significantly important to the model.

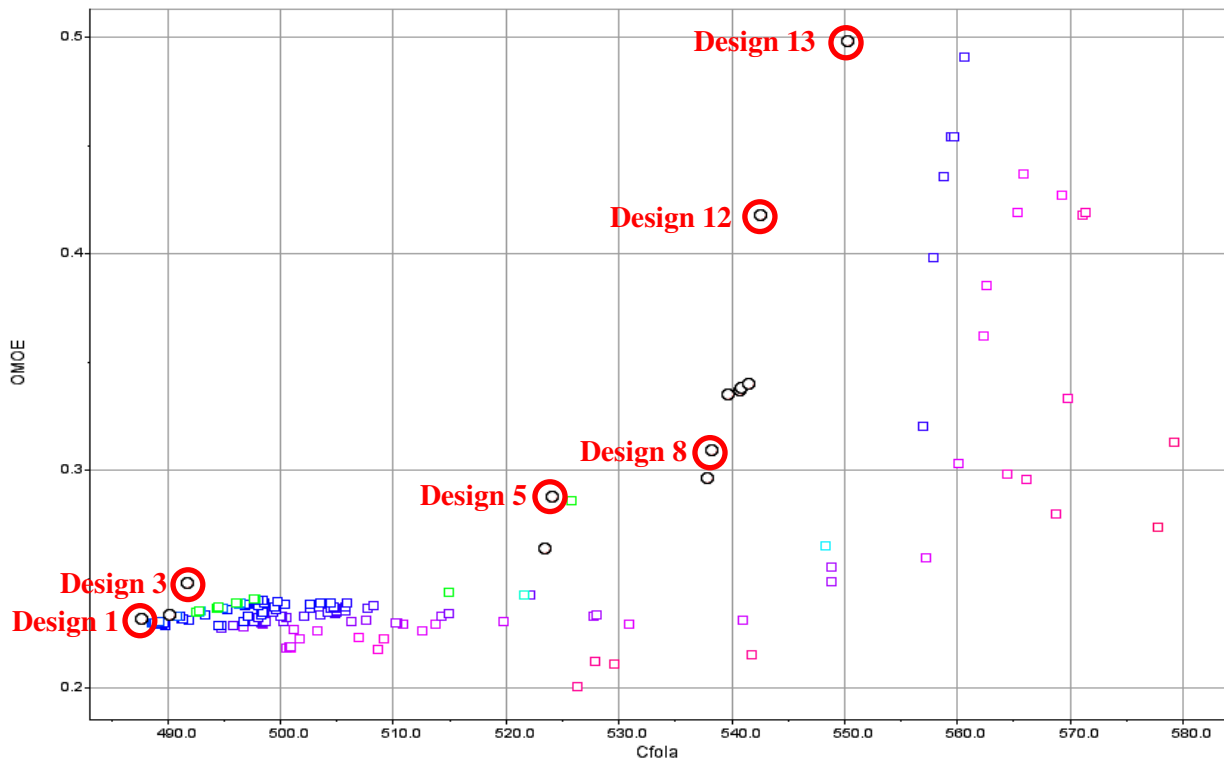


Figure 44 – Non-Dominated Frontier Part II

Table 39 – Significant Design Comparison

| Design | LWL (m) | CHB (m) | D10 (m) | HullSep (m) | VD (m ³) | TALDS (days) | V _s (knts) | E (nm) | Cost (\$M) | OMOE |
|-------------|---------|-------------|-------------|-------------|----------------------|--------------|-----------------------|--------|------------|--------|
| 23 (Part I) | 187.0 | (11.5) | (12.1) | (13.9) | 600 | 5.0 | 42.5 | 3236 | 572.3 | 0.3434 |
| 1 | 156.0 | 12.5 (9.6) | 9.5 (10.1) | 11.0 (11.6) | 380 | 2.0 | 46.1 | 7937 | 487.7 | 0.2313 |
| 3 | 158.1 | 12.5 (9.7) | 9.5 (10.2) | 11.1 (11.8) | 490 | 3.3 | 46.0 | 5143 | 491.8 | 0.2479 |
| 5 | 159.1 | 12.5 (9.8) | 11.1 (10.3) | 11.0 (11.8) | 460 | 4.4 | 43.1 | 3563 | 524.2 | 0.2883 |
| 8 | 181.5 | 12.4 (11.2) | 10.4 (11.8) | 11.6 (13.5) | 1180 | 4.8 | 44.7 | 3322 | 539.7 | 0.3355 |
| 12 | 166.5 | 12.4 (10.3) | 11.8 (10.8) | 11.2 (12.4) | 740 | 5.4 | 42.1 | 3307 | 542.6 | 0.4179 |
| 13 | 163.9 | 12.1 (10.1) | 12.6 (10.6) | 12.0 (12.2) | 690 | 6.0 | 41.1 | 2417 | 550.3 | 0.4982 |

