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DRAFT

Optimization and Overall Measure of Effectiveness (OMOE) for the Preliminary Design of LHA(R)

NSWC CISD Innovation Cell Project Report

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Executive Summary

This study uses a total system approach to revisit the LHA(R) preliminary design, including a structured search of design space based on a multi-objective consideration of effectiveness and cost. LHA(R) is a modified-repeat design and the design variables are very different from a clean-sheet-of-paper design. Most are trade-off alternative selections with an associated total-ship impact. There is very little flexibility to modify other ship characteristics. Although this limits the application of a structured design and optimization process, significant benefit and insights can still be obtained.

A secondary goal of this study is to integrate existing ship synthesis (e.g., ASSET) and mission effectiveness tools with multi-objective optimization tools and techniques, to provide an optimization framework that can be applied to the LHA(R) preliminary design. When this design study began, the LHA(R) preliminary design was already nearing completion and most individual trade studies had been performed. This study revisits the prior trade studies using a total ship optimization that considers all combinations of the multiple trade alternatives, and their combined impact on cost and effectiveness. A Multi-Objective Genetic Optimization (MOGO) is used to search the design space and identify non-dominated designs. Model Center is used as the design environment. Optimization requires mathematically-defined objective functions for effectiveness and cost. An Overall Measure of Effectiveness (OMOE) objective function is developed using the Analytical Hierarchy Process (AHP), Multi-Attribute Value Theory (MAVT) and expert opinion. Acquisition cost is calculated using a modified weight-based cost model.

Significant benefit and insights were obtained:

- The OMOE development process was demonstrated in a real US Navy acquisition setting. The process structured the discussion of alternatives and provided insight to a panel of experts in a way that they had been unable to achieve in an unstructured meeting format. The results of this process were also useful and indicated that for LHD(R) the most important improvements are those associated with aviation and aviation maintenance.
- The optimization was successfully linked to ASSET. This is the first time ASSET has been used in this manner, and the benefit for future applications was clearly demonstrated. Individual trade studies cannot begin to search the entire trade space. This structured optimization process in MC can search millions on combinations efficiently and with confidence of convergence. This application makes ASSET more than a trade-study tool.
- A multi-objective optimizer and user interface were developed in Model Center.
- The optimization results showed excellent convergence to a non-dominated frontier. They were consistent and repeatable.

However, some of the results of this study are questionable because a number of compromises were made:

- The cost model used in this project was weight-based which is useful for new design concept exploration, but does not provide an accurate estimate of the change in cost for the specific change alternatives considered here. It was the only model available, and it was used primarily to finish the study and assess the process.
- Arrangement-based constraints were not used which caused a number of the design variables to consider only their goal values. They were unconstrained and there was no cost or impact to restrict them.
- Only one OMOE pair-wise comparison session was used. Results would benefit from some improvement to the OMOE hierarchy, and at least one more round of comparisons.

The first two of these deficiencies can be corrected with a modest additional effort to obtain cost impact estimates and establish arrangement constraints. The optimization could then be rerun and more valid results obtained.

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1 Introduction and Motivation

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 synthesized or presented to support efficient and effective decisions. This study uses a total system approach to revisit the LHA(R) preliminary design process, including a structured search of design space based on the multi-objective consideration of effectiveness and cost [1, 2, 3]. LHA(R) is a modified-repeat design and the design variables are very different from a clean-sheet-of-paper design. In most cases they are simply trade-off alternative selections considering their associated total-ship impact, but with very little flexibility to modify other ship characteristics. Although this limits the application of a structured design and optimization process, significant benefit and insights can still be obtained.

A secondary goal of this study is to integrate existing ship synthesis (e.g., ASSET) and mission effectiveness tools with multi-objective optimization tools and techniques, to provide an optimization framework that can be applied to the LHA(R) preliminary design. Using this approach, the Navy will have better-informed decision-makers making better ship acquisition choices. This will result in a more effective and innovative LHA(R) design at a lower cost.

When this design study began, the LHA(R) preliminary design was already nearing completion and most individual trade studies had already been performed. This study revisits the prior trade studies using a total ship optimization that considers all combinations of the multiple trade alternatives, and their combined impact on cost and effectiveness.

