Multi-Objective Optimization in Naval Ship Concept Design

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ABSTRACT

This paper proposes a total-ship system design and requirements definition methodology that includes important components necessary for a systematic approach to naval ship concept design. The methodology is described in the context of an Offshore Patrol Vessel (OPV) project conducted by senior undergraduate design students at Virginia Tech. Concept Exploration trade-off studies and design space exploration are accomplished using a Multi-Objective Genetic Optimization (MOGO) after significant technology research and definition. Objective attributes for this optimization are cost, risk (technology, cost, schedule and performance) and mission effectiveness. The product of this optimization is a series of cost-risk-effectiveness frontiers which are used to select alternative designs and define Operational Requirements based on the customer's preference for cost, risk and effectiveness.

The notional OPV requirement is based on an OPV Initial Capabilities Document and Virginia Tech OPV Acquisition Decision Memorandum (ADM). The OPV is intended to replace the in-service US Coast Guard (USCG) Medium Endurance Cutters (MECs) including 13 Famous Class cutters (82.3 meters, built in 1980s), 16 Reliance Class cutters (64 meters, built in 1960s) and 2 single cutters built in 1944 and 1968. These vessels are reaching or past their safe service life with capabilities that are inadequate for current USCG missions. The primary OPV mission functional areas and capabilities include: Port, Waterway and Coastal Security (PWCS); Search And Rescue (SAR); Drug Interdiction (DRUG); Migrant Interdiction (AMIO); Protect Living Marine Resources (LMR); Other Law Enforcement (OLE); and Defense Readiness (DR).

The selected OPV alternative is a low risk, low cost, knee-in-the-curve displacement monohull design on the cost-risk-effectiveness frontier. This design was chosen because it provides a sharp increase in effectiveness with a minimal increase in cost at a low cost and risk level based on the MOGO results.

The emphasis of this paper is on the concept exploration design and requirements process.

MOTIVATION & INTRODUCTION

The traditional approach to ship design is largely an 'ad hoc' process. Experience, design lanes, rules of thumb, preference, and imagination guide selection of design concepts for assessment. Often, objective attributes are not adequately quantified or presented to support efficient and effective decisions. This paper proposes a total-ship system design and requirements definition methodology (Figure 1) that includes important components necessary for a systematic approach to naval ship concept exploration (Brown 2005, Brown and Thomas 1998, Shahak 1998). These include:

- 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.
- 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.
- Practical and quantitative methods for measuring risk. An Overall Measure of Risk (OMOR) must include technology schedule, production, performance, and cost risk.
- An accepted cost model sensitive to important producibility characteristics, but with a level of detail appropriate for concept exploration.
- An efficient and robust method to search the design space for optimal concepts.
- An effective framework for transitioning and refining concept development in a multidisciplinary design optimization (MDO).
- A means of using the results of first-principle analysis codes at earlier stages of design.
- An efficient and effective search of design space for optimal or non-dominated designs.

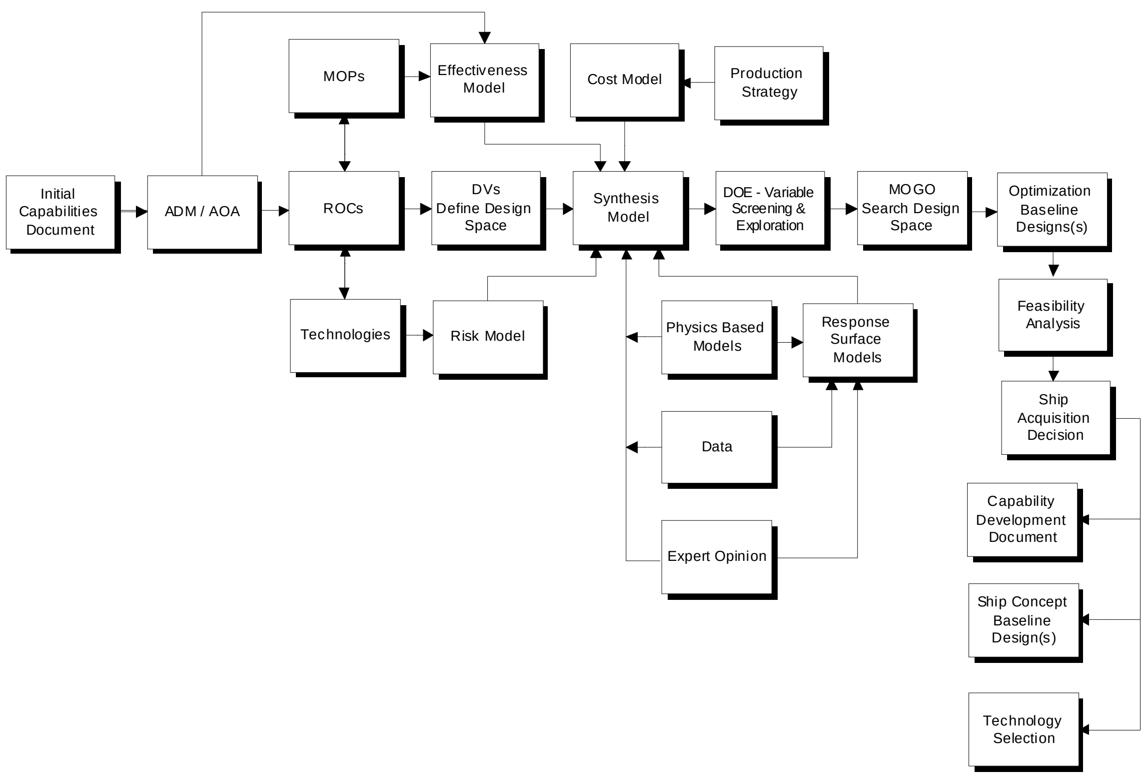

Figure 1 - Concept Exploration Process (Brown 2005)

The process uses a multiple-objective genetic optimization (MOGO) (Brown and Salcedo 2002) to search the design space and perform trade-offs. A simple ship synthesis model is used to balance the designs, assess feasibility and calculate cost, risk and effectiveness. Alternative designs 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.