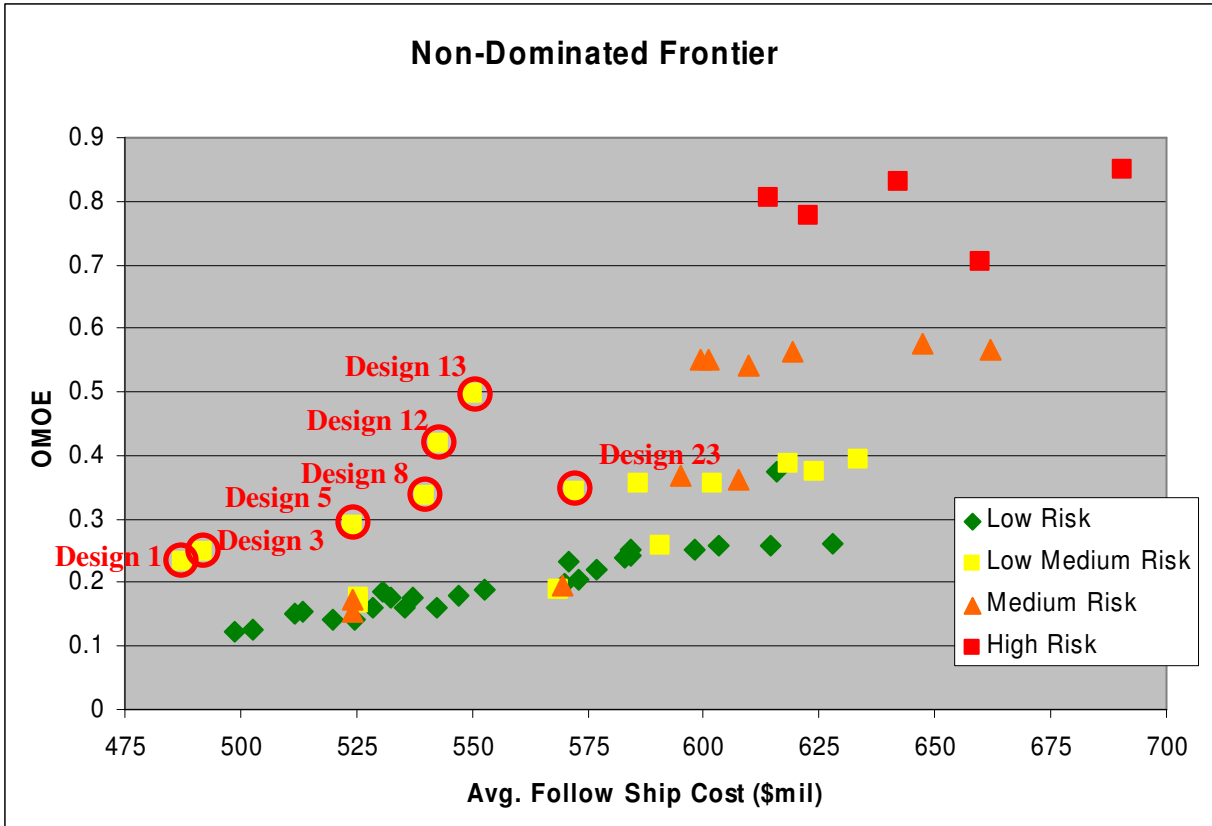


Figure 45 – Part I Non-Dominated Frontier with Part II Significant Designs

This case study shows that Response Surface Models and Design of Experiments simplify and speed up the process of a ship synthesis model. Finite element codes such as MAESTRO improve the accuracy of the ship synthesis models which in turn lower costs later in the design process. By using a more accurate structural weight equation the ship synthesis model is improved and closer represents the design later in the naval ship design process. By splitting the optimization process to pre-select discrete variables then run the optimization again to select the continuous variables yields non-dominated designs with higher effectiveness for a given cost and risk.

CHAPTER 6 CONCLUSIONS AND FUTURE WORK

6.1 OMOE Experiment Conclusions

A method is presented that uses the Analytic Hierarchy Process combined with Multi-Attribute Value Theory to build Overall Measure of Effectiveness and Overall Measure of Risk functions to properly rank and approximately measure the relative mission effectiveness and risk of design alternatives, using expert opinion to replace complex analysis tools.

This method is validated by comparing the ranking of 16 ships using two methods. The first method uses the OMOE and expert opinion and the second method uses the results of direct combat simulation. Results show that the OMOE function created from the expert opinion questionnaire average provides a good prediction of direct simulation results, proving this method can be an acceptable tool for ranking design alternatives in concept exploration ship optimization.

6.2 OMOE Experiment Future Work

Future work of this experiment can investigate if there is a need to include the experts as a level in the OMOE hierarchy. In this thesis all experts were considered to have equal experience and therefore their individual opinions were treated equal. If experts have different backgrounds and differing experience levels the AHP allows for weighting of the experts themselves by including them as a level in the hierarchy.

6.3 ASC Ship Synthesis Model Conclusions

This case study shows that Response Surface Models and Design of Experiments simplify and speed up the process of a ship synthesis model. Finite element codes such as MAESTRO improve the accuracy of the ship synthesis models which in turn lower costs later in the design process. By using a more accurate structural weight equation the ship synthesis model is improved and closer represents the design later in the naval ship design process. By splitting the optimization process to pre-select discrete variables then run the optimization again to select the continuous variables yields non-dominated designs with higher effectiveness for a given cost and risk.

6.4 ASC Ship Synthesis Model Future Work

This ship synthesis model is created to evolve with evolving technology and learned experience. As newer and more accurate software becomes available for ship disciplines they can be wrapped and substituted into this model. The MAESTRO model itself can be expanded to include a library of parent ship hull forms. As indicated in Chapter 5 many problems used temporary solutions that can be further researched and developed.

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APPENDIX A – DETAILED SHIP CLASS CHARACTERISTICS

[16]

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CG 47 Ticonderoga

These cruisers, when launched, ushered in a new age in coordinated air defense. The Aegis system is a set of fully integrated sensors and weapons systems, all working together to automatically detect, track, and engage large swarms of aircraft and missiles.

While having the capability for just about any surface warfare task, the Ticonderoga's were designed for one principle task; air defense. With large magazines for SM-2 missiles, plus the high sustained engagement rate of the Aegis system, these cruisers are generally the air defense backbone of every US carrier group. Ticonderogas cannot carry the longer range SM-2ER (extended range) version of the standard missiles, which means they should stay near the center of a formation (5 nm or so) where their air defense umbrella can be extended over all high value units. Like all US cruisers, these ships could use more point defense.

The first two ships of the class, the Ticonderoga and the Yorktown (the "baseline 0" ships), are not fitted to carry the LAMPS III Seahawk and so carrying the SH-Z Seasprite instead. They are otherwise the same as the follow-on Ticonderoga baseline 1.

Ship Type: CG -- Surface Combatant

Max Speed: 35 knots

General Armor: Light

Engineering Armor: Medium

Bridge Armor: Light

Sensor Armor: Light

Displacement: 7015 tons

Damage Points: 216

Length: 172.8 m

Crew: 358

Maximum Sea State: 5

| Detection Signatures | bow | side | stern |
|----------------------|-----|------|-------|
| Passive Sonar | 97 | 98 | 100 |
| Active Sonar | 25 | 40 | 25 |
| Visual | 238 | 297 | 237 |
| Infra-red | 138 | 227 | 168 |
| Radar | 208 | 267 | 208 |

Air Facilities:

Hangar X 2 Medium Aircraft

Pad with Haul-Down X 1 Medium Helo

Propulsion: LM 2500 COGAG

Sensors:

AN/SPS-55 360 (000 - 000)

AN/SPY-1A 360 (000 - 000)

AN/SPS-49(V)7 360 (000 - 000)

AN/SPQ-9A 360 (000 - 000)

AN/SPG-62 (Mk-99) BOW (225 - 135)

AN/SPG-62 (Mk-99) STRN (045 - 315)

AN/SLQ-32(V)3 (ESM BAND 1) 360 (000 - 000)

AN/SLQ-32(V)3 (ECM) 360 (000 - 000)

AN/SLQ-25 Nixie 360 (000 - 000)

Decca (Series) 360 (000 - 000)