Mission effectiveness and cost 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 more for the same effectiveness or accept less effectiveness for the same cost. Various combinations of ship characteristics and alternatives yield designs of different effectiveness and cost. A non-dominated frontier, Figure 1, represents the best effectiveness that can be achieved for a given cost. Each point on the frontier represents a candidate ship design. 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 and effectiveness. This preference may be affected by the shape of the frontier and cannot be rationally determined a priori. It is possible that designs already selected in the individual LHA(R) trade studies may not be non-dominated. A thorough search of the design space is required to determine this.

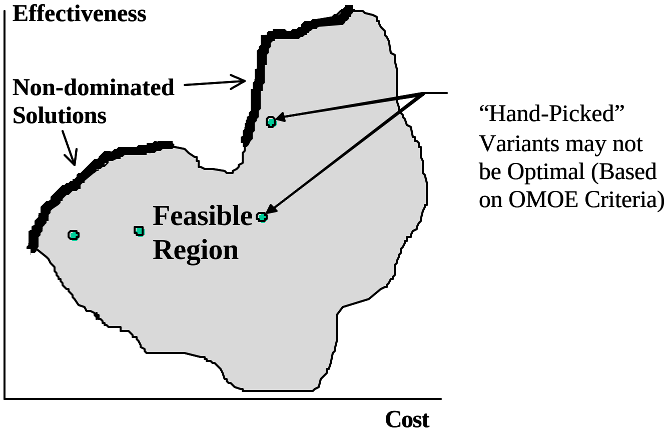


Figure 1 – Notional Non-Dominated Frontier (NDF)

In this study, a Multi-Objective Genetic Optimization (MOGO) is used to search the design space and identify non-dominated designs [1, 2, 3]. A flow chart for the MOGO is shown in Figure 2. The MOGO generates, assesses and improves a population of designs in sequential generations. In the first design generation, the optimizer randomly defines a population of ships using the ship synthesis model (ASSET in this study) to balance each ship and to calculate cost and effectiveness. Each of these designs is ranked based on their fitness or dominance in effectiveness and cost 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. A subset of these is selected for crossover or swapping of some of their design variable values. A very 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 and define the effectiveness/cost design space and frontier. There is no magic to a genetic optimization and the quality of results is only as good as the preparation and process that precedes running the optimization, but it enables the designer to assess a large design space, 10^7+ feasible variants in this case, efficiently and quickly with confidence that the best designs have been found.

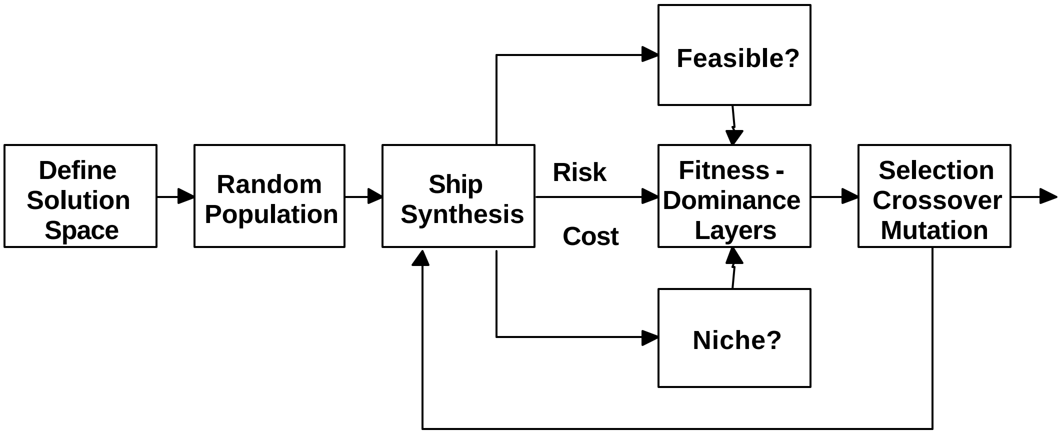


Figure 2 - Multi-Objective Genetic Optimization

Optimization requires mathematically-defined objective functions for effectiveness and cost. In this study, an Overall Measure of Effectiveness (OMOE) objective function is developed using the Analytical Hierarchy Process (AHP), Multi-Attribute Value Theory (MAVT) and expert opinion. Acquisition cost is calculated using a modified weight-based cost model. This cost model was not a good selection for this problem, but it was the only cost model made available to us.