MISSION DEFINITION

Concept Exploration (Figure 1) must consider those capabilities and design parameters that are necessary to perform the ship's mission, and that have a significant impact on ship balance, military effectiveness, cost and risk. The first step in this process is to develop a clear and precise mission definition and list of required operational and functional capabilities. The process must not begin by jumping into specific requirements or design characteristics. The process described in this paper is initiated by an Integrated Capabilities Document (ICD) that describes the required mission of OPV in the context of an integrated Deepwater acquisition program illustrated in Figure 2. Refinement of the ICD mission definition typically includes a Concept of Operations (CONOPs), Projected Operational Environment (POE), specific missions and mission scenarios, and Required Operational Capabilities (ROCs).

Figure 2 – USCG Deepwater

The USCG Deepwater Program acquisition also includes a new class of National Security Cutters (NSCs) to replace the current High Endurance Cutters (HECs) and Fast Response Cutters (FRCs) to replace current Patrol Boats (PBs). The OPV will bridge the gap between these designs. The primary OPV mission functional areas and capabilities include:

- Port, Waterway and Coastal Security (PWCS)
- Search And Rescue (SAR)
- Drug Interdiction (DRUG)
- Migrant Interdiction (AMIO)
- Protect Living Marine Resources (LMR)
- Other Law Enforcement (OLE)
- Secondary: Defense Readiness (DR)

Service life for this design is expected to be 2018-2050. This extended timeframe demands flexibility in upgrade and capability over time. Specific OPV capability gaps and requirements are listed in Table 1.

Table 1 – OPV Capability Gaps with Goals and Thresholds

Priority	Capability Description	Threshold Systems or metric	Goal Systems or metric
1	Mobility	Sustained speed = 20 knots Range = 5000 nm @14 knots Endurance = 30 days FAS capable	Sustained speed = 28 knots Range = 9500nm @14 knots Endurance = 60 days FAS capable
2	Aviation Support	Hangar and support for 1x SH-60, MH-60T or MH-65C and 1xVUAV	Hangar and support for 1xSH-60, MH-60T or MH-65C and 2xVUAV
3	Small Boat Support	Single stern ramp launch for 1x Short Range Prosecutor (SRP) or 1 x Long Range Interceptor (LRI)	Single stern ramp launch for 1 x Short Range Prosecutor (SRP) and 1 x Long Range Interceptor (LRI)
4	Combat Systems	SPS-73 radar MK 110 57 mm gun 2 x 50cal machine guns MK15 CIWS MK53 SRBOC/NULKA/SLQ32	EADS TRS 3-D radar MK 45 5in/54 gun 2 x 50cal machine guns MK15 CIWS MK 53 SRBOC/NULKA/SLQ32 CB&R citadel

OPV must be fully operational through SS5 (combat systems, aviation and boat), support limited operations through SS7 and survive in SS8. OPV must be able to tow up to its equivalent weight, and rescue multiple individuals directly from the water and cross-deck at forward and aft stations. OPV's Command, Control, Communication, Computers, Intelligence, Surveillance and Reconnaissance (C4ISR) equipment suite must be compliant with federal information security standards and be interoperable with the C4ISR systems of the National Security Cutter (NSC) and other assets. Reliability is a key performance parameter. Two propulsion shafts are required. OPV will be classed to ABS Navy Vessel Rules (NVR). OPV follow-ship acquisition cost must be less than $250M with IOC in 2020. Twenty-five ships of this class will be built.

TRADE STUDIES, TECHNOLOGIES, CONCEPTS AND DESIGN VARIABLES

Available technologies and concepts necessary to provide required functional capabilities are identified and defined in terms of performance, cost, risk, and ship impact (weight, area, volume, power). Trade-off studies are performed using technology and other design variables to select trade-off options in a multi-objective genetic optimization (MOGO) for the total ship design.

A displacement monohull hull form similar to NSC (Figure 3) was used as a parent hull form for OPV.

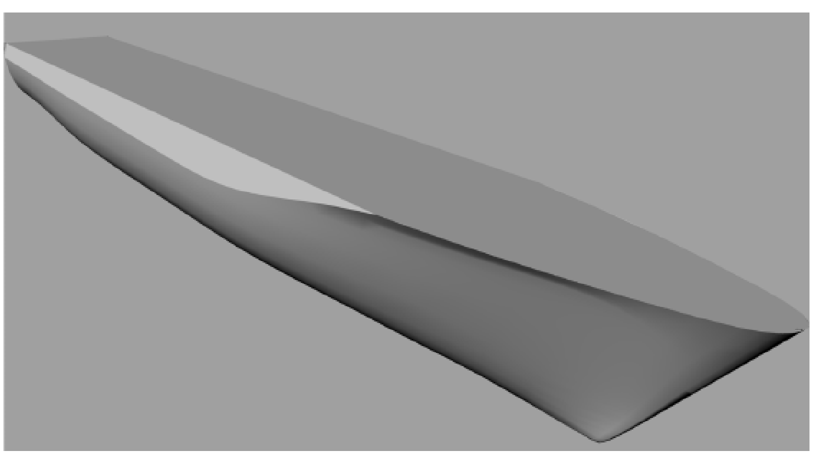

Figure 3 - OPV Parent Hull Form

This hull form was generated using Rhino/ORCA3D Hull Assistant software. Design variables and parameters in ORCA3D provide a flexible and consistent framework for specifying and modifying the hull form. The hull form design space for OPV is based on design lanes for similar designs consistent with the OPV mission with LOA equal to 90-110 meters, Length to Beam ratio of 6.6-7.6, Beam to Draft ratio of 2.7-3.2, Depth of 8.5-11.5 meters, Longitudinal Prismatic Control ratio of 0.25-0.5, and Transom Deck Width ratio of 0.8-0.9. A Design of Experiments (DOE) was run using Model Center software and Rhino/ORCA3D to develop a Response Surface Model (RSM) relating these design variables to resulting design characteristics (Figure 4). This allows the RSM to be used instead of repeated calls to Rhino/ORCA3D by the synthesis model and MOGO which greatly speeds up the design optimization process.

