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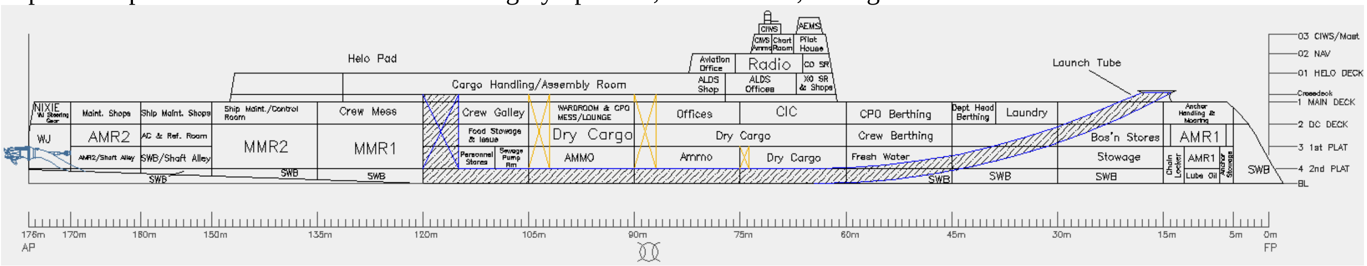

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Multi-Objective Concept Design of an Advanced Logistics Delivery System Ship (ALDV)

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 Advanced Logistics Delivery System Ship (ALDV) project conducted by senior undergraduate design students at Virginia Tech. This design won second prize in the 2005 ASNE/SNAME Dr. James A. Lisnyk Ship Design Competition. 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 ALDV requirement is based on an ALDV Mission Need Statement (MNS) and Virginia Tech ALDV Acquisition Decision Memorandum (ADM). ALDV is required to support troops ashore operating from a seabase or shuttle ship using an Advanced Logistics Delivery System (ALDS). ALDS is a ship-launched, over-the-beach, logistics delivery system that uses cargo-filled unmanned gliders and other revolutionary technologies. ALDS is an original concept developed by the Center for Innovation in Ship Design (CISD) at the Naval Surface Warfare Center – Carderock Division (NSWCCD) (Good et al. 2004). Necessary ALDS support by ALDV includes providing rapid transport of ALDS stores and ammunition, employing automated techniques for assembling the unmanned ALDS gliders, and providing a mechanical launching system for the gliders. ALDV must also support V-22 Ospreys and LAMPS, providing for launch and takeoff, landing, fueling, planning and control. ALDV will operate in sensitive littoral regions, close-in, depend on passive survivability and stealth, with requirements for high endurance and low manning.

The selected ALDV alternative is a low risk, low cost, knee-in-the-curve trimaran 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 risk level based on the MOGO results. ALDV has a wave-piercing bow to decrease wave resistance and improve high speed performance in waves. It has a tumblehome hullform and other stealth technology such as an Advanced Enclosed Mast/Sensor (AEM/S) to reduce radar cross section. ALDV has an ALDS Mission Bay located in the cross-deck for automated glider assembly, and a unique Linear Induction Motor (LIM) for mechanical launch of aircraft. It uses other automation technology such as watch standing technologies that include GPS, automated route planning, electronic charting and navigation (ECDIS), collision avoidance, and electronic log keeping. ALDV also employs automated cargo handling technologies such as conveyor belts, cargo elevators, robotic pickers, and radio frequency identification (RFID) (Good et al. 2005).

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 are:

- 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.

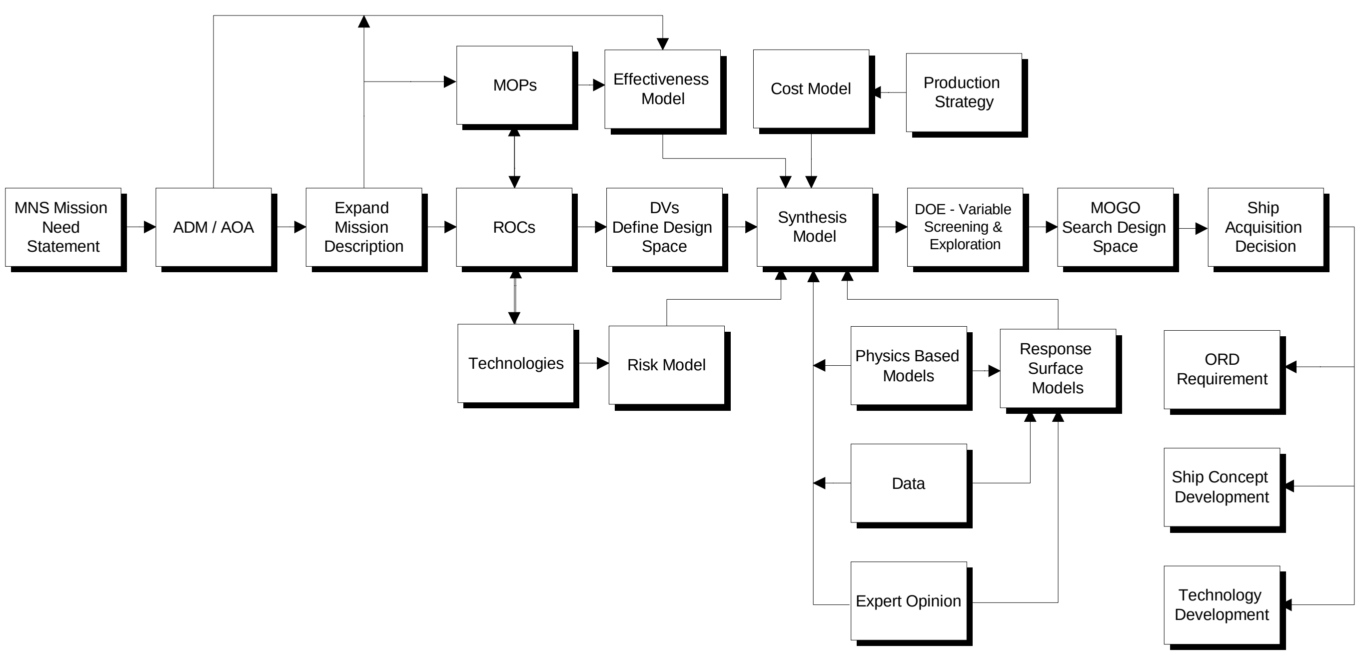

Figure 1 - Concept Exploration Process (Brown 2005)

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 may be initiated by a Mission Need Statement, as used under DoD 5000, or by an Integrated Capabilities Document (ICD) as is required today. Refinement of the mission definition typically includes a Concept of Operations (CONOPs), Projected Operational Environment (POE) and threat, specific missions and mission scenarios, and Required Operational Capabilities (ROCs).