2 LHA(R) Preliminary Design

LHA(R) is a modified-repeat LHD-8 design. Amphibious warships are designed to support the Marine Corps tenets of Operational Maneuver from the Sea (OMFTS) and Ship to Objective Maneuver (STOM). They must be able to sail in harm's way and provide a rapid buildup of combat power ashore in the face of opposition. Because of their inherent capabilities, these ships have been and will continue to be called upon to also support humanitarian and other contingency missions on short notice. The United States maintains the largest and most capable amphibious force in the world. The WASP-class ships are currently the largest amphibious ships in the world. LHDs 1-7 are in-service, LHD 8 is under construction and expected to deliver in July 2007.

Beginning in fiscal year 2001, the Navy conducted an analysis of alternatives study to determine the preferred choice between a modification to the LHD class design or a brand new hull configuration, variously known as the LH(X) or LHA(R) class. The Navy set out to determine the appropriate design for the LHA(R), considering a modified-repeat of the LHD design, a modified LHD, and a completely new design. It is hoped that LHA(R) may also benefit by incorporating C4I technologies from the CVNX program.

In March 2001, the Navy and Joint Staff approved and validated the LHA(R) Mission Need Statement. The office of the Under-secretary of Defense for Acquisition, Technology, and Logistics authorized Milestone "A" Acquisition status for the program, and its entry into the Concept Exploration phase in July 2001. Preliminary design began in 2003 (Figure 3).