LN-66 360 (000 - 000)

AN/SQS-53 BOW (225 - 135)

AN/SSQ-72 360 (000 - 000)

LowLight TV 360 (000 - 000)

Mounts:

127mm/54 Mk45 c20 BOW (225 - 135)
127mm/54 Mk45 c20 STRN (045 - 315)
Mk36 SRBOC c6 PF (270 - 360)
Mk36 SRBOC c6 SF (000 - 090)
Mk141 c4 PS (180 - 360)
Mk141 c4 SS (000 - 180)
12.7mm MG c100 PEA (180 - 315)
12.7mm MG c100 PEF (225 - 045)
12.7mm MG c100 SEA (045 - 180)
12.7mm MG c100 SEF (000 - 135)
Mk26 Mod 2 c64
Mk15 Block 0 CIWS c3 PS (180 - 360)
Mk15 Block 0 CIWS c3 SS (000 - 180)
Mk26 Mod 0 c24 BOW (225 - 135)
Mk50 Mod 2 Decoy Launcher c1 PMA +
Mk50 Mod 2 Decoy Launcher c1 SMA +
25mm/87 Mk38 Bushmaster c15 PEA (180 - 315)
25mm/87 Mk38 Bushmaster c15 SEA (045 - 180)
324mm Mk32 SVTT Triple c3 PS (225 - 315)
324mm Mk32 SVTT Triple c3 S (045 - 135)

Communications:

Link 11
AN/WSC-3
Link 14
Link 4A
VHF (Sec)
UHF (Sec)
U/W Telephone
SATCOM
AN/WSC-3A
LAMPS III Ship Datalink
Standard Command DL (Aegis)

Fuel Storage:

Gas Fuel X 2000
Diesel Fuel X 2000
Aviation Fuel X 20

Magazines:

Mk-46 NEARTIP c6
Mk-50 ALWT c6
20mm Mk-15 Mod 0 CIWS Burst c20
20mm Mk-15 Mod 0 CIWS Burst c20
127mm/54 Mk-42/Mk-45 c400
Mk36 SRBOC Magazine c96
SLQ-49 Magazine c8
Ticonderoga I/II c30

Ship Flags:

Refuel Astern In x 2
Refuel from Port x 2
Refuel from Starboard x 2
Replenish from Port x 2
Replenish from Starboard x 2

Helo in-flight refuel capable

DD 963 Spruance (VLS)

The original Spruance design was criticized as being under armed in comparison with similar Soviet vessels. With only two 127 mm guns, a woefully short-ranged Sea Sparrow launcher, and an ASROC launcher on its (at the time) oversized hull, it looked painfully inadequate. Lurking in that big hull, however, was possibly the quietest surface ship in service with a sonar array that rivaled that on the newest American attack subs. The Spruance was designed to find and kill subs before they could attack, even with horizon missiles. The primary ASW weapon of the Spruance is not ASROC, as in earlier ships, but its LAMPS helicopters, giving it a standoff range of over 60 miles. Even better, the Spruances from the outset were designed for modular replacement of sensors and weapons, allowing upgrades as newer equipment became available. This flexibility equipped with Tomahawk and HARPOON missiles and Mk41 VLS systems. Despite the addition since its design, the Spruance, even in its improved form is first and foremost an Anti-Sub platform.

Ship Type: DD -- Surface Combatant

Max Speed: 35 knots

General Armor: Light

Engineering Armor: Medium

Bridge Armor: Light

Sensor Armor: Light

Displacement: 5916 tons

Damage Points: 195

Length: 171.7 m

Crew: 346

Maximum Sea State: 6

| Detection Signatures | bow | side | stern |
|----------------------|-----|------|-------|
| Passive Sonar | 92 | 96 | 99 |
| Active Sonar | 25 | 40 | 25 |
| Visual | 238 | 296 | 238 |
| Infra-red | 138 | 226 | 168 |
| Radar | 208 | 266 | 208 |

Air Facilities:

Hangar X 2 Medium Aircraft

Pad with Haul-Down X 1 Medium Helo

Propulsion: LM 2500 COGAG

Sensors:

AN/SPS-40 SMA + SS + PS + PMA + PMF + PB

AN/SPS-55 360 (000 - 000)

AN/SPQ-9A 360 (000 - 000)

AN/SLQ-32(V)3 (ESM BAND 1) 360 (000 - 000)

AN/SLQ-32(V)3 (ECM) SMA + SS + PS + PMA + PMF + PB

AN/SLQ-25 Nixie 360 (000 - 000)

TAS (Mk 23) 360 (000 - 000)

AN/SPG-60 BOW (225 - 135)

LN-66 360 (000 - 000)

AN/SQR-19 360 (000 - 000)

AN/SQS-53 BOW (225 - 135)

AN/SSQ-104 360 (000 - 000)

Mk 91 FCS Radar STRN (045 - 315)

Mk 91 FCS ElectroOptical STRN (045 - 315)

Mounts:

127mm/54 Mk45 c20 BOW (225 - 135)

127mm/54 Mk45 c20 STRN (045 - 315)

Mk36 SRBOC c6 PS (225 - 315)

Mk36 SRBOC c6 S (045 - 135)

Mk141 c4 PS (180 - 360)

Mk141 c4 SS (000 - 180)

12.7mm MG c100 PEA (180 - 315)

12.7mm MG c100 PEF (225 - 045)
12.7mm MG c100 SEA (045 - 180)
12.7mm MG c100 SEF (000 - 135)
Mk29 NATO Sea Sparrow c8 STRN (045 - 315)
Mk15 Block 1 CIWS c4 SS + PS +
Mk15 Block 1 CIWS c4 SWF (315 - 135)
Mk50 Mod 2 Decoy Launcher c1 PA (180 - 270)
Mk50 Mod 2 Decoy Launcher c1 SA (090 - 180)
25mm/87 Mk38 Bushmaster c15 PS (225 - 315)
25mm/87 Mk38 Bushmaster c15 S (045 - 135)
324mm Mk32 SVTT Triple c3 PS (225 - 315)
324mm Mk32 SVTT Triple c3 S (045 - 135)
Mk41 VLS (3) (Spruance) c61 360 (000 - 000)

Communications:

Link 11
AN/WSC-3
URN-25
Link 14
VHF (Sec)
UHF (Sec)
AN/WSC-3A
LAMPS III Ship Datalink

Fuel Storage:

Gas Fuel X 1650
Aviation Fuel X 16

Magazines:

Mk-50 ALWT c12
20mm Mk-15 Mod 1 CIWS Burst c20
20mm Mk-15 Mod 1 CIWS Burst c20
127mm/54 Mk-42/Mk-45 c400
Mk36 SRBOC Magazine c96
SLQ-49 Magazine c8
Spruance (VLS) c290

Ship Flags:

Refuel Astern In x 2
Refuel from Port x 2
Refuel from Starboard x 2
Replenish from Port x 1
Replenish from Starboard x 1
Nuclear Shock Resistant
Helo in-flight refuel capable

DDG 51 Arleigh Burke

The US Navy's next generation destroyer, the Burke class incorporates VLS and Aegis fire control technologies from the initial design stages. Primarily intended to stop air attacks, the Burkes are also very capable anti-surface and anti-sub platforms, although the class lacks full helo facilities. Able to launch standard ZRM SAMs, Tomahawk and HARPOON SSMs, and potentially VL ASROC anti-sub weapons, the Burkes can be mission tailored merely by altering their weapons loadout. Future weapons can also be easily installed as long as they fit in the Mk41 launch cells, as the digital fire control systems are easily adapted to new weapons.

By 1996, with most of the old CGs, DDGs, and FFGs being scrapped or decommissioned, the Burkes will make up the bulk of out light carrier group escorts, with Spruances retained in the ASW role. The Burke is inferior to the newer Ticonderoga cruisers only in its slightly smaller weapons capacity and lack of helo facilities.

Ship Type: DDG -- Surface Combatant

Max Speed: 35 knots

General Armor: Medium

Engineering Armor: Medium

Bridge Armor: Light

Sensor Armor: Light

Displacement: 6625 tons

Damage Points: 210

Length: 153.8 m

Crew: 303

Maximum Sea State: 6

| Detection Signatures | bow | side | stern |
|----------------------|-----|------|-------|
| Passive Sonar | 95 | 96 | 98 |
| Active Sonar | 25 | 40 | 25 |
| Visual | 242 | 287 | 242 |
| Infra-red | 142 | 217 | 172 |
| Radar | 212 | 257 | 212 |

Air Facilities:

Pad with Haul-Down X 1 Medium Helo

Open Parking X 1 Medium Aircraft

Propulsion:

LM 2500 COGAG

Sensors:

AN/SPS-67 360 (000 - 000)
AN/SPG-62 (Mk-99) BOW (225 - 135)
AN/SPG-62 (Mk-99) STRN (045 - 315)
AN/SPS-64(iv) 360 (000 - 000)
AN/SPY-1D 360 (000 - 000)
AN/SLQ-32(V)3 (ESM BAND 1) 360 (000 - 000)
AN/SLQ-32(V)3 (ECM) 360 (000 - 000)
AN/SLQ-25 Nixie 360 (000 - 000)
AN/SQR-19 360 (000 - 000)
AN/SQS-53 BOW (225 - 135)
AN/SLQ-32(V)3 (ESM BAND 2) 360 (000 - 000)
AN/SSQ-104 360 (000 - 000)
LowLight TV 360 (000 - 000)

Mounts:

127mm/54 Mk45 c20 BOW (225 - 135)
Mk36 SRBOC c6 PF (270 - 360)
Mk36 SRBOC c6 SF (000 - 090)
Mk141 c4 PS (180 - 360)
Mk141 c4 SS (000 - 180)
12.7mm MG c100 PEA (180 - 315)
12.7mm MG c100 PEF (225 - 045)
12.7mm MG c100 SEA (045 - 180)

12.7mm MG c100 SEF (000 - 135)
Mk41 VLS (1) c29 360 (000 - 000)
Mk41 VLS (2) c61 360 (000 - 000)
Mk15 Block 1 CIWS c4 BOW (225 - 135)
Mk15 Block 1 CIWS c4 STRN (045 - 315)
25mm/87 Mk38 Bushmaster c15 PEA (180 - 315)
25mm/87 Mk38 Bushmaster c15 SEA (045 - 180)
324mm Mk32 SVTT Triple c3 PS (225 - 315)
324mm Mk32 SVTT Triple c3 S (045 - 135)

Communications:

Link 11
AN/WSC-3
Link 14
Link 4A
VHF (Sec)
UHF (Sec)
AN/WSC-3A
LAMPS III Ship Datalink
Standard Command DL (Aegis)

Fuel Storage:

Aviation Fuel X 10
Diesel Fuel X 1500

Magazines:

Mk-50 ALWT c12
20mm Mk-15 Mod 1 CIWS Burst c20
20mm Mk-15 Mod 1 CIWS Burst c20
127mm/54 Mk-42/Mk-45 c400
Mk36 SRBOC Magazine c96
Arleigh Burke c138

Ship Flags:

Refuel Astern In x 2
Refuel from Port x 2
Refuel from Starboard x 2
Replenish from Port x 1
Replenish from Starboard x 1
Helo in-flight refuel capable

FFG 7 Perry

A radical departure from previous frigate design philosophies, the Perry class missile frigates provide adequate all-around capability for a reasonable price. Carrying a Mk13 launcher in place of the ASROC carried on earlier designs, the Perry's have fair air defense capability using standard 1 MR missiles, as well as an anti-ship capability using HARPOONS.

Early construction FFG's, most of which are now in reserve, have hangar facilities which can accommodate the Seasprite LAMPS I, but not the larger Seahawk LAMPS III. Later flights can carry two Seahawks, giving them a much improved standoff ASW capability. With the retirement of the Adams and Coontz class destroyers, Perrys will be forced to take places in carrier battle groups (something they are not really capable of doing) until sufficient numbers of Arleigh Burke class destroyers become available. These ship have an aluminum superstructure and only one propeller. They were originally designed to fulfill the "low end" (quantity over quality) obligations of the US Navy.

Several allied nations now produce versions of the Perry class with slightly different loadout and sensors.