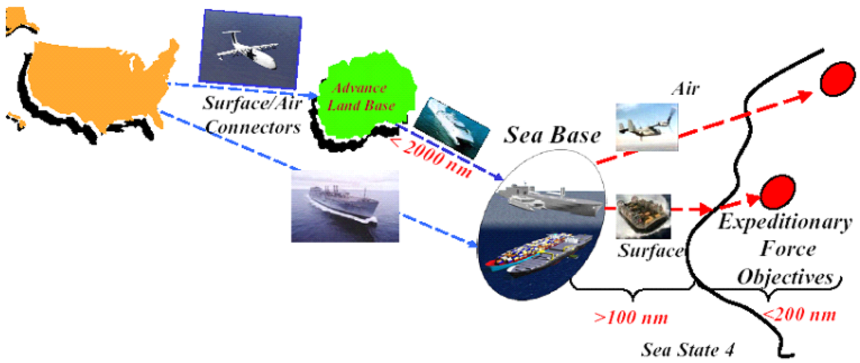

Figure 2 - ASN Seabase Operational Scenario (England et al. 2004)

The ALDV Concept of Operations (CONOPs) is based on a MNS for a ship-launched, over-the-beach Advanced Logistics Delivery System (ALDS) that solves the problem of establishing a safe and efficient logistics chain from a seabase (Figure 2) or from a logistics support ship to maneuvering troops ashore. ALDS is an original concept developed by the Center for Innovation in Ship Design (CISD) at the Naval Surface Warfare Center – Carderock Division (NSWCCD) (Good et al. 2004). The ALDV will travel from the seabase or blue water environment at high speeds to a location approximately 20 nautical miles off the coastline, where it will launch unmanned cargo-filled gliders to troops ashore (Figure 3). The ship must operate in "safe" waters, be escorted, or the design must provide for self-defense. ALDV will launch 233 gliders daily for a period of three to eight days to meet the landing force daily re-supply requirements for one Marine Expeditionary Brigade (MEB) (CNEL 1999). ALDV will function as a cargo distribution center. ALDV will deliver all of the MEB dry cargo needs and 10 percent of the MEB wet cargo needs to account for troops that are further inland and in hazardous areas where manned V-22 Ospreys are not a safe option.

The dry cargo includes food, ammunition, medical, and other supplies that a MEB requires per day, and the wet cargo includes 10 percent of the fuel and water that a MEB requires per day. ALDV must also carry the necessary components of the logistics delivery system, which includes unmanned gliders and small rockets to augment the glider range. ALDV will also support V-22 Osprey missions by providing a V-22 haven: at least one helicopter pad and refueling capabilities. The ALDV payload includes V-22 Osprey fuel to support long-range V-22 Osprey missions. A summary of the ALDV payload is listed in Table 1.

A typical twenty-four hour day includes time to launch the gliders, travel time along the coast, and general maintenance time. Launches may occur every two minutes resulting in 7.75 hours of launch time per day. The ship is assumed to travel 250 nautical miles along the coast at 40 knots for 6.25 hours. The remaining 10 hours of the day is used for maneuvering time, emergency launches, trips to and from the sea base, glider assembly, and general maintenance.

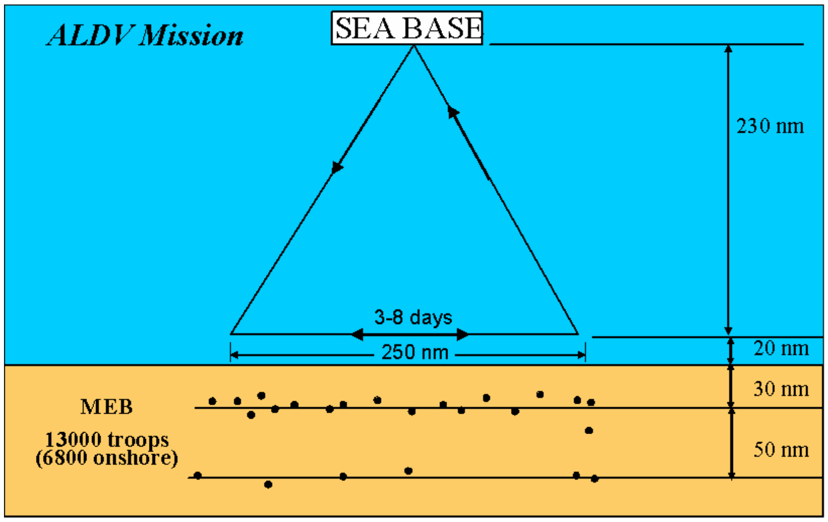

Figure 3 - ALDV Idealized Mission Schematic (Good et al. 2004)

Table 1 - ALDV Payload Breakdown (Good et al. 2005)

Type of Cargo	Weight of Cargo (short tons)	Total Percentage of Cargo
Dry Cargo	75	24%
Wet Cargo	41.5	13%
Rocket Weight	3.5	1%
Glider Weight	58	19%
V-22 Fuel	136	43%

Secondary missions of ALDV are to support V-22 logistics operations by providing helicopter landing and refueling facilities, and to support humanitarian aid missions.

The ALDV is to function in either a seabase operational environment or in conjunction with a shuttle ship. A seabase is envisioned as a collection of ships and other platforms at least 100 miles from shore that supports military littoral missions. Objectives of seabasing include: to minimize the operational reliance on shore infrastructure, enhance afloat positioning of joint assets, integrate joint logistics, and improve vertical delivery methods (England et al. 2004). ALDV is expected to operate the airborne delivery system in littoral regions, which may have a sea state between 0 and 5, and cruise in open water with sea states between 0 and 7. ALDV will either be escorted by a combatant vessel or be outfitted with self defense systems. Specific threats that could be encountered by ALDV include surface ships, high-speed boats, land and surface-launched cruise missiles, land-based air assets, mines, and diesel/electric submarines.

Specific mission scenarios and Required Operational Capabilities (ROCs) are developed based on the ALDV CONOPs, POE and mission types. Required functional capabilities are developed based on the ROCs, and if within the scope of the concept exploration design space, the ship's ability to perform these functional capabilities is measured by explicit Measures of Performance (MOPs), Table 3.

Included in ALDV's required capabilities are the following unique capabilities required to support ALDS:

- Employ automated techniques for assembling an airborne logistics delivery system. The unmanned gliders will be assembled at sea to provide on-demand logistics delivery with minimal manning requirements.
- Support a mechanical launching system for an air delivery system. A mechanical launching system such as a Linear Induction Motor (LIM) will be required to obtain the required glider launch speeds and accelerations.
- Store the dry and wet cargo necessary to support a MEB ashore. ALDV must store the food, ammunition, medical, and other dry supplies as well as some of the fuel/water needs of a MEB.

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.

The following general requirements were developed for hull and deckhouse:

- Threshold endurance range - 2500 nm at 20 knots (final requirement may be greater)
- Threshold sustained (sprint) speed - 40 knots
- Threshold sprint range - 250 nm
- Hull life - 30 years
- Safely launch and recover gliders in Sea State 5
- Long hull to allow for the launch of gliders
- Large deck area for V-22 Osprey refueling
- Large object space for glider factory and logistics suport
- Producible

An approximate Transport Factor (TF) was used to identify alternative hull types that could carry the loads required at a high speed (Kennell 1998). Four hullforms that would yield a modest to moderately high TF (10 – 30) at high speeds (40 – 50 knots) were selected for further review. These hullforms are:

- Surface Effect Ship
- Slender Monohull
- Catamaran
- Trimaran

A trimaran was ultimately selected for further concept exploration. The trimaran offers a compromise between the monohull and catamaran options. It is able to incorporate the length of a monohull with the transverse stability of the catamaran. The center hull can be designed to be long and slender and thereby give the length needed for the glider launching tube, and the two side hulls provide increased stability. Deck area is large, with the potential for a significant large object space in the cross structure. There are several disadvantages to the trimaran option. The Navy has no experience building trimarans, so ship acquisition cost would be higher than a monohull. Trimarans are also less structurally efficient with larger transverse bending moments than a monohull. Radar Cross Section (RCS) for a trimaran is also likely to be higher than a monohull, especially when taken end-on.

A trimaran parent hullform was developed for ALDV concept exploration based on R/V Triton, a research vessel built by the Royal Navy. Approximately 164 ft of parallel midbody was added to the R/V Triton form to make the hull long enough to launch the ALDV gliders, and the transom was modified to support water jets (Figure 4). Geosims of this parent hullform were considered in the initial concept exploration and MOGO.