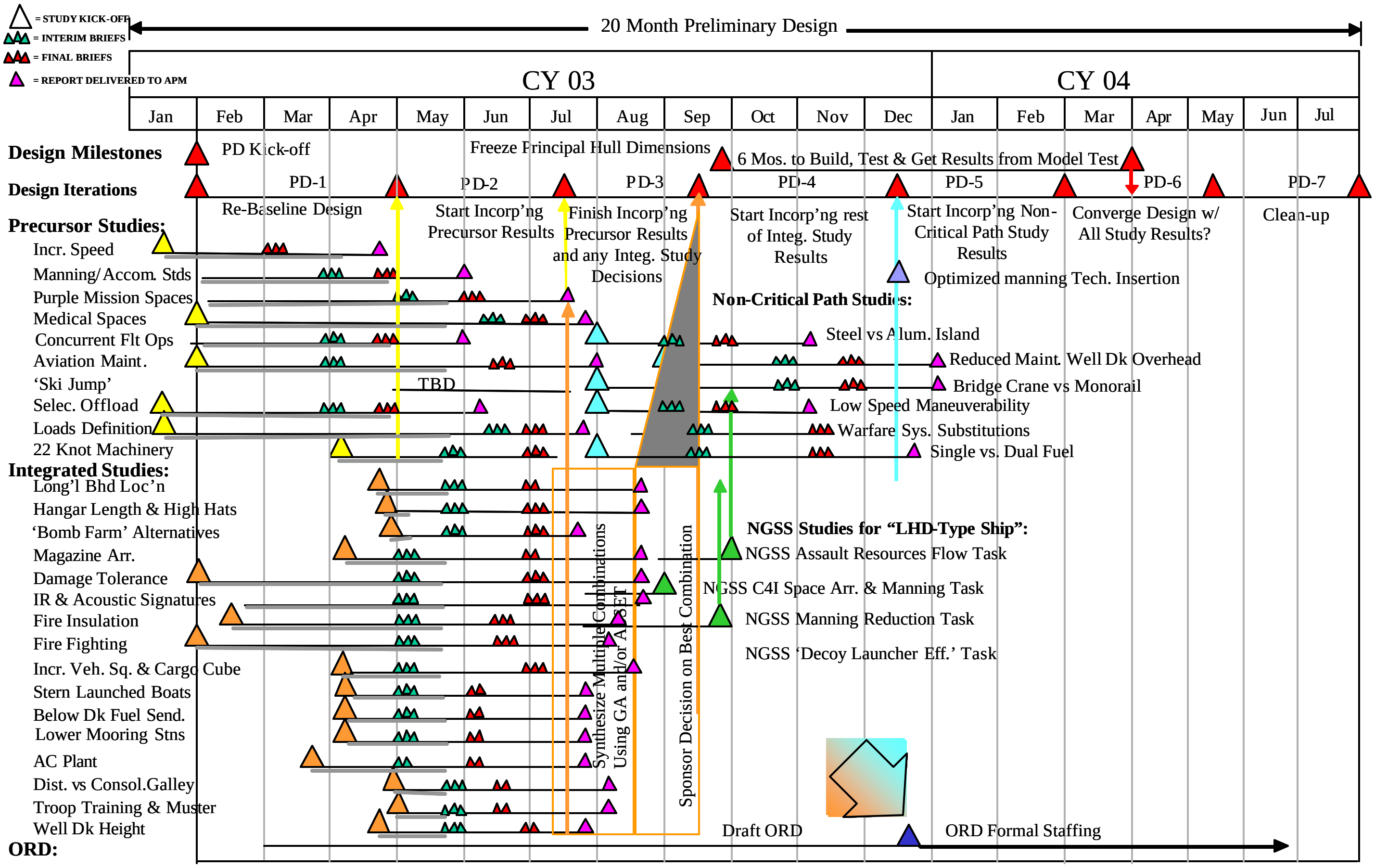
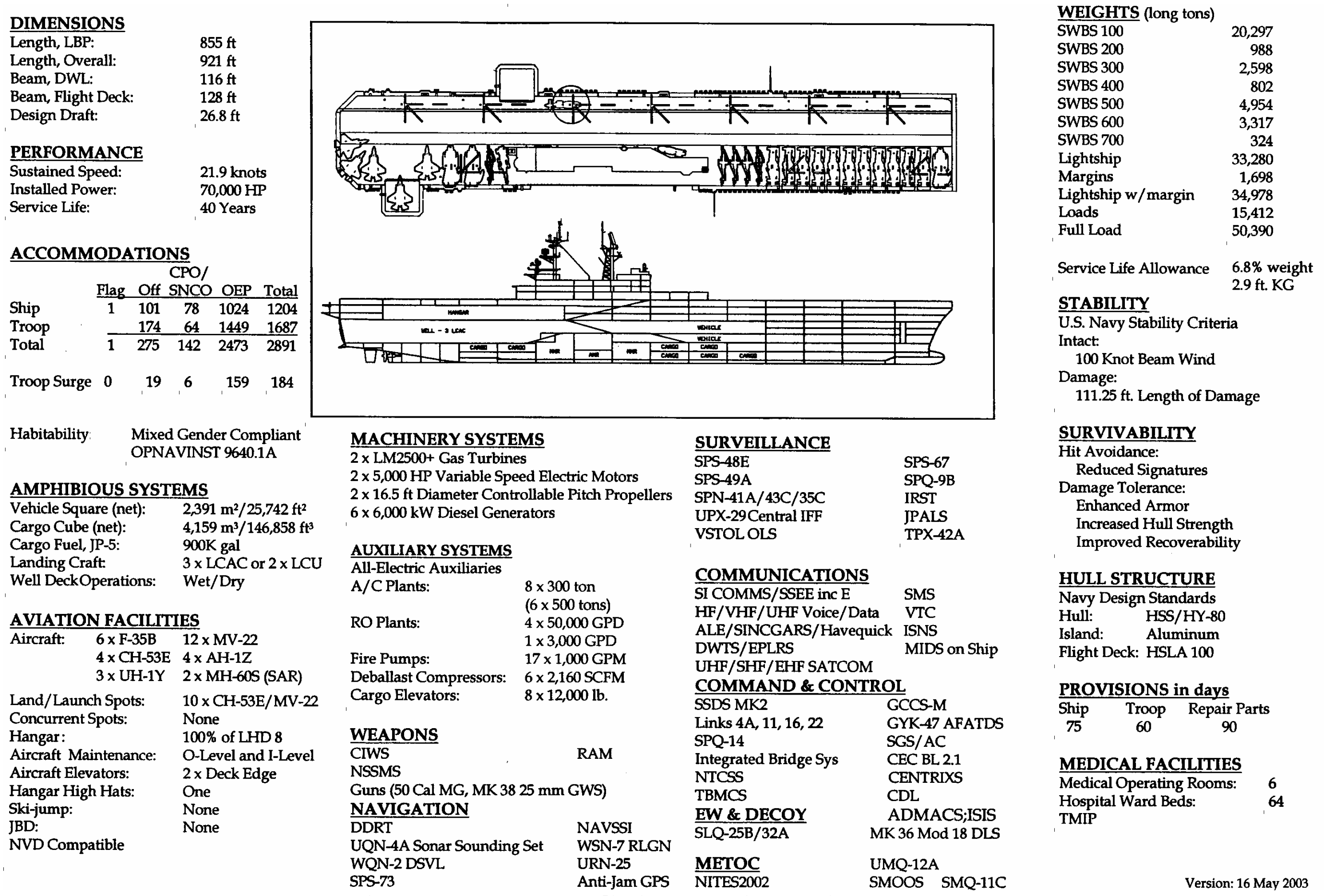