Ship Type: FFG -- Surface Combatant

Max Speed: 33 knots

General Armor: Light

Engineering Armor: Light

Bridge Armor: Light

Sensor Armor: Light

Displacement: 3169 tons

Damage Points: 102

Length: 135.6 m

Crew: 217

Maximum Sea State: 5

| Detection Signatures | | bow | side | stern |
|----------------------|-----|-----|------|-------|
| Passive Sonar | 95 | 96 | 98 | |
| Active Sonar | 22 | 39 | 22 | |
| Visual | 219 | 276 | 219 | |
| Infra-red | 119 | 206 | 149 | |
| Radar | 189 | 246 | 189 | |

Air Facilities:

Hangar X 2 Small Aircraft

Pad X 1 Small Helo

Propulsion: LM-2500 (Dual) Single Shaft

Sensors:

AN/SPS-55 360 (000 - 000)

STIR 360 (000 - 000)

AN/SPS-49(V)4 360 (000 - 000)

AN/SLQ-25 Nixie 360 (000 - 000)

AN/SQR-19 360 (000 - 000)

AN/SQS-56 BOW (225 - 135)

AN/SLQ-32(V)2 (ESM BAND 1) 360 (000 - 000)

AN/SLQ-32(V)2 Sidekick (ECM) 360 (000 - 000)

Mk 92 Mod 2 360 (000 - 000)

Mounts:

Mk36 SRBOC c6 PF (270 - 360)

Mk36 SRBOC c6 SF (000 - 090)

12.7mm MG c100 PS (180 - 360)

12.7mm MG c100 SS (000 - 180)

Mk15 Block 0 CIWS c3 STRN (045 - 315)

76mm/62 OTO Melara Comp c13 SMA + SS + PS + PMA + PMF +

Mk13 Mod 4 c40 BOW (225 - 135)

324mm Mk32 SVTT Triple c3 PS (225 - 315)

324mm Mk32 SVTT Triple c3 S (045 - 135)

Communications:

- AN/WSC-3
- URN-25
- Link 14
- VHF (Sec)
- UHF (Sec)
- AN/WSC-3A

Fuel Storage:

- Aviation Fuel X 64
- Diesel Fuel X 587

Magazines:

- Mk-46 NEARTIP c12
- Mk-50 ALWT c6
- 20mm Mk-15 Mod 0 CIWS Burst c20
- Mk36 SRBOC Magazine c96
- O.H.Perry c18

Ship Flags:

- Refuel Astern In x 2
- Refuel from Port x 1
- Refuel from Starboard x 1
- Replenish from Port x 1
- Replenish from Starboard x 1
- Passive or Single Stabilizers

APPENDIX B – SCENARIO LIST

Global Conflicts 1

Dawn Patrol (Russia): 1 squadron
Assault on Zion (Israel): 3 small surface vessels
White Death (Chile): 1 squadron
A Naval Border War (Ecuador): 2 squadrons, 3 small merchant ships, 1 diesel sub
Operation Ratcatcher (Sweden): 3 squadrons, 1 diesel sub
Ichon Again (US): 1 squadron
Lightning Bolt (South Africa): 2 squadrons, 2 diesel subs
Break the Blockade (Britain): 2 squadrons, 1 nuclear sub
To Protect the Queen (Britain): 1 squadron, 2 nuclear subs, 1 diesel sub
Okinawa (US): 2 squadrons, 3 nuclear subs
Malvinas Part II (Britain): 2 squadrons, 1 nuclear sub
Blood Feud (Taiwan): 1 squadron
Taking of Sakhalin (Japan): 1 squadron, 3 diesel subs
Black Sea Fleet (Russia): 2 squadrons, 1 nuclear sub, 1 diesel sub
A Fight to the Death (US): 1 squadron, 1 nuclear sub

Global Conflicts 2

Halfway to Haifa (US): 2 squadrons, 2 nuclear subs
Attack on Kamchatka (US): 1 squadron, 1 nuclear sub
Battle for Khusestan Part I (US): 1 squadron
Battle for Khusestan Part II (US): 1 squadron
Battle for Tehran (US): 1 squadron
Return to Yankee Station (US): 1 squadron, 2 nuclear subs
Bengali Bridges (US): 1 squadron, 1 nuclear sub
Red Sea Rescues (US): 2 squadrons, 1 nuclear sub
Those Futile Fjords (Soviets): 4 squadrons, 1 nuclear sub
The PLO Returns (Israel): 1 squadron
The Merge (US): 2 squadrons, 2 nuclear subs
Pretorian Gold (US): 1 squadron, 1 nuclear sub
Hunters (Soviets): 1 squadron, 1 nuclear sub, 1 diesel sub
Killers (US): 2 squadrons, 2 nuclear subs
Sea of Okhotsk (US): 1 squadron, 3 nuclear subs

Global Conflicts 3

Opening Moves (NATO): 3 squadrons, 4 diesel subs
Vodka or Sake (Soviets): 1 squadron, 2 nuclear subs
Rum Punch (US): 5 air squadrons, 1 aircraft
Panama Hats (US): 2 squadrons, 1 surface vessel (cutter)
Linchpin – Red (NATO): 1 squadron, 5 nuclear subs
Neutrality Violated (Soviets): 1 aircraft
Nordic Revenge (Soviets): 1 squadron
Retaking the Diego Garcia (US): 1 squadron, 2 nuclear subs
Airlane Gambit (US): 1 nuclear sub, 2 surface vessels (frigate)
Thief in the Night (US): 1 squadron, 6 nuclear subs
Battle of the Bay of Bengal (US): 3 squadrons, 1 nuclear sub
Bay of Pigs Part II (US): 3 air squadrons, 1 squadron
Polar Bears (US): 1 squadron, 1 nuclear sub
Second Battle of Tsushima Straights (Soviets): 1 squadron, 4 nuclear subs
Linchpin – Blue (US): 2 squadrons, 2 nuclear subs

Cold War

Air Lane Raiders (US): 1 squadron
Reinforcing the Northern Flank (NATO): 2 squadrons, 2 nuclear subs
Car Carrier Convoys (US): 11 surface vessels (6 merchant, 3 destroyers, 2 frigates)
Tremors (US): 3 squadrons, 16 surface vessels (7 tankers, 6 containers, 1 nuclear sub, 1 cutter, 1 cruise liner)
Enemy on Island (US): 3 air squadrons, 3 nuclear subs
Watch that First Step (US): 5 surface vessels (1 destroyer, 2 nuclear subs, 2 cutters)

Midway Revisited (US): 1 squadron
Bring Along Some Friends (US): 1 squadron
Vietnam Escort (US): 2 squadrons, 1 nuclear sub
Fish in a Barrel (US): 1 squadron
Black Sea Surprise (US): 2 nuclear subs
Visit to Valdez (US): 1 squadron, 2 nuclear subs, 2 surface vessels (cutters)
Battle of the North Sea (NATO): 2 squadrons, 14 surface vessels (drilling rigs)
End Run (US): 1 squadron
Battle of the Western Approaches (NATO): 2 squadrons