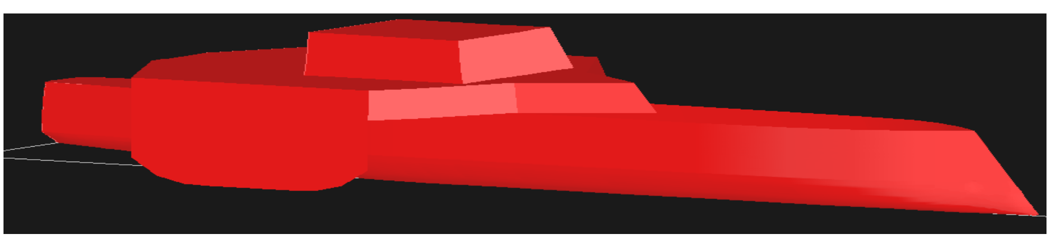

Figure 4 - ALDV Parent Trimaran Hull (Good et al. 2005)

General power and propulsion requirements were as follows:

- Propulsion engines must be non-nuclear, grade A shock certified, and Navy qualified. Machinery system alternatives must span a total power range of approximately 50000–120000 SHP with total ship service power greater than 10000 kW MFLM to support ALDS, unless a pulse power configuration is used. The propulsion engines should have a low IR signature, and cruise/boost options should be considered for high endurance.

- The ship shall be capable of a threshold sustained (sprint) speed of 40 knots in the full load condition, calm water, and clean hull using no more than 80% of the installed engine rating (maximum continuous rating, MCR) of the main propulsion engine(s) or motor(s), as applicable for mechanical drive plants or electric propulsion plants. The sustained speed goal is 50 knots.
- The ship shall have sufficient burnable fuel in the full load condition for a threshold range of 2500 nautical miles at 20 knots. The fuel rate for the propulsion engines and generator sets shall be calculated using methods described in DDS 200-1. Low speed, fuel efficient propulsion options such as an Integrated Power System (IPS) shall be considered.
- An integrated bridge system shall be provided in the Navigating Bridge to incorporate integrated navigation, radio communications, interior communications, and ship maneuvering equipment and systems and shall comply with ABS Guide for One Man Bridge Operated (OMBO) Ships.

Based on these general requirements, nine machinery plant alternatives were considered in the concept exploration and MOGO. These concepts are listed in Figure 5. The mission of ALDV requires that the vessel be able to operate at high speeds, so a high power density configuration is necessary. To that end only alternatives with gas turbine engines are considered. Alternatives 1, 2 and 3 are mechanical drive systems with epicyclic (planetary) reduction gears. Alternatives 4, 5 and 6 are mechanical drive systems with a secondary (cruise IPS/boost GT) integrated power system (IPS). Alternatives 7, 8 and 9 are full IPS alternatives. All alternatives include a number of ship service gas turbine generators (SSGTGs), depending on ship service needs and other requirements. ALDV sprint speed is required to be greater than 40 knots. At this speed, maximum propulsion efficiency is achieved with waterjet propulsion. In ALDV, waterjets similar to Kamewa 225SII are considered. These waterjets are capable of producing 16 to 30 MW of power. ALDV can accommodate up to three waterjets in its center hull.

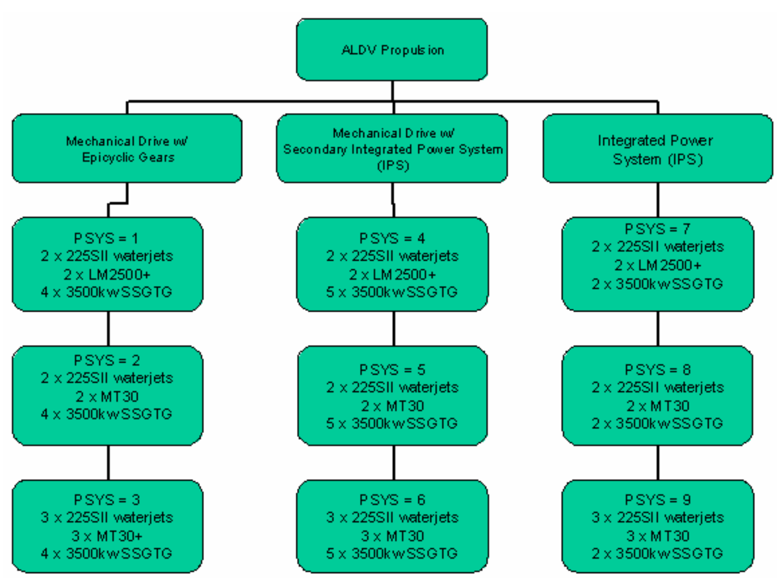

Figure 5 - ALDV Propulsion and Power Trade-Off Alternatives (Good et al. 2005)

ALDV must function as a cargo transport and distribution center providing cargo needs for troops ashore. A high level of automation is necessary to organize and distribute large quantities of cargo in short periods of time. Increased automation and reduced manning may also reduce ALDV life cycle cost and minimize personnel vulnerability. Many automated cargo handling technologies from industry are applicable to ALDV. Some of these processes include conveyor belts, elevators, robotic pickers, and radio frequency identification (RFID). While these technologies exist, their application onboard a ship may present some new challenges. Other general automation technologies that may be considered for ALDV include enabling technologies (ex. fiber optics), watch standing technologies (ex. electronic log keeping), and condition based maintenance technologies (ex. Integrated Condition Assessment System-ICAS).

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.

A range of 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).

The only design variable for the ALDS Mission System is the number of days ALDV is required to deliver MEB cargo without replenishment. The payload characteristics for ALDS components vary with the number of mission days.

ALDS cargo requirements include 75 short tons of dry cargo per MEB day. Dry cargo includes food, ammunition, medical, and other supplies required by a MEB, and it is assumed that dry cargo is packaged in standard 4'x 4' x 4' pallets stacked two high in the ship. Dry cargo is broken down into two general categories, ammunition cargo and other dry cargo, for payload characteristics calculations since ammunition cargo must be stored in a magazine. A secondary mission of ALDS is to provide 10 percent of the wet cargo needs for a MEB which supports troops that are further inland and in hazardous areas where manned V-22 Ospreys are not a safe option. ALDS wet cargo stores account for the space required to store this fuel and water, and the space required to store JP-5 fuel used for V-22 refueling.

ALDS cargo handling requires a pallet stowage room accessed with automated pickers (Figure 6). It is assumed that containers are opened and broken down into pallets at the sea base or on the shuttle ship. Forklifts transport the pallets over a retractable ramp directly to the pallet stowage room. The pallets are placed in specified locations in aisles running longitudinally in the ship. Once the pallets are loaded from the sea base platform and the ship is underway, an automated picker (Figure 7) selects the requested cargo and places it into the ALDS center-bodies.

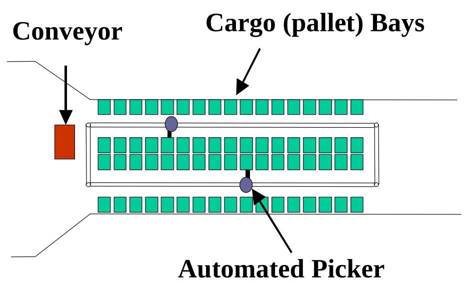

Figure 6 - ALDS Cargo Handling Room (Good et al. 2004)

Figure 7 - Automated Picker (RoboLoop 2005)

Each ALDS unmanned glider consists of several components: center-body bottom, center-body top, ribs, spars, cargo plate, gas tanks, control surfaces, and wing pods. Some of these components are illustrated in Figure 8.