Figure 3 - LHA(R) Preliminary Design Schedule

2.1 Baseline Designs (PD1 and PD2)

Prior to the start of this study a series of trade studies had already been completed to identify desirable modifications and improvements to LHD-8. The first baseline in this development, PD-1, is shown in Figure 4. Major PD-1 characteristics are illustrated and listed in Figure 5. Work on PD-2 was also nearly complete. Trade studies revisited in this study represent a selected subset of PD-1 and PD-2 studies. They are described in Section 2.2. PD-2 is the baseline for this study.



DIMENSIONS

Length, LBP:	855 ft
Length, Overall:	921 ft
Beam, DWL:	116 ft
Beam, Flight Deck:	128 ft
Design Draft:	26.8 ft

PERFORMANCE

Sustained Speed:	21.9 knots
Installed Power:	70,000 HP
Service Life:	40 Years

ACCOMMODATIONS

	Flag	Off	CPO/ SNCO	OEP	Total
Ship	1	101	78	1024	1204
Troop		174	64	1449	1687
Total	1	275	142	2473	2891
Troop Surge	0	19	6	159	184

Habitability: Mixed Gender Compliant
OPNAVINST 9640.1A

AMPHIBIOUS SYSTEMS

Vehicle Square (net):	2,391 m²/25,742 ft²
Cargo Cube (net):	4,159 m³/146,858 ft³
Cargo Fuel, JP-5:	900K gal
Landing Craft:	3 x LCAC or 2 x LCU
Well Deck Operations:	Wet/Dry

AVIATION FACILITIES

Aircraft:	6 x F-35B	12 x MV-22
	4 x CH-53E	4 x AH-1Z
	3 x UH-1Y	2 x MH-60S (SAR)

Land/Launch Spots:	10 x CH-53E/MV-22
Concurrent Spots:	None
Hangar:	100% of LHD 8
Aircraft Maintenance:	O-Level and I-Level
Aircraft Elevators:	2 x Deck Edge
Hangar High Hats:	One
Ski-jump:	None
JBD:	None
NVD Compatible	

MACHINERY SYSTEMS

2 x LM2500+ Gas Turbines
2 x 5,000 HP Variable Speed Electric Motors
2 x 16.5 ft Diameter Controllable Pitch Propellers
6 x 6,000 kW Diesel Generators

AUXILIARY SYSTEMS

All-Electric Auxiliaries

A/C Plants:	8 x 300 ton (6 x 500 tons)
RO Plants:	4 x 50,000 GPD 1 x 3,000 GPD
Fire Pumps:	17 x 1,000 GPM
Deballast Compressors:	6 x 2,160 SCFM
Cargo Elevators:	8 x 12,000 lb.

WEAPONS

CIWS RAM
NSSMS
Guns (50 Cal MG, MK 38 25 mm GWS)

NAVIGATION

DDRT	NAVSSI
UQN-4A Sonar Sounding Set	WSN-7 RLGN
WQN-2 DSVL	URN-25
SPS-73	Anti-Jam GPS

SURVEILLANCE

SPS-48E	SPS-67
SPS-49A	SPQ-9B
SPN-41A/43C/35C	IRST
UPX-29 Central IFF	JPALS
VSTOL OLS	TPX-42A

COMMUNICATIONS

SI COMMS/SSEE inc E	SMS
HF/VHF/UHF Voice/Data	VTC
ALE/SINCGARS/Havequick	ISNS
DWTS/EPLRS	MIDS on Ship
UHF/SHF/EHF SATCOM	