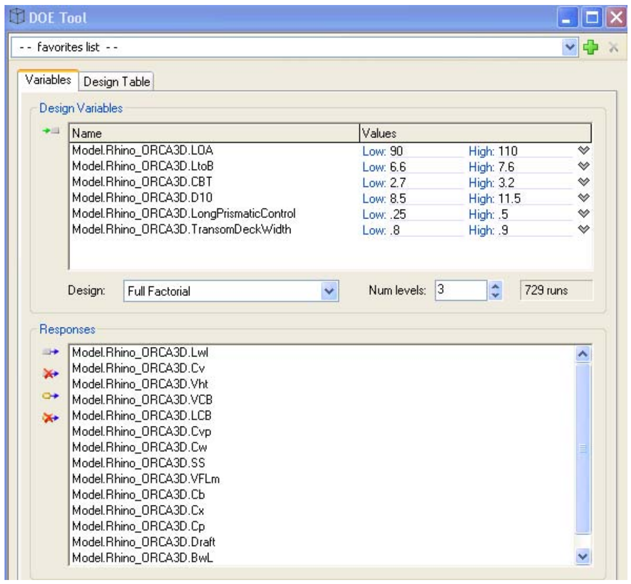

Figure 4 – Hull Form DOE/RSM in Model Center

General power and propulsion requirements for OPV were used to specify the power and propulsion design space illustrated in Figure 5. Two options are considered for the gas turbine boost engines: LM2500-PLUS (31 MW) and Rolls-Royce Spey MGT (19.5 MW); three options are considered for the diesel propulsion engines: CAT 3616 (5 MW), CAT 3618 (7.2 MW), and PC 2.5 V18 (8.7 MW); and three options are considered for the SSDGs: CAT 3508B (750 kW), CAT 3512B (1 MW) and CAT 3516B (1.5 MW).

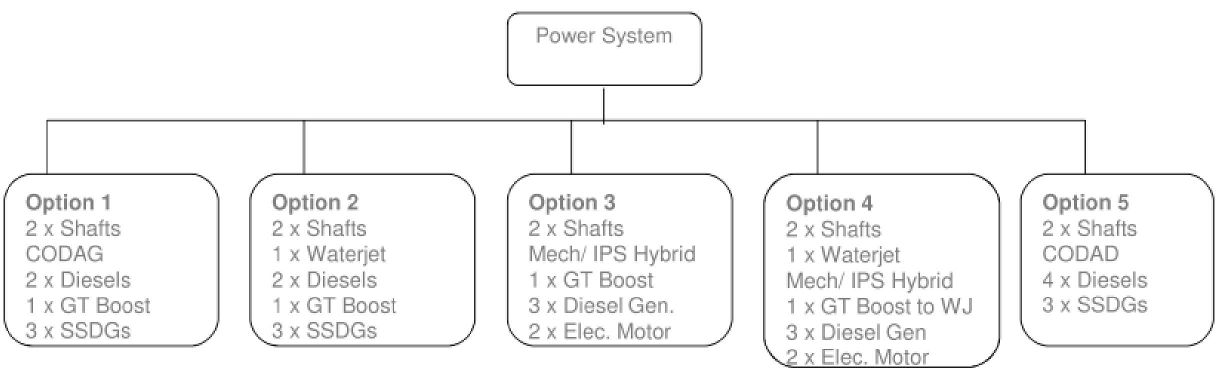

Figure 3 - OPV Propulsion and Power Trade-Off Alternatives

Manning is a major life cycle cost driver, but automation can impact reliability and acquisition cost. In concept exploration it is difficult to deal with automation manning reductions explicitly, so a ship manning and automation factor is used. This factor represents reductions from "standard" manning levels resulting from automation. The manning factor, C_{MAN}, varies from 0.5 to 1.0. It is used in the regression-based manning equations. A manning factor of 1.0 corresponds to a "standard" fully-manned and conventionally-automated ship. A ship manning factor of 0.5 results in a 50% reduction in manning and implies a large increase in automation. The manning factor is also applied using simple expressions based on expert opinion for automation cost, automation risk, damage control performance and repair capability performance.

Table 2 - OPV Design Space

DV	Description	Metric	Range
1	Length Overall (LOA)	meters	90-110
2	Length to Beam ratio (LtoB)		6.6-7.6
3	Beam to Draft ratio (BtoT)		2.7-3.2
4	Depth (D10)	meters	8.5-11.5
5	Longitudinal Prismatic Control ratio		0.25-0.5
6	Transom Deck Width ratio		0.8-0.9
7	Deckhouse Volume (VDH)	m3	1000-2000
8	Deckhouse Material Type	alternative	1 – steel, 2 – aluminum, 3 - composite
9	Propulsion System	alternative	1-5
10	Gas Turbine Boost Engine	alternative	1 – LM2500-PLUS 2 – RR Spey
11	Diesel Propulsion Engine	alternative	1 – PC 2.5 V18 (8.7 MW) 2 – CAT 3618 (7.2 MW) 3 – CAT 3616 (5 MW)
12	Ship Service Diesel Generator	alternative	1 – CAT 3516B (1.5 MW) 2 – CAT 3512B (1 MW) 3 – CAT 3508B (750 kW)
13	Manning and Automation Factor		0.5 – 1.0
14	AAW	alternative	1 – EADS TRS 3-D Radar, SLQ-32V2, MK 15 CIWS, IRST, MK 53 SRBOC/NULKA, TACAN, SSDS 2 - SEA GIRAFFE AMB, SLQ-32V2, MK 15 CIWS, IRST, MK 53 SRBOC/NULKA, TACAN, SSDS 3 - SLQ-32V2, MK 15 CIWS, IRST, MK 53 SRBOC/NULKA, TACAN, SSDS
15	ASUW	alternative	1 – MK45 5in/54, SPS-73 radar, 2 x ROSAM 50cal machine guns, OSS, small arms 2 - MK 3 57mm gun, SPS-73 radar, 1 x ROSAM 50cal machine gun, 1 x 50cal machine gun, OSS, small arms 3 - MK 3 57mm gun, SPS-73 radar, 2 x 50cal machine gun, OSS, small arms
16	C4ISR	alternative	1 – Enhanced C4ISR 2 – Basic C4ISR
17	HELO/UAV	alternative	1 - 1 x MH-65C, 2 x VUAV 2 - 2 x MH-65C, 2 x VUAV 3 – 1 x MH-65C, 1 x VUAV
18	BOAT	alternative	1 - 2 x SRP, 1 x LRI 2 - 1 x SRP, 1 x LRI
19	Degaussing System	alternative	0 – none, 1- degaussing system
20	Collective Protection System	alternative	0 - none, 1 - partial
21	Provisions Duration	days	45-60