WestPac

Sanctions (US): 5 surface vessels (2 frigates, 2 destroyers, 1 cruiser)
Reunification by Force Part I (North Korea): 3 squadrons, 2 diesel subs
Reunification by Force Part II (North Korea): 5 squadrons, 2 diesel subs
Infiltration (North Korea): 4 surface vessels (patrol boats)
Battle for the Yellow Sea (US): 1 squadron
Block the Oil (Russia): 1 squadron, 3 nuclear subs, 3 surface vessels (2 frigates, 1 destroyer)
Defense of a Friend (US): 1 squadron, 2 nuclear subs
Phone Tap (US): 1 nuclear sub
Whose Islands are They (China): 2 squadrons
Australasian War Part I (ANZEF): 1 squadron, 1 diesel sub
Australasian War Part II (Singapore): 3 squadrons
Operation Big Bash (US): 1 squadron, 1 nuclear sub
Piracy (Malaysia): 5 surface vessels (small combatants)
Gunboat Diplomacy (Philippines): 9 surface vessels (small combatants)
Fish Stick Theory (Malaysia): 3 squadrons

Regional Conflicts 1

Fish Net (Japan): 3 squadrons, 2 diesel subs
The Rising (Japan): 3 squadrons, 2 diesel subs
The Gas Line (Japan): 2 squadrons, 2 diesel subs
Desperate Times (Japan): 2 squadrons, 1 diesel sub
The Fruit (Japan): 4 squadrons, 1 diesel sub
Fortune Cookies (UK): 1 nuclear sub
Women and Children First (UK): 1 squadron, 1 nuclear sub
A Fork in the Road (UK): 2 squadrons, 1 nuclear sub
Yellow Surprise (UK): 2 nuclear subs, 1 frigate, 5 surface vessels
The Grand Game (UK): 2 squadrons, 1 nuclear sub
The Eyes of Inchon (US): 3 squadrons, 2 nuclear subs, 1 frigate
Chaperones (US): 3 squadrons, 1 nuclear sub
Back War (US): 2 squadrons, 3 nuclear subs
A Tale of Two Oceans (US): 2 squadrons, 2 nuclear subs
The Beijing Split (US): 2 squadrons

Regional Conflicts 2

Flash Point (Iran): 2 patrol boats
Retribution (Iran): 4 patrol boats
A Tooth for a Tooth (Iran): 3 squadrons
Escalation (Iran): 4 squadrons
Kilo Patrol (Iran): 2 patrol boats, 3 diesel subs
Sons of Islam (Saudi Arabia): 2 squadrons
David and Goliath (Iran): 2 patrol boats, 5 squadrons
The Great Satan (US): 1 squadron, 1 nuclear sub, 1 cruiser
Cleansing (US): 1 squadron
Stand Down (Coalition): 3 squadrons
Pacification (Iran): 3 squadrons
Straight Jacket (Iran): 4 squadrons
Oman Revisited (Iran): 2 squadrons
Is a Formidable Foe (Iran): 4 squadrons
Are Quite Unaccustomed to Fear (US): 2 squadrons

Winner. Cheap Shot (France): 1 squadron
Runnerup Falklands War I (UK): 1 squadron, 3 diesel subs
Runnerup Fleet EX-95-3.2 (Blue Forces): 1 squadron, 1 nuclear sub, 1 ocean survey vessel
Runnerup Newfoundlands Scouts (NATO): 3 squadrons, 3 nuclear subs
Runnerup Seward's Folly (US): 1 squadron
Runnerup The Jugular (Japan): 2 squadrons, 3 diesel subs
Runnerup Caribbean Snowstorm (US): 4 DEA boats, 2 cutter, 2 nuclear subs, 1 squadron