COMMAND & CONTROL

SSDS MK2	GCCS-M
Links 4A, 11, 16, 22	GYK-47 AFATDS
SPQ-14	SGS/AC
Integrated Bridge Sys	CEC BL 2.1
NTCSS	CENTRIXS
TBMCS	CDL
	ADMACS;ISIS

EW & DECOY

SLQ-25B/32A MK 36 Mod 18 DLS

METOC

NITES2002 UMQ-12A
SMOOS SMQ-11C

WEIGHTS (long tons)

SWBS 100	20,297
SWBS 200	988
SWBS 300	2,598
SWBS 400	802
SWBS 500	4,954
SWBS 600	3,317
SWBS 700	324
Lightship	33,280
Margins	1,698
Lightship w/margin	34,978
Loads	15,412
Full Load	50,390
Service Life Allowance	6.8% weight 2.9 ft. KG

STABILITY

U.S. Navy Stability Criteria
Intact:
 100 Knot Beam Wind
Damage:
 111.25 ft. Length of Damage

SURVIVABILITY

Hit Avoidance:
 Reduced Signatures
Damage Tolerance:
 Enhanced Armor
 Increased Hull Strength
 Improved Recoverability

HULL STRUCTURE

Navy Design Standards

Hull:	HSS/HY-80
Island:	Aluminum
Flight Deck:	HSLA 100

PROVISIONS in days

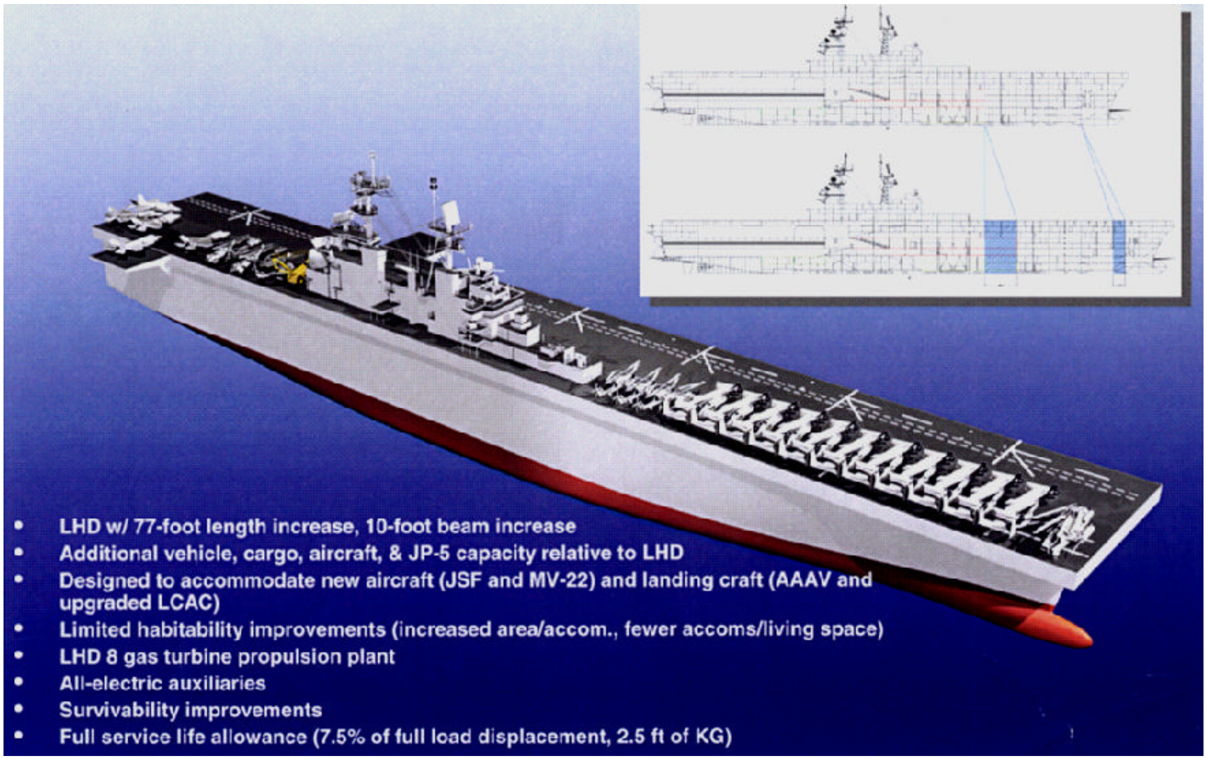
Ship	Troop	Repair Parts
75	60	90

MEDICAL FACILITIES

Medical Operating Rooms:	6
Hospital Ward Beds:	64
TMIP	

Version: 16 May 2003

Figure 4 – LHD(R) Preliminary Design Variant 1 (PD-1)