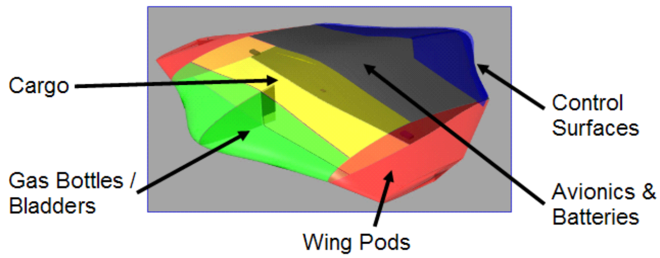

Figure 8 - ALDS Unmanned Glider Components (Good et al. 2005)

The center-body of the ALDS glider is a large and hollow structure, and the ALDS mission requires the launch of 233 of these gliders each day for a number of days. The large volume requirement resulting from storing assembled ALDS gliders onboard the ship makes the off-board fabrication and assembly unattractive. To address this problem, methods of manufacturing and assembling the ALDS glider onboard the ship were investigated. The two main manufacturing options researched were Plastic Injection Molding (PIM) and High Velocity Electro-Magnetic Stamping (HVEMS). PIM involves heating thermoplastics in a heat chamber and then forcing that material into a mold through the use of a pressure gradient (PIM 2002), while HVEMS involves high speed stamping to allow aluminum to be stretched to higher levels of strain (Daehm 2005). Although PIM and HVEMS manufacturing methods significantly reduce the ALDS glider space requirement, they are both complex and costly systems that have not been developed for something as large as an ALDS center-body.

Since the technology has not been developed for a complete manufacturing and assembly process, an assembly-only process was also investigated, referred to as “Stacking”. Stacking involves separating each ALDS center-body into a top and bottom-half and then stacking these separate halves within each other in a manner similar to packaged plastic cups. A conceptual assembly room onboard the ship was developed using the “Stacking” method (Figure 9).

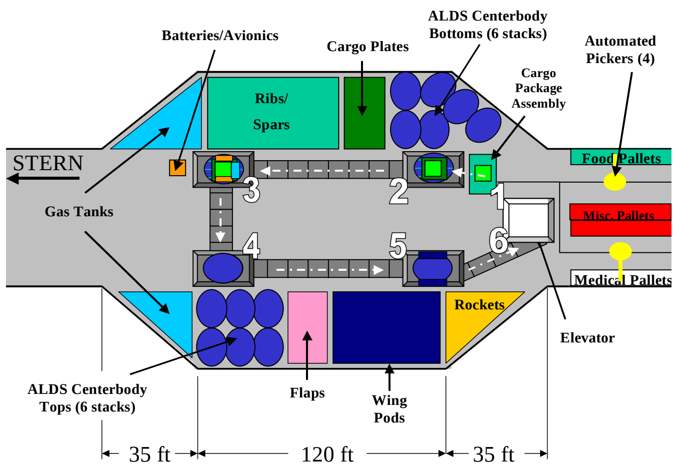

Figure 9 - ALDS Glider Assembly Process (Overhead View) (Good et al. 2004)

The ALDS glider assembly and delivery process is broken down into six distinct steps. In the first step, four automated pickers select the desired cargo from the food, medical, and miscellaneous pallets and drop it off at a common location where the required 30 ft^3 cargo package is assembled. This cargo package is then placed in the ALDS glider during its construction. The next four steps occur in a counterclockwise assembly line fashion. The first of these steps includes the attachment of the ribs and spars within the ALDS center-body bottom, and the placement of the cargo plate. The cargo package is then loaded onto this cargo plate, and the partially assembled ALDS glider is placed on a conveyer belt and transported to the next assembly step. During the third step, batteries, avionics, and gas tanks are placed into the center-body. Note that the batteries and avionics are very small in size and can be transported and stored as a single pallet. The fourth step of the ALDS glider assembly and delivery process includes the attachment of the center-body top and the installation of flaps. After another conveyer belt, the glider reaches the fifth step where the inflatable wing pods are attached. A rocket can also be attached to the glider at this point to augment its range. The glider is now ready to be delivered to the linear induction motor tube located in the inner bottom of the ship and is placed on a final conveyer belt and transported to the elevator.

A linear induction motor (LIM) is simply a rotary motor sliced and rolled flat (Figure 10). The primary of a LIM is analogous to a stator and usually makes up the windings of the track. Similarly, the secondary of a LIM is analogous to the rotor. During operation, an alternating electric current is supplied to the coils of the primary to change the polarity of the magnetized coils. This change of polarity results in a magnetic field in front of the vehicle that pulls it forward and a magnetic field behind the vehicle that pushes it forward. Examples of this concept can be seen in modern day roller coaster design.

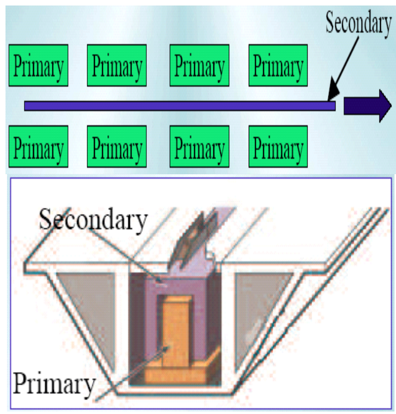

Figure 10 - Conceptual LIM Illustration (Good et al. 2005)

To meet the requirements of the ALDS mission specified in the MNS, the ALDV LIM must launch 1500 pound gliders at a speed of 500 knots with an acceleration of 30 g's. A 365 ft long track is required to achieve this acceleration. The weight and power estimates were based on calculations performed at NSWCCD and EMALS (Electro-Magnetic Aircraft Launch System) specifications (Doyle et al. 2004).

The LIM track design is constrained by the requirement that each ALDS glider be launched at an angle of 30 degrees. A sudden 30 degree turn at the end of a horizontal track creates large forces on both the track and the ship, and it also results in energy losses and decreased range for the glider. These disadvantages eliminate the possibility of using a completely horizontal track with a sudden turn and encourage a curved track design. The optimal curved design involves the largest radius of curvature that yields a launch angle of 30 degrees. A large radius of curvature is ideal because increasing the radius of curvature decreases the centrifugal force exerted on the track. However, there is a limit on the radius of curvature of the track based on the depth of the ship. As a compromise, a partially horizontal and partially curved track was selected and placed along the keel of the ship. This final track design is shown in Figure 11. The track, which is enclosed in a watertight tube, extends just above the main deck to increase curvature without decreasing navigation visibility.

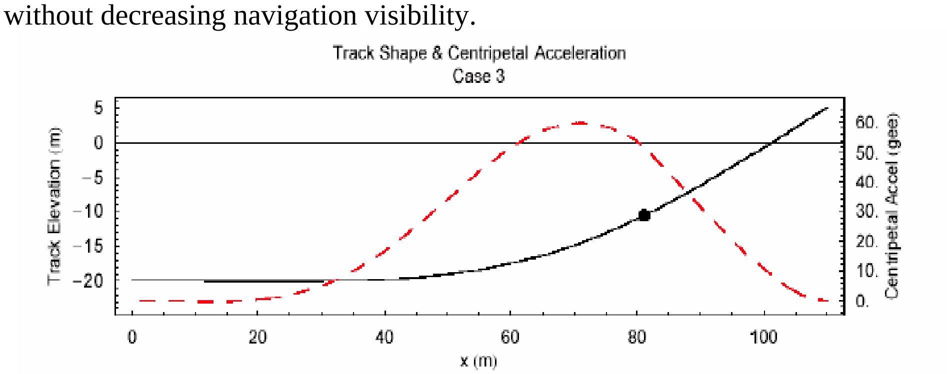

Figure 11 - LIM Track Design (Good et al. 2005)