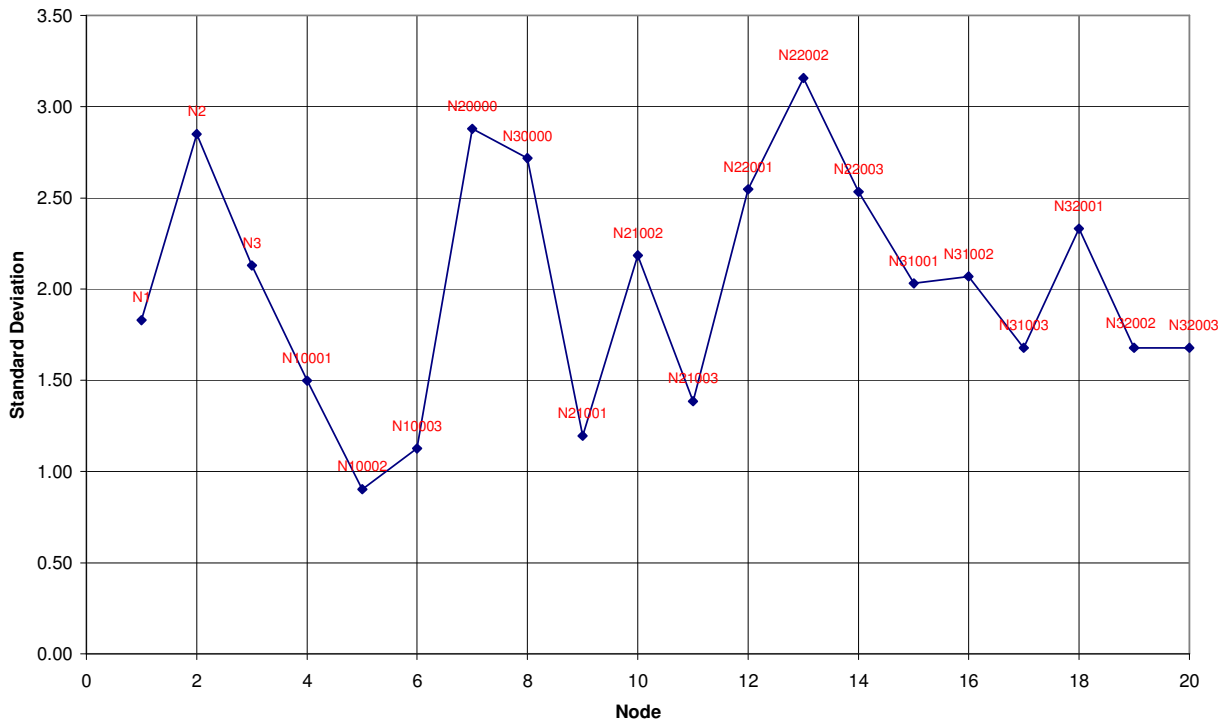
APPENDIX C – QUESTIONNAIRE DATA

| Name | N1 | N2 | N3 | N10001 | N10002 | N10003 | N20000 | N30000 | N21001 | N21002 | N21003 | N22001 | N22002 | N22003 | N31001 | N31002 | N31003 | N32001 | N32002 | N32003 |
|---------|-------|-------|------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| James | -2 | -4 | -3 | 7 | 9 | 5 | 7 | -5 | 4 | 9 | 4 | 9 | 9 | 9 | 5 | 9 | 3 | 7 | 5 | 2 |
| Mike | -5 | -7 | 3 | 7 | 9 | 3 | 1 | -5 | 3 | 5 | 1 | 1 | 1 | 1 | 7 | 9 | 5 | 7 | 7 | 1 |
| Dave H. | -7 | -6 | -2 | 7 | 9 | 7 | 4 | 3 | 3 | 5 | 2 | 3 | 7 | 4 | 1 | 3 | 1 | 1 | 3 | 1 |
| Jared | -8 | 1 | 5 | 4 | 9 | 4 | 1 | 4 | 1 | 3 | 1 | 1 | 1 | 1 | 2 | 6 | 2 | 5 | 8 | 5 |
| Dave C. | -5 | -7 | -3 | 5 | 7 | 5 | -5 | -3 | 3 | 5 | 3 | 3 | 5 | 3 | 5 | 7 | 5 | 3 | 5 | 3 |
| Justin | -7 | -3 | 3 | 5 | 9 | 5 | 1 | -5 | 5 | 9 | 5 | 5 | 9 | 5 | 3 | 6 | 3 | 1 | 4 | 1 |
| Jay | -6 | 3 | 2 | 3 | 7 | 5 | 3 | -3 | 2 | 4 | 3 | 4 | 7 | 4 | 6 | 9 | 6 | 4 | 7 | 5 |
| ave. | -5.71 | -3.86 | 1.57 | 5.43 | 8.43 | 4.86 | 2.00 | -2.57 | 3.00 | 5.71 | 2.71 | 3.71 | 5.57 | 3.86 | 4.14 | 7.00 | 3.57 | 4.00 | 5.57 | 2.57 |
| normal | -6 | -3 | 2 | 5 | 8 | 5 | 2 | -3 | 3 | 6 | 3 | 4 | 6 | 4 | 4 | 7 | 4 | 4 | 6 | 3 |
| outlier | -8/-2 | -7/3 | -3/5 | 3/7 | 7/9 | 3/7 | -5/7 | -5/4 | 1/5 | 3/9 | 1/5 | 1/9 | 1/9 | 1/9 | 1/7 | 3/9 | 1/6 | 1/7 | 3/8 | 1/5 |

| Normalized | N1 | N2 | N3 | N10001 | N10002 | N10003 | N20000 | N30000 | N21001 | N21002 | N21003 | N22001 | N22002 | N22003 | N31001 | N31002 | N31003 | N32001 | N32002 | N32003 |
|------------|-------|-------|------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| | -1 | -3 | -2 | 6 | 8 | 4 | 6 | -4 | 3 | 8 | 3 | 8 | 8 | 8 | 4 | 8 | 2 | 6 | 4 | 1 |
| | -4 | -6 | 2 | 6 | 8 | 2 | 0 | -4 | 2 | 4 | 0 | 0 | 0 | 0 | 6 | 8 | 4 | 6 | 6 | 0 |
| | -6 | -5 | -1 | 6 | 8 | 6 | 3 | 2 | 2 | 4 | 1 | 2 | 6 | 3 | 0 | 2 | 0 | 0 | 2 | 0 |
| | -7 | 0 | 4 | 3 | 8 | 3 | 0 | 3 | 0 | 2 | 0 | 0 | 0 | 0 | 1 | 5 | 1 | 4 | 7 | 4 |
| | -4 | -6 | -2 | 4 | 6 | 4 | -4 | -2 | 2 | 4 | 2 | 2 | 4 | 2 | 4 | 6 | 4 | 2 | 4 | 2 |
| | -6 | -2 | 2 | 4 | 8 | 4 | 0 | -4 | 4 | 8 | 4 | 4 | 8 | 4 | 2 | 5 | 2 | 0 | 3 | 0 |
| | -5 | 2 | 1 | 2 | 6 | 4 | 2 | -2 | 1 | 3 | 2 | 3 | 6 | 3 | 5 | 8 | 5 | 3 | 6 | 4 |
| ave. | -4.71 | -2.86 | 0.57 | 4.43 | 7.43 | 3.86 | 1.00 | -1.57 | 2.00 | 4.71 | 1.71 | 2.71 | 4.57 | 2.86 | 3.14 | 6.00 | 2.57 | 3.00 | 4.57 | 1.57 |
| variance | 3.35 | 8.12 | 4.53 | 2.24 | 0.82 | 1.27 | 8.29 | 7.39 | 1.43 | 4.78 | 1.92 | 6.49 | 9.96 | 6.41 | 4.12 | 4.29 | 2.82 | 5.43 | 2.82 | 2.82 |

| Normalized outlier dropped | N1 | N2 | N3 | N10001 | N10002 | N10003 | N20000 | N30000 | N21001 | N21002 | N21003 | N22001 | N22002 | N22003 | N31001 | N31002 | N31003 | N32001 | N32002 | N32003 |
|----------------------------|-------|-------|------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| | -4 | -3 | 2 | 6 | 8 | 4 | 6 | -4 | 2 | 4 | 0 | 0 | 8 | 0 | 4 | 8 | 2 | 6 | 4 | 1 |
| | -6 | -6 | -1 | 6 | 8 | 2 | 0 | -4 | 2 | 4 | 1 | 2 | 6 | 3 | 6 | 8 | 4 | 0 | 6 | 0 |
| | -7 | -5 | 4 | 6 | 8 | 3 | 3 | 2 | 0 | 2 | 0 | 0 | 0 | 0 | 1 | 5 | 1 | 4 | 7 | 0 |
| | -4 | 0 | -2 | 3 | 8 | 4 | 0 | -2 | 2 | 4 | 2 | 2 | 4 | 2 | 4 | 6 | 4 | 2 | 4 | 4 |
| | -6 | -6 | 2 | 4 | 6 | 4 | 0 | -4 | 4 | 8 | 4 | 4 | 8 | 4 | 2 | 5 | 2 | 0 | 3 | 2 |
| | -5 | -2 | 1 | 4 | 8 | 4 | 2 | -2 | 1 | 3 | 2 | 3 | 6 | 3 | 5 | 8 | 5 | 3 | 6 | 0 |
| ave. | -5.33 | -3.67 | 1.00 | 4.83 | 7.67 | 3.50 | 1.83 | -2.33 | 1.83 | 4.17 | 1.50 | 1.83 | 5.33 | 2.00 | 3.67 | 6.67 | 3.00 | 2.50 | 5.00 | 1.17 |
| normal | -5 | -4 | 1 | 5 | 8 | 4 | 2 | -2 | 2 | 4 | 2 | 2 | 5 | 2 | 4 | 7 | 1 | 3 | 5 | 1 |
| non-normal | -6 | -5 | 2 | 6 | 9 | 5 | 3 | -3 | 3 | 5 | 3 | 3 | 6 | 3 | 5 | 8 | 2 | 4 | 6 | 2 |
| variance | 1.22 | 4.89 | 4.00 | 1.47 | 0.56 | 0.58 | 4.81 | 4.56 | 1.47 | 3.47 | 1.92 | 2.14 | 7.56 | 2.33 | 2.89 | 1.89 | 2.00 | 4.58 | 2.00 | 2.14 |

Questionnaire Data Standard Deviation Plot



Appendix D – sample scenario summary form

Objective: Navigate your squadron to surround the peninsula and engage North Korea.