- LHD w/ 77-foot length increase, 10-foot beam increase
- Additional vehicle, cargo, aircraft, & JP-5 capacity relative to LHD
- Designed to accommodate new aircraft (JSF and MV-22) and landing craft (AAAV and upgraded LCAC)
- Limited habitability improvements (increased area/accom., fewer accoms/living space)
- LHD 8 gas turbine propulsion plant
- All-electric auxiliaries
- Survivability improvements
- Full service life allowance (7.5% of full load displacement, 2.5 ft of KG)

Figure 5 – LHD Modifications to LHD-8 for LHA(R) PD-1

2.2 Trade Studies

Sixteen LHA(R) Preliminary Design trade studies are revisited in this study. Table 1 provides brief descriptions of these trade studies. Specific alternatives considered in each of these trade studies are summarized in Table 3. Ship impacts are described in Table 4. Supplementary descriptions are provided in the following sections.

Table 1 – LHA(R) Trade Studies Considered in this Study

Trade Study Name	Description
22 Knot Machinery Plant	Improvements in the machinery plant to increase sustained speed and improve fuel efficiency – 5 options
Purple Mission Spaces	Increase area designated as Joint Spaces. This Trade Study focused on the minimum capabilities that include Joint Spaces (designated Purple) to include C4I (Joint), office spaces, mission planning and berthing to support Small Scale Contingency (SSC) JTF or, if designated by the Operational Commander, MEB/CPG staff (135 total staff billets). Its intent is to designate these spaces as separate and distinct from those used routinely by embarked PHIBRON/MEU staff. – 4 options
Hanger Length and High Hats	Increase the Hanger Area and Volume to better support future ACE systems – 5 options
Aviation Maintenance and Stowage	Identify best volume and space options for supporting future ACE – 2 options
'Bomb Farm' Alternatives	Change bomb propositioning area ('Bomb Farm') from the flight deck to the main deck – 2 options
Increased Cargo Cube	Increase the volume designated for cargo to support amphibious operations – 4 options
Increased Vehicle Square	Increase the area designated for vehicle storage – 4 options
Distributed vs. Consolidated Galley	Change the galley to lessen congestion and improve habitability – 3 options
Dedicated Troop Training and Muster Space	Identify alternatives for large/dedicated vs. multi-purpose troop training space and assess ability to also use large training space as muster space while considering required routes to aircraft and landing craft – 4 options
Boat Stowage and Handling	Determine impacts of both internal boat stowage and external davit boat stowage – 2 options
Medical	Determine the impacts of decreasing the medical/dental area – 2 options
Damage Tolerance Plating	Consideration of different bottom and side plating alternatives to reduce UNDEX damage vulnerability – 2 options
Damage Tolerance DAPS	[Sensitive Material] – 7 options
UNDEX Damage Tolerance Material	Consideration of different bottom and side plating material alternatives to reduce UNDEX damage vulnerability – 2 options
IR Signatures	[Sensitive Material] – 3 options
Acoustic Signatures	[Sensitive Material] – 3 options

2.2.1 Propulsion Study - 22 Knot Machinery Plant

The purpose of this study was to compare various machinery configurations with the LHD 8 propulsion/power generation configuration to improve sustained speed, fuel efficiency and maintainability. Constraints imposed on the LHD 8 design from the LHD 7 are relaxed. Configurations studied include:

- Option A - LHD 8 Main Machinery Configuration (Figure 6)
- Option B – "Flipped Shaft" w/New Reduction Gear Design
- Option C – New Reduction Gear Design (keeping long shaft on port side)
- Option D - Integrated Power System Configuration.

- Option E - Combined Gas Turbine and Auxiliary Propulsion System configuration.
- Option F - LHD 8 Main Machinery Configuration Utilizing De-rated MT-30 Gas Turbine (40,000 hp)