A range of mission/combat system alternatives was identified, and ship impact was assessed for each configuration. The Analytical Hierarchy Process (AHP, Saaty 1996) and Multi-Attribute Value Theory (MAVT, Belton 1986) are used to estimate the Value of Performance (VOP) for each system alternative. These VOPs are included in the OMOE objective attribute calculation, Equation (1) and options are listed in Table 2.

Table 2 is the resulting design space for OPV. Twenty-one design variables are used. The optimizer chooses the design variable values from the range provided and inputs the values into the ship synthesis model. Once the design variable values are input into the ship synthesis model, the ship is balanced, checked for feasibility, and assessed based on risk, cost, and effectiveness. This process is described in the following sections.

SHIP SYNTHESIS MODEL

The ship synthesis model is necessary to balance and assess the feasibility of designs selected by the optimizer in Concept Exploration. Modules in the ship synthesis model are integrated and executed in the program Model Center (MC). Design variables and other inputs are compiled in the Input Module, which is linked to all of the other modules. There are 13 other modules, nine of which make up the primary ship synthesis model. The other four modules include Feasibility, Cost, Risk, and OMOE. The Feasibility Module determines the overall design feasibility of each OPV design by comparing available design characteristics to required design characteristics and checking for sufficient space, power and stability. The Cost, Risk, and OMOE Modules calculate the three objectives of the optimization process. The goal of optimization is to maximize effectiveness while minimizing cost and risk. The Multi-Objective Genetic Optimization (MOGO) is run in MC. Figure 6 shows the OPV ship synthesis model in MC. Measures of Performance (MOPs), Values of Performance (VOPs), an Overall Measure of Effectiveness (OMOE), Overall Measure of Risk (OMOR), and Average Follow Ship Acquisition Cost are calculated by the synthesis model.