Table 2 - ALDV Design Variables (DVs) (Good et al. 2005)

DV	Description	Metric	Range
1	Length (used to geosim parent)	m	150-200
2	Deck house Volume	m3	500-1200
3	Deck house Material Type	alternative	1 – steel, 2 – aluminum
4	Ballast Type	alternative	0 – clean ballast, 1- compensated fuel system
5	Propulsion System Alternatives	alternative	1-9
6	Manning and Automation Factor	ND	0.5 – 1.0
7	AAW Alternatives	alternative	1 (goal) – SLQ-32V3, 2xCIWS, RAM, SRBOC/Nulka, SSDS, Combat DF, AIMS IFF 2 - SLQ-32V2, 1xCIWS, SRBOC/Nulka, SSDS, Combat DF, AIMS IFF 3 - SLQ-32V2, SRBOC/Nulka, SSDS, Combat DF, AIMS IFF 4 - (threshold) - Combat DF, AIMS IFF
8	ASUW Alternative	alternative	1 (goal) – SPS-73 radar, IRST, CIGS, small arms 2 - SPS-73 radar, IRST, small arms 3 (threshold) – SPS-73 radar, small arms
9	ASW Alternative	alternative	1 (goal) - Nixie 2 (threshold) - none
10	MCM Alternative	alternative	1 (goal) – Degaussing and mine avoidance sonar 2 (threshold) - Degaussing
11	C4I Alternative	alternative	1 (goal) – Level A 2 (threshold) – Level B
12	LAMPS	alternative	1 (goal) – ASW Control, LAMPS and hangar, 2 – ASW Control, LAMPS helo deck 3 – Lamps helo deck 4 (threshold) – LAMPS in-flight refueling
13	Degaussing System	alternative	0 – none, 1- degaussing system
14	Collective Protection System	alternative	0 - none, 1 - partial, 2 - full
15	Provisions Duration	days	20-45
16	ALDS Mission Duration	days	3-8

Sixteen design variables (Table 2) are used to describe the ALDV design. 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.

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 modified from previous models in Fortran, and the model is incorporated 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 ALDV design by comparing available design characteristics to required design characteristics. 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 using the Darwin optimization plug-in. Figure 12 shows the ALDV 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.

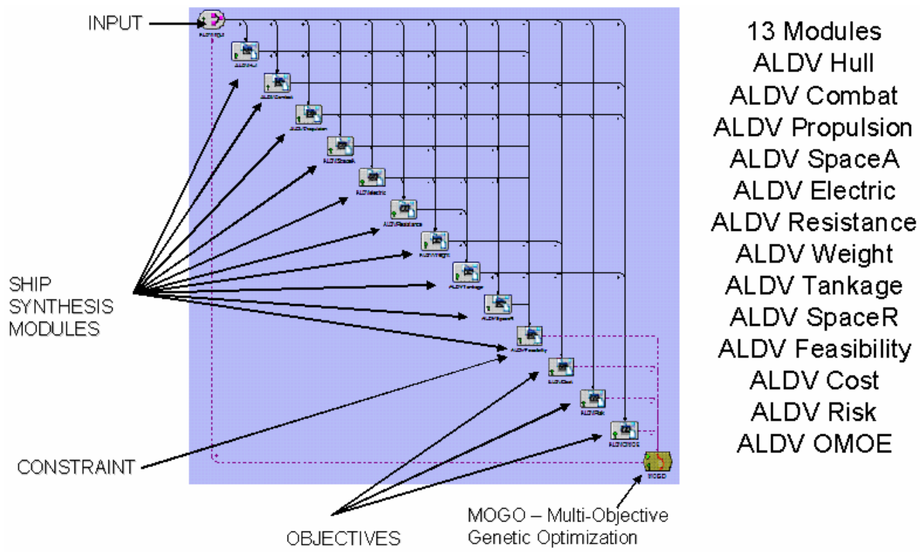

Figure 12 - Ship Synthesis Model in Model Center (MC) (Good et al. 2005)

MULTI-OBJECTIVE GENETIC OPTIMIZATION (MOGO)

The ALDV 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). ALDV MOPs are listed in Table 3.

Table 3 – ALDV MOPs (Good et al. 2005)

MOP	Threshold	Goal	Related DV
MOP1 – MCM	MCM = 2	MCM = 1	DV10 - MCM
MOP2 - C4SI	C4SI = 2	C4SI = 1	DV11 - C4SI
MOP3 – ASUW	ASUW = 4	ASUW = 1	DV8 - ASUW
MOP4 – ASW	ASW = 2	ASW = 1	DV9 - ASW
MOP5 – AAW	AAW = 4	AAW = 1	DV7 - AAW
MOP6 - Sprint Range	250 nm	500 nm	DV1 - Length
MOP7 - Endurance Range	2500 nm	3500 nm	DV1 - Length
MOP8 – Ship Provisions Duration	20 days	45 days	DV15 - Provisions Duration
MOP9 - Sprint Speed	40 knots	50 knots	DV5 - Propulsion System Type
MOP10 – RCS	300 m3	150 m3	DV2 - Deck house Volume
MOP11 - Acoustic Signature	Mechanical	IPS	DV5 - Propulsion System Type
MOP12 - Magnetic Signature	No Degaussing	Degaussing	DV13 - Degaussing System
MOP13 - Personnel Vulnerability	60	35	DV6 - Manning and Automation Factor
MOP14 – CBR	No CPS	Full CPS	DV14 - Collective Protection System Type
MOP15 - ALDS Combat Cargo	3 days	8 days	DV15 - ALDS Mission Duration

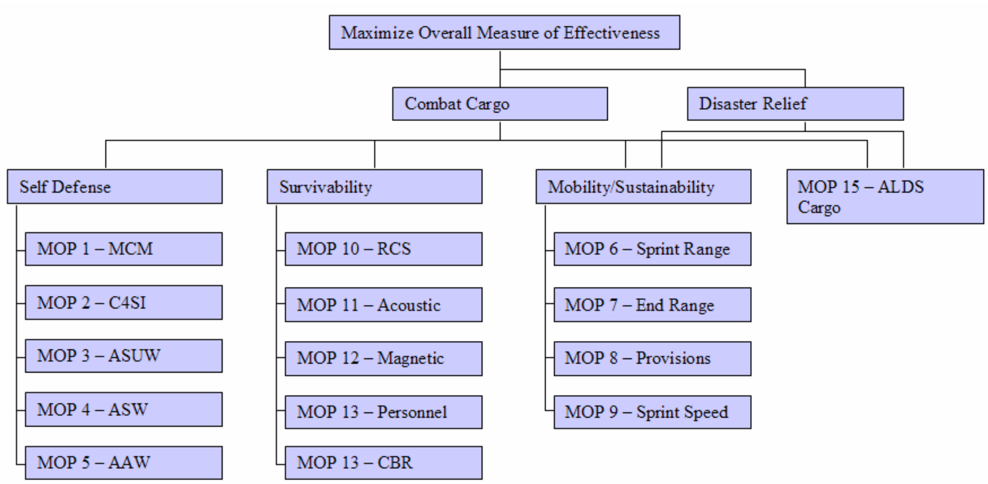

Figure 13 - OMOE Hierarchy (Good et al. 2005)

Figure 13 illustrates the OMOE hierarchy for ALDV derived from Table 3. MOPs are grouped under two missions (Combat Cargo, Disaster Relief), which have four categories of MOPs (Self Defense, Mobility/Sustainability, Survivability, ALDS Cargo duration) with Mobility/Sustainability and ALDS Cargo duration being the only categories under Disaster Relief. MOP weights are calculated using pair-wise comparison as illustrated in Figure 14. Results are shown in Figure 15 and Table 4. MOP weights and value functions are finally assembled in a single OMOE function, Equation (1).