Victory conditions: Destroy 2 destroyers
Destroy 7 patrol boats
No loss of US units

Run Name: SHIP

Victory Conditions Met

| | | |
|-------------------------------|-------|----|
| Destroy 2 DD units | yes | no |
| Destroy 7 PG or PCM units | yes | no |
| No loss of US units | yes | no |
| If all met time of completion | _____ | |

Losses/ %Damaged:

US

North Korea

China

Comments By Player/ Observations of ship characteristics

APPENDIX E – ALDV MISSION NEED STATEMENT [23]

FOR AN

Advanced Logistics Delivery Ship – ALDV

1. DEFENSE PLANNING GUIDANCE ELEMENT.

The policy definition for the ALDV is based on four unclassified documents: “Forward...from the Sea,” the 2001 Quadrennial Defense Review Report, the Naval Transformational Roadmap, and Sea Power 21.

With the collapse of the Cold War, the Department of the Navy developed a new policy, called "Forward...from the Sea". This document outlines a significant change in priorities from a "Blue Water Navy fighting a traditional Super Power". This policy set forth a directive for the Navy and Marine Corps team to have faster and more conflict specific responses. Most recently, the Quadrennial Defense Review Report and the Department of the Navy's new whitepaper, “Naval Transformational Roadmap,” provide additional unclassified guidance and clarification on current DOD and USN defense policies and priorities.

The Quadrennial Defense Review Report identifies six critical US military operational goals. These are: protect critical bases of operations; assure information systems; protect and sustain US forces while defeating denial threats; deny enemy sanctuary by persistent surveillance, tracking and rapid engagement; enhance space systems; and leverage information technology.

The Naval Transformational Roadmap provides the US Navy's plan to support these goals using warfighting capabilities in the areas of Sea Strike – Projecting precise and persistent offensive power using strategic agility, maneuverability, ISR, and time-sensitive strikes; Sea Shield – Projecting global defensive assurance by projecting defense around allies, controlling the seas and countering threats; and Sea Base – Projecting joint operational independence using accelerated deployment and employment times and enhanced seaborne positioning of joint assets. Sea Power 21 also focuses on Sea Shield, Sea Strike and Sea Basing.

This Mission Need Statement specifically addresses the lack of an adequate logistics delivery solution that reduces cost, minimizes personnel in harms way and efficiently delivers large quantities of supplies to inland troops.

2. MISSION AND THREAT ANALYSIS.

a. Threat.

Adversaries may range from Super Powers to numerous regional powers, and as such the US requires increased flexibility to counter a variety of threat scenarios that may rapidly develop. There are two distinct classes of threats to US national security interests:

- (1) Threats from nations with a major military capability, or the demonstrated interest in acquiring such a capability. Specific weapons systems that could be encountered include ballistic missiles, land and surface launched cruise missiles, and significant land based air assets and submarines.
- (2) Threats from smaller nations who support, promote, and perpetrate activities which cause regional instabilities detrimental to international security and/or have the potential for development of nuclear weapons. Specific weapon systems include diesel/electric submarines, land-based and surface-launched anti-ship missiles, chemical/biological weapons and mines.

b. Required Mission Capabilities.

Enhance our ability to provide the following capabilities:

- (1) Transport supplies from off-shore seabase or logistic support (shuttle) ships to the coast.
- (2) Store dry and liquid cargo necessary to support a MEB ashore.
- (3) Assemble an Airborne Logistics Delivery System (ALDS).
- (4) Deliver supplies over the coast to inland troops by launching ALDS.

- (5) Support V-22 Osprey refueling operations.

Given the following significant constraints:

- (1) Minimize personnel in harms way.
- (2) Reduce cost.
- (3) Provide an efficient and reliable supply delivery method.

c. Need.

Current logistics delivery methods include:

- (1) Landing Craft, Air-Cushioned (LCAC) and convoy lines
- (2) Helicopter delivery
- (3) Air-drops

These methods are costly and/or put significant numbers of personnel in harms way. Convoy lines are slow and unreliable and endanger military personnel. Using helicopters to deliver supplies has also proven itself an inadequate solution. Helicopters make easy targets, thereby endangering personnel and expensive equipment. In addition, helicopters can only carry a limited amount of supplies and must maneuver from location to location to deliver the supplies to different areas. Air-drops have the same shortcomings as helicopters, but also create problems in that they need a land base from which to operate. Friendly land bases are not often nearby while performing missions in hostile territories.

There is a mission need for a system that efficiently and effectively delivers large quantities of supplies to inland troops in various locations while minimizing risk to personnel and equipment. The solution must be expendable, unmanned, safe, inexpensive, and easy to produce.

3. NON-MATERIAL ALTERNATIVES.

- a. Change the US role in the world by reducing international involvement.
- b. Increase reliance on foreign political and military support.
- c. Increase reliance on non-military assets and options to enhance U.S. performance of missions identified above; requiring a smaller naval force.

4. POTENTIAL MATERIAL ALTERNATIVES.

- a. Create a mortar launch delivery system.
- b. Higher altitude air-drops.
- c. Assign supply delivery responsibilities to aircraft carriers.
- d. Create a new ship (ALDV) with an expendable gilder delivery system (ALDS) that replenishes from off-shore base or logistic support (shuttle) ships.

5. CONSTRAINTS

- a. The platform must be non-nuclear powered, to keep down cost and manning.
- b. The platform must minimize cost.
- c. The platform must require low manning due to high levels of automation.
- d. The ALDS must be highly producible, minimal time from design to production.
- e. The ship must be able to operate in shallow water and high sea states.
- f. The platform must support the V-22 Osprey mission.
- g. The platform must be a high speed vessel for a rapid, 'just-in-time' delivery