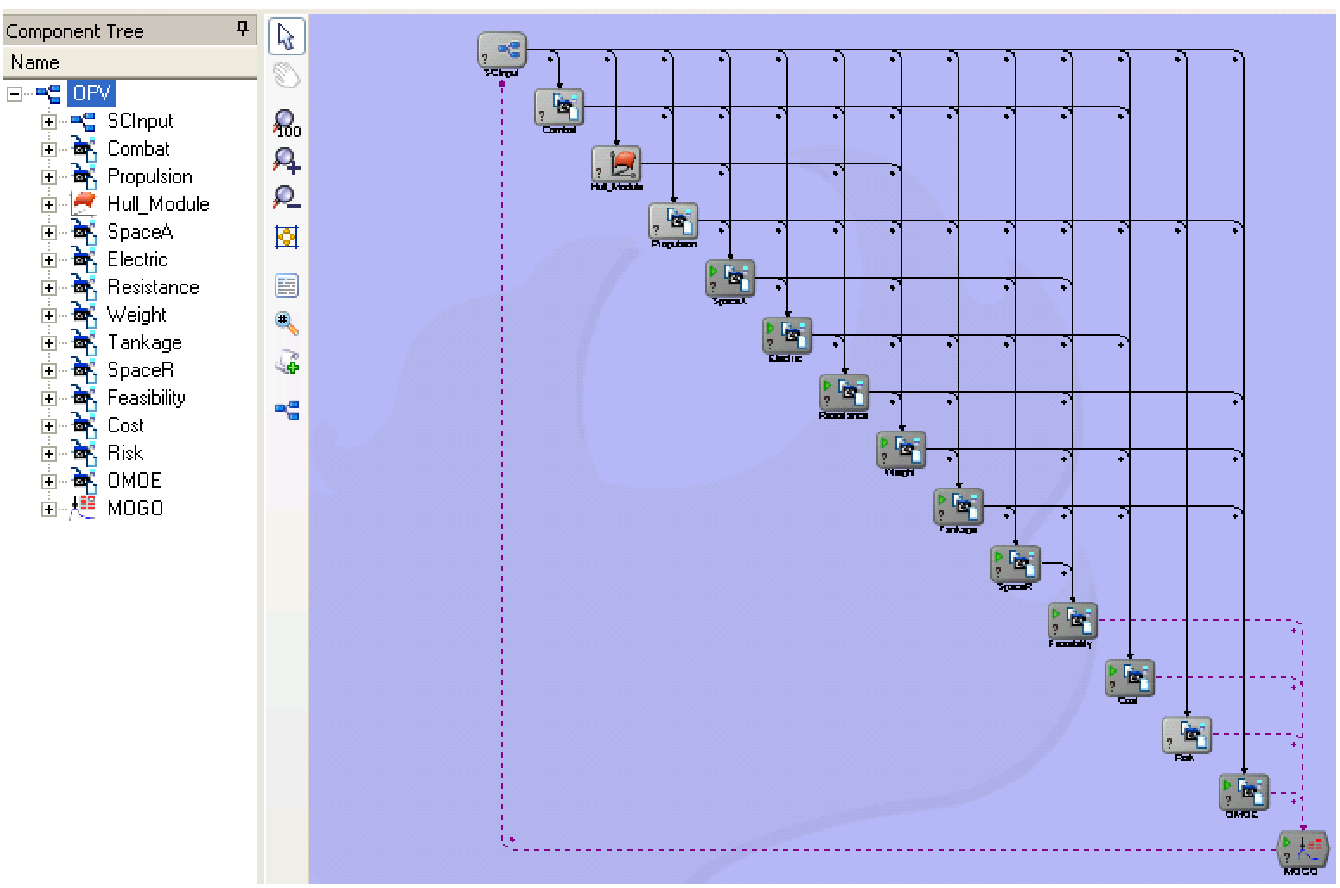

Figure 6 – OPV Ship Synthesis Model in Model Center (MC)

MULTI-OBJECTIVE GENETIC OPTIMIZATION (MOGO)

The OPV optimization requires mathematically-defined objective functions for effectiveness (OMOE), cost and risk (OMOR). Mission effectiveness, cost and risk have different metrics and cannot logically be combined into a single objective attribute. Multiple objectives associated with a range of designs must be presented separately, but simultaneously, in a manageable format for trade-off and decision-making. There is no reason to pay or risk more for the same effectiveness or accept less effectiveness for the same cost or risk. Various combinations of ship features and dimensions yield designs of different effectiveness, cost and risk. A non-dominated frontier represents designs with the highest effectiveness for a given level of cost and risk. Preferred designs must always be on the non-dominated frontier. The selection of a particular non-dominated design depends on the decision-maker's preference for cost, effectiveness and risk. This preference may be affected by the shape of the frontier and cannot be rationally determined a priori.

The first objective attribute developed for this optimization is an Overall Measure of Effectiveness (OMOE). Important terminology used in describing the process for developing the OMOE metric includes:

- 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.

There are a number of inputs which must be considered when determining overall mission effectiveness in a naval ship: defense policy and goals; threat; mission need; mission scenarios; modeling and simulation or war gaming results; expert opinion. All information about the problem can be included in a master war-gaming model to calculate resulting measures of effectiveness for a matrix of ship performance inputs in a sequence of probabilistic scenarios. Regression analysis could be applied to the results to define a mathematical relationship between input ship MOPs and output effectiveness. The accuracy of such a simulation depends on modeling the detailed interactions of an intricate human and physical system and its response to a large 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 is not yet available for practical applications.

An alternative to modeling and simulation is to use expert opinion directly to incorporate these various inputs, and assess the value or utility of ship MOPs in an OMOE function. This can be structured as a multi-attribute decision problem. Two methods for structuring these problems are Multi-Attribute Utility Theory (Belton 1986) and the Analytical Hierarchy Process (Saaty 1996). 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. This approach is adapted here for deriving an OMOE and OMOR (Brown 2005, Brown and Thomas 1998, Mierzwicki and Brown 2004)

Measures of Performance are determined based on ROCs and design variables (DVs). Goal and threshold values or options are identified for each MOP. MOPs are used in the ship synthesis model to calculate the Overall Measure of Effectiveness (OMOE).

Figure 7 shows the OMOE hierarchy for OPV. MOPs are grouped under three missions (Law Enforcement, Defense Readiness, and Humanitarian), each of which has three categories of MOPs (Mission, Mobility and Survivability). MOP weights are calculated using pair-wise comparison and expert opinion. Results are shown in Figure 8. MOP weights and value functions are finally assembled in a single OMOE function, Equation (1).

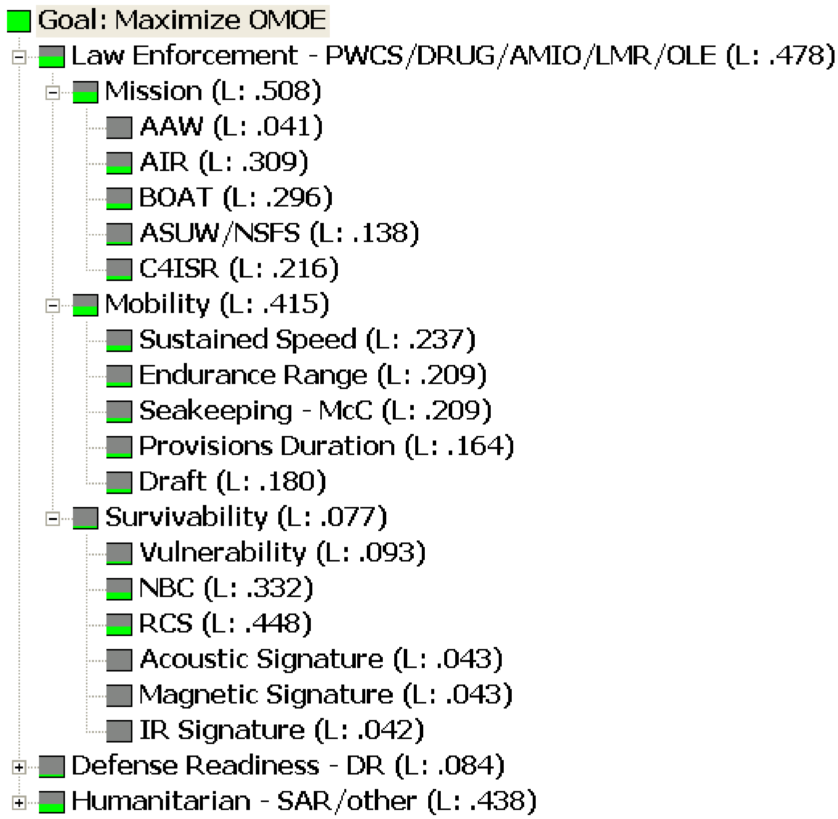

Figure 7 – OPV OMOE Hierarchy

$$OMOE = g\left[VOP_i\left(MOP_i\right)\right] = \sum_i w_i VOP_i\left(MOP_i\right) \qquad (1)$$