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

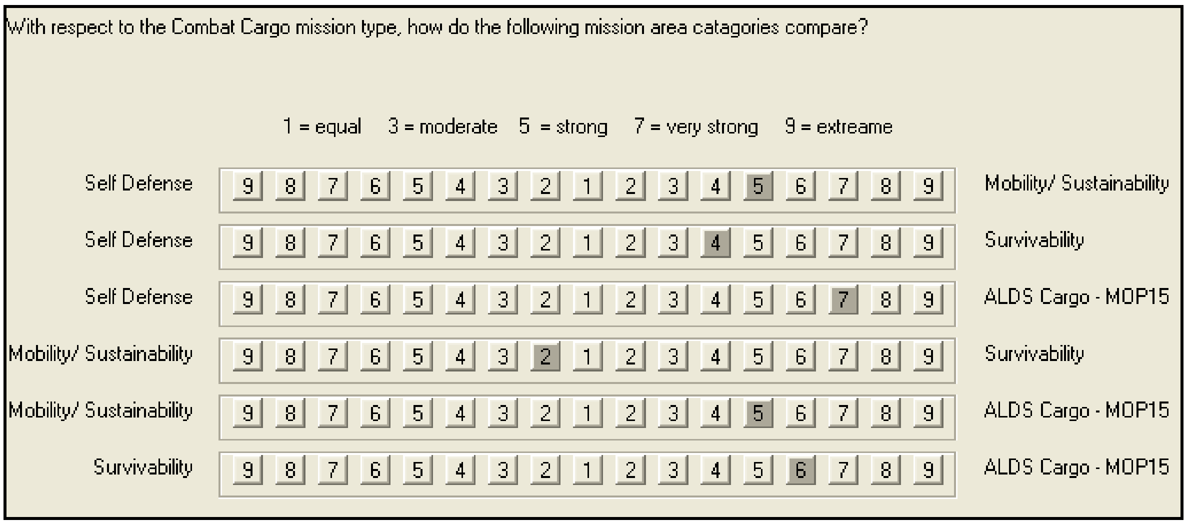

Figure 14 - Example of AHP Pair-wise Comparison (Good et al. 2005)

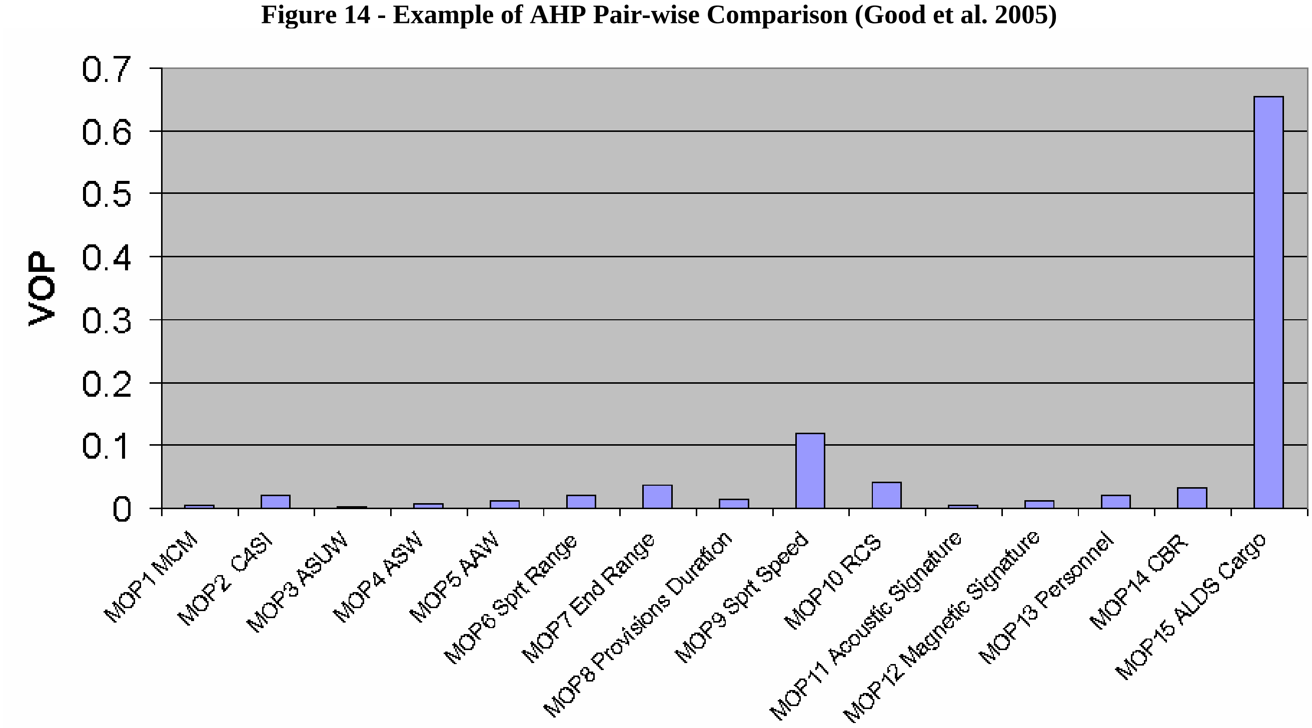

Figure 15 - Bar Chart Showing MOP Weights (Good et al. 2005)

Table 4 - MOP Weights

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 Combat Cargo	0.6541

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 ALDV 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 5 and Table 6. 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).

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

Table 5 - 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 6 - 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 16 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. ALDV life cycle cost includes these acquisition costs plus selected operating and support costs (fuel and manning).

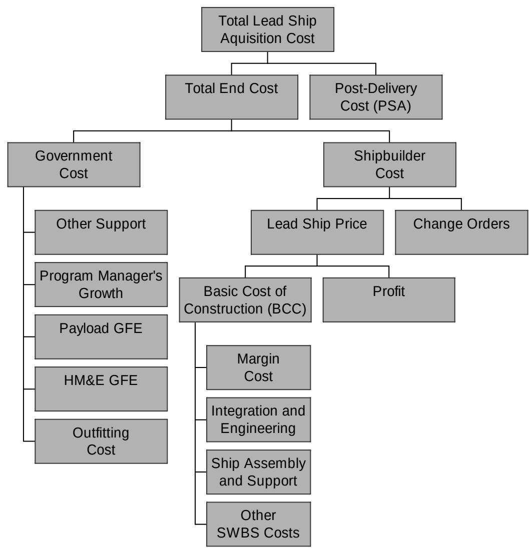

Figure 16 - Naval Ship Acquisition Cost Components

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 17 (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.

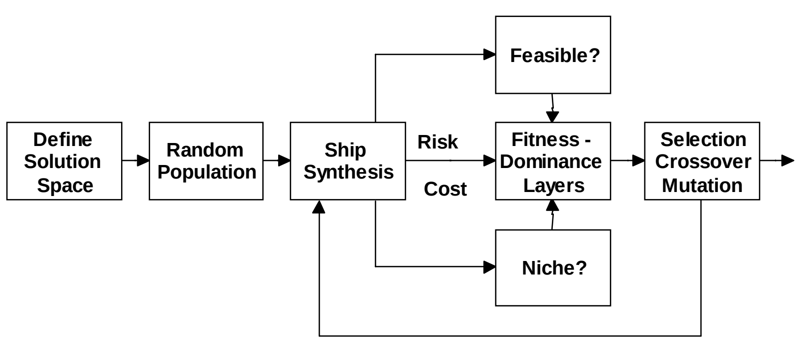

Figure 17 – Multi-Objective Genetic Optimization (Brown and Salcedo 2002)

RESULTS

Figure 18 and Figure 19 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 18 is a three-dimensional representation showing how the non-dominated frontier improves over the optimization generations. Feasible designs are represented in Figure 19 with cost and effectiveness on the axes, and risk indicated by color as low (OMOR<0.22), medium (0.22<OMOR<0.3), or high (OMOR>0.3).

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. Table 7 lists the design variable values for some of these possibilities. Since the number of MEB support days is the most important MOP for this design, TALDS increases consistently with effectiveness and cost. As the ship becomes larger, it is necessary to have more automation to reduce volume and weight and eventually shift to an aluminum deckhouse to reduce weight. The group of lower cost designs (LO through med2) are able to satisfy the threshold sustained speed requirement with two waterjets (Propulsion Option 2, Figure 5) while larger designs require three waterjets and more power (Options 3 and 6). There is a region between these two groups with no non-dominated designs. Low cost designs have primarily threshold combat systems (Table 2). High cost designs have degaussing and CPS, but even the most effective design (HI) includes only AAW Option 2 and LAMPS Option 2 because additional cargo adds more effectiveness than the goal combat systems.

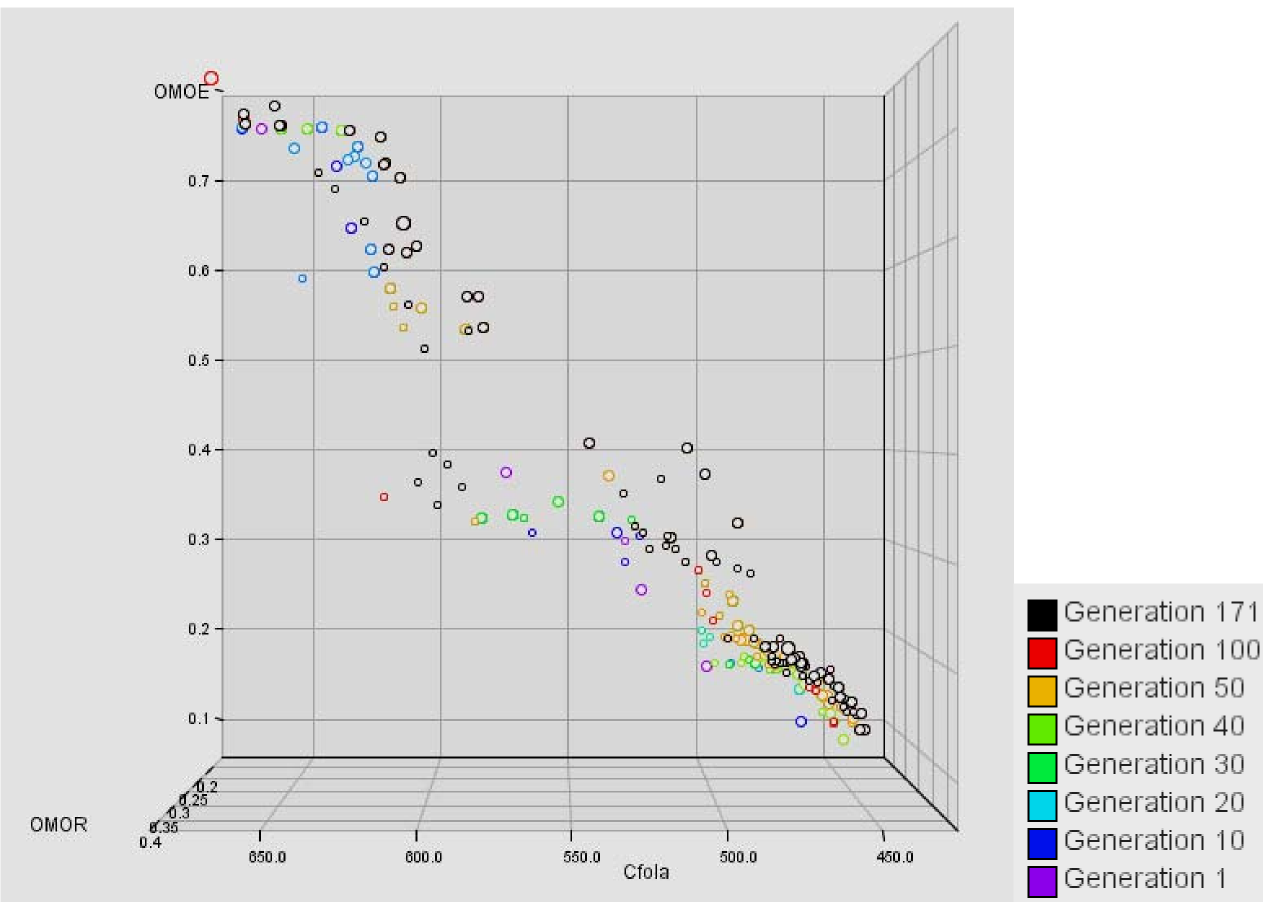

Figure 18 – 3-D Non-Dominated Frontier Generation Improvement

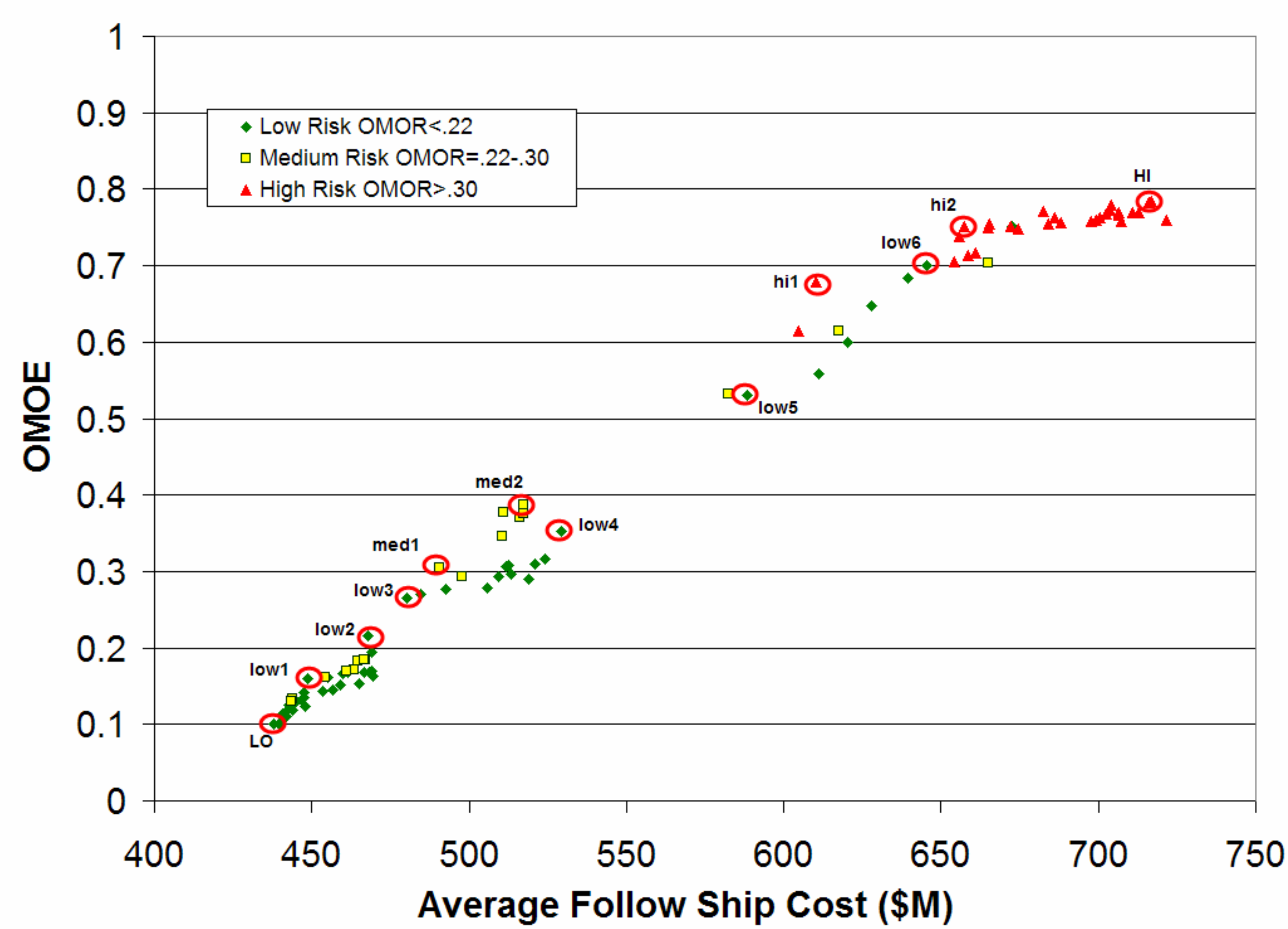

Figure 19 - Non-Dominated Frontier based on Follow Ship Acquisition Cost

Table 7 – Preferred Designs

Design	Cfola	OMOR	OMOE	LWL	VD	CMan	TALDS	Ts	CDHMAT	BALtyp	PSYS	AAW	ASUW	ASW	MCM	C4I	LAMPS	Ndegaus	Ncps
	$M			m	m3		days												
LO	438.0	0.214	0.100	161	620	0.96	3	39	1	0	2	4	3	2	2	2	4	0	0
low1	448.8	0.182	0.160	165	560	0.99	3	39	1	1	2	4	3	2	2	2	4	0	2
low2	467.8	0.202	0.216	176	500	0.999	4	29	1	0	2	4	3	1	2	1	4	1	2
low3	480.0	0.182	0.265	172	660	0.99	4.5	32	2	0	2	4	3	2	2	1	4	0	2
low4	529.2	0.182	0.352	179	620	0.99	5	40	2	1	2	2	3	2	1	2	2	0	2
med1	490.6	0.247	0.305	177	640	0.93	5	43	2	1	2	3	3	2	2	2	4	0	0
med2	517.2	0.269	0.388	180	950	0.91	5.4	40	2	1	2	3	3	2	1	2	4	0	1
low5	588.5	0.203	0.530	192	730	0.97	5.9	41	2	0	3	3	3	2	2	2	4	0	2
low6	645.5	0.203	0.700	199	960	0.97	7	35	2	1	3	2	3	2	2	2	4	1	1
hi1	610.5	0.301	0.678	195	720	0.88	7.2	34	2	1	3	4	3	2	1	2	4	0	1
hi2	657.4	0.617	0.752	198	500	0.83	7.4	31	2	0	6	4	2	2	2	1	4	0	2
HI	717.0	0.628	0.783	200	790	0.82	7.5	34	2	0	6	2	3	2	2	1	2	1	2

Design “low2” was one of two designs selected for concept development. Characteristics for Design “low2” are listed in Table 8, Table 9, and Table 10. This is a low risk, relatively low cost design that maximizes cargo capacity for its size with minimum automation, and depends largely on passive survivability with minimum self-defense systems.

Table 8 - Design "low2" Design Variable Summary

Design Variable	Description	Trade-off Range	Design Values
DV 1	Length	150-200 m	176 m
DV 2	Deck house Volume	500-1200 m^3	500 m^3