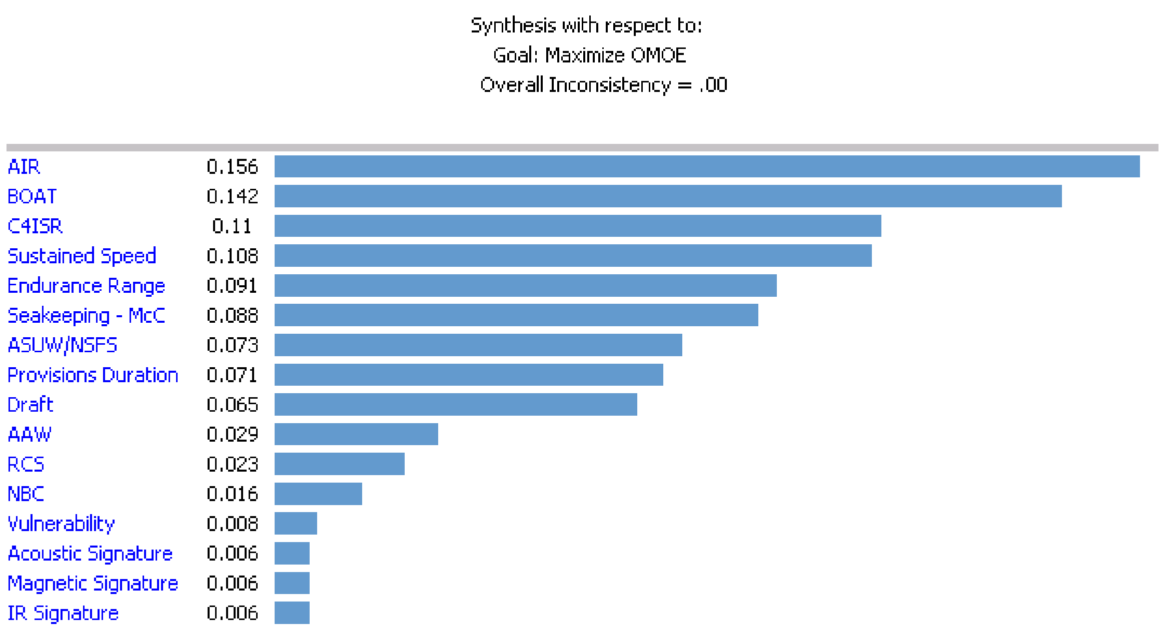

Figure 8 - OPV MOP Weights

The second objective attribute is an Overall Measure of Risk (OMOR) (Mierzwicki 2003, Mierzwicki and Brown 2004, DSMC 2001). The naval ship concept design process often embraces novel concepts and technologies that carry with them an inherent risk of failure simply because their application is the first of its kind. This risk may be necessary to achieve specified performance or cost reduction goals. Three types of technology risk events are considered in the OPV risk calculation: performance, cost and schedule. The initial assessment of risk performed in Concept Exploration is a very simplified first step in the overall Risk Plan and the Systems Engineering Management Plan (SEMP). After the ship's missions and required capabilities are defined and technology options identified, these options and other design variables are assessed for their potential contribution to overall risk. MOP weights, tentative ship and technology development schedules and cost predictions are also considered. Calculating the OMOR first involves identifying risk events associated with specific design variables, required capabilities, cost, and schedule. Once possible risk events are identified, a probability of occurrence, P_i, and a consequence of occurrence, C_i, is estimated for each event using Table 3 and Table 4. AHP and expert pair-wise comparison are used to calculate OMOR hierarchy weights, W_{perf}, W_{cost}, W_{sched}, w_i, w_j and w_k. The OMOR is calculated using these weights and probabilities in Equation (2).

$$OMOR = W_{perf} \sum_i \frac{w_i}{\sum_i w_i} P_i C_i + W_{cost} \sum_j w_j P_j C_j + W_{sched} \sum_k w_k P_k C_k \tag{2}$$

Table 3 - Event Probability Estimate

Probability	What is the Likelihood the Risk Event Will Occur?
0.1	Remote
0.3	Unlikely
0.5	Likely
0.7	Highly likely
0.9	Near Certain

Table 4 - Event Consequence Estimate

Consequence Level	Given the Risk is Realized, What Is the Magnitude of the Impact? Performance	Schedule	Cost
0.1	Minimal or no impact	Minimal or no impact	Minimal or no impact
0.3	Acceptable with some reduction in margin	Additional resources required; able to meet need dates	<5%
0.5	Acceptable with significant reduction in margin	Minor slip in key milestones; not able to meet need date	5-7%
0.7	Acceptable; no remaining margin	Major slip in key milestone or critical path impacted	7-10%
0.9	Unacceptable	Can't achieve key team or major program milestone	>10%

The third objective attribute in the optimization is cost. Figure 9 illustrates lead-ship acquisition cost components calculated in the cost model. The Basic Cost of Construction (BCC) is the sum of all SWBS group costs including engineering, assembly, and support. Construction costs are estimated for each SWBS group using modified weight-based equations that also consider important producibility characteristics. Follow-ship cost is calculated for the middle (N/2) ship in the run and includes cost reductions in ship assembly and support, and SWBS group cost reductions due to learning. OPV life cycle cost includes these acquisition costs plus selected operating and support costs (fuel and manning).