DV 3	Deck house Material Type	1. steel 2. aluminum	1- steel
DV 4	Ballast Type	0. clean ballast 1. compensated fuel system	0 - clean ballast
DV 5	Propulsion System Type	1. 2xLM2500+, 4x3500kw SSGTG, 2x225SII waterjets, mech 2. 2xMT30, 4x3500kw SSGTG, 2x225SII waterjets, mech 3. 3xMT30, 4x3500kw SSGTG, 3x225SII waterjets, mech 4. 2xLM2500+, 5x3500kw SSGTG, 2x225SII waterjets, IPS & mech 5. 2xMT30, 5x3500kw SSGTG, 2x225SII waterjets, IPS & mech 6. 3xMT30, 5x3500kw SSGTG, 3x225SII waterjets, IPS & mech 7. 2xLM2500+, 2x3500kw SSGTG, 2x225SII waterjets, IPS 8. 2xMT30, 2x3500kw SSGTG, 2x225SII waterjets, IPS 9. 3x MT30, 2x3500kw SSGTG, 3x225SII waterjets, IPS	2 - 2xMT30, 4x3500kw SSGTG, 2x225SII water-jets, mechanical drive
DV 6	Automation Factor	0.5-1.0	1.0
DV 7	AAW Alternative	1 (goal), 2, 3, 4(threshold)	4 (threshold) - Combat DF and AIMS
DV 8	ASUW Alternative	1 (goal), 2, 3 (threshold)	3 (threshold) – SPS-73
DV 9	ASW Alternative	1 (goal), 2 (threshold)	1 (goal) - Nixie
DV 10	MCM Alternative	1 (goal), 2 (threshold)	2 (threshold) - none
DV 11	C4I Alternative	1 (goal), 2 (threshold)	1 (goal) – Level A
DV 12	LAMPS	1 (goal), 2, 3, 4 (threshold)	4 (threshold) - refueling
DV 13	Degaussing System	0. none 1. degaussing system	1- degaussing
DV 14	Collective Protection System	0. none 1. partial 2. full	2 – full CPS
DV 15	Provisions Duration	20 – 45 days	29 days
DV 16	ALDS Mission Duration	3 – 8 days	4 days

Table 9 – "low2" Objective Attribute Summary

MOP	Description	MOP Metric	VOP (Value of Performance)
MOP 1	MCM	Option 2 (threshold)	0.0
MOP 2	C4I	Option 1 (goal)	1.0
MOP 3	ASUW	Option 3 (threshold)	0.0
MOP 4	ASW	Option 1 w/o LAMPS	0.2
MOP 5	AAW	Option 4 (threshold)	0.0
MOP 6	Sprint Range	1145 nm	1.0
MOP 7	Endurance Range	6485 nm	1.0
MOP 8	Ship Provisions Duration	29 days	0.26
MOP 9	Sprint Speed	40 knots	0.0
MOP 10	RCS	500 m3	0.26
MOP 11	Acoustic Signature	Mechanical drive	0.0
MOP 12	Magnetic Signature	Degaussing	1.0
MOP 13	Personnel Vulnerability	manning = 45	0.6
MOP 14	CBR	Full CPS	1.0
MOP 15	ALDS Combat Cargo	4 days	0.1
OMOE	Overall Measure of Effectiveness		0.216
OMOR	Overall Measure of Risk		0.202
	Follow Ship Acquisition Cost	$467.8 Million	
	Life Cycle Cost	$599.8 Million	

Table 10 - Concept Exploration Baseline Design "low2" Principal Characteristics

Characteristic	Value
Hullform	Trimaran
Δ (MT)	5350
LWL (m)	176
Beam (m)	28.3
Draft (m)	4.78
D10 (m)	15.4
W1 (MT)	1354
W2 (MT)	449
W3 (MT)	228
W4 (MT)	133
W5 (MT)	448
W6 (MT)	149
W7 (MT)	6
Lightship weight w/margin (MT)	2822
Loads (MT)	2528
Total Manning	45

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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