The Multi-Objective Genetic Optimization (MOGO) is performed in Model Center using the Darwin optimization plug-in. A flow chart for the MOGO is shown in Figure 10 (Brown and Salcedo 2002, Salcedo 1999). In the first design generation, the optimizer randomly selects 200 balanced ships using the ship synthesis model to balance each ship and to calculate cost, effectiveness and risk. Each of these designs is ranked based on their fitness or dominance in effectiveness, cost and risk relative to the other designs in the population. Penalties are applied for infeasibility and niching or bunching-up in the design space. The second generation of the optimization is randomly selected from the first generation, with higher probabilities of selection assigned to designs with higher fitness. Twenty-five percent of these are selected for crossover or swapping of some of their design variable values. A small percentage of randomly selected design variable values are mutated or replaced with a new random value. As each generation of ships is selected, the ships spread across the effectiveness/cost/risk design space and frontier. After 300+ generations of evolution, the non-dominated frontier (or surface) of designs is defined. Each ship on the non-dominated frontier provides the highest effectiveness for a given cost and risk compared to other designs in the design space.

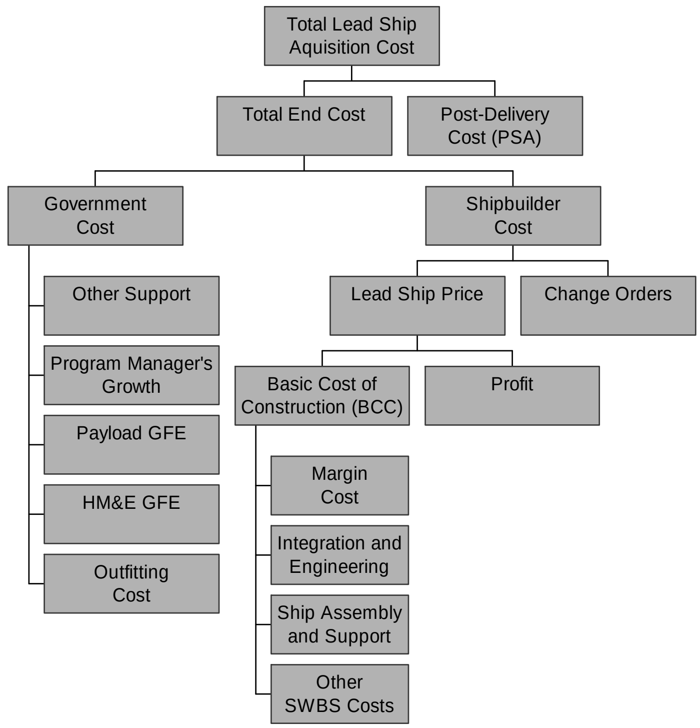

Figure 9 - Naval Ship Acquisition Cost Components

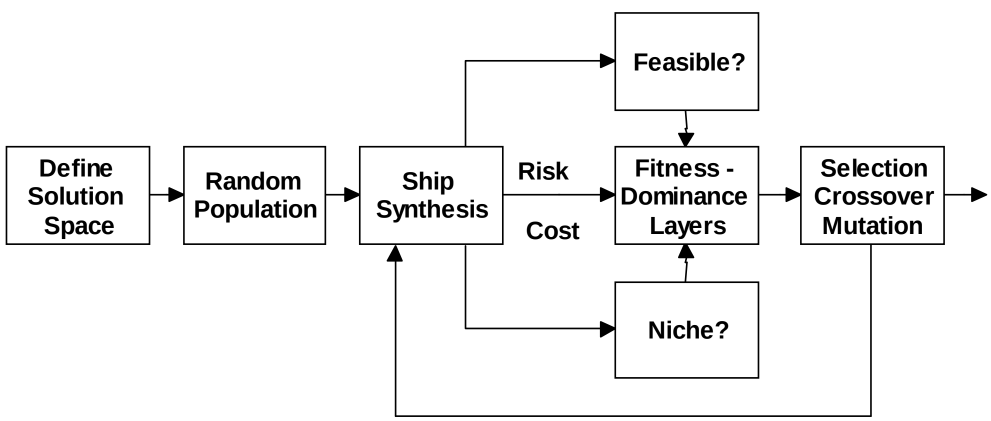

Figure 10 – Multi-Objective Genetic Optimization (Brown and Salcedo 2002)

RESULTS

Figure 11 and Figure 12 show the final effectiveness-cost-risk non-dominated frontier generated by the multi-objective genetic optimization (MOGO). Each point on the frontier represents objective attribute values for a feasible non-dominated ship design. Figure is a three-dimensional representation. Feasible designs are represented in Figure 12 with cost and effectiveness on the axes, and risk indicated by color.

Important (preferred) design possibilities for the customer are those that occur at the extremes of the frontier and at “knees” in the curve. The designs located at the “knees” are considered because they represent a sharp increase in effectiveness with a relatively small increase in cost at a particular level of risk.

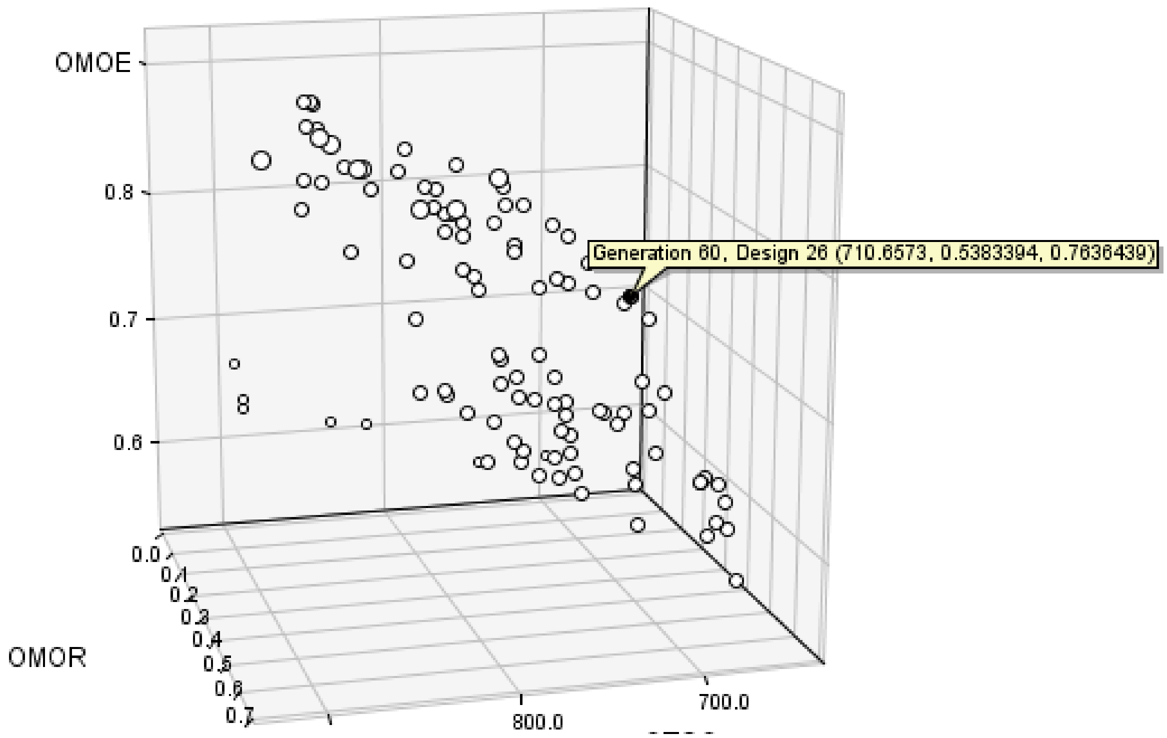

Figure 11 – 3-D Non-Dominated Frontier Generation Improvement

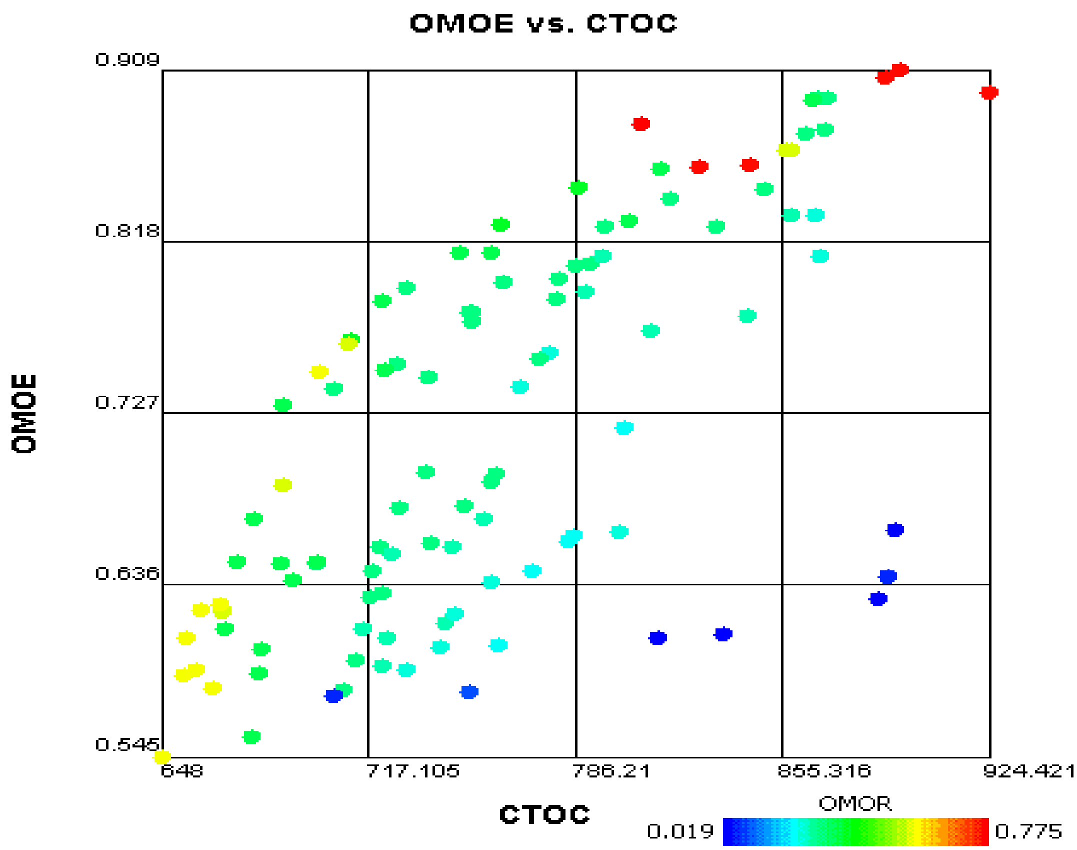

Figure 12 - Non-Dominated Frontier based on Total Ownership Cost

CONCLUSIONS

A process is demonstrated that performs Concept Exploration trade-off studies and design space exploration using a Multi-Objective Genetic Optimization (MOGO) after significant technology research and definition. Objective attributes for this optimization are cost, risk (technology cost, schedule and performance) and mission effectiveness. The product of this optimization is a series of cost-risk-effectiveness frontiers which are used to select alternative designs and define Operational Requirements based on the customer's preference for cost, risk and effectiveness.

A thorough search of the design space considering all combinations of design variables (vice considering only a limited trade-off matrix), and a demonstrated progression from less effective to more effective designs greatly increases confidence that the designs being considered (ND frontier) have the best possible effectiveness for a given cost and risk. The consideration of a broad range of designs, risk and cost provides a clear picture of their relationship to performance and effectiveness which enables a rational definition of requirements at the very beginning of the design process. This facilitates a subsequent cost as an independent variable (CAIV) approach that has a reasonable probability of achieving specified performance thresholds. Future work which considers model uncertainty will quantify the probability of achieving these thresholds.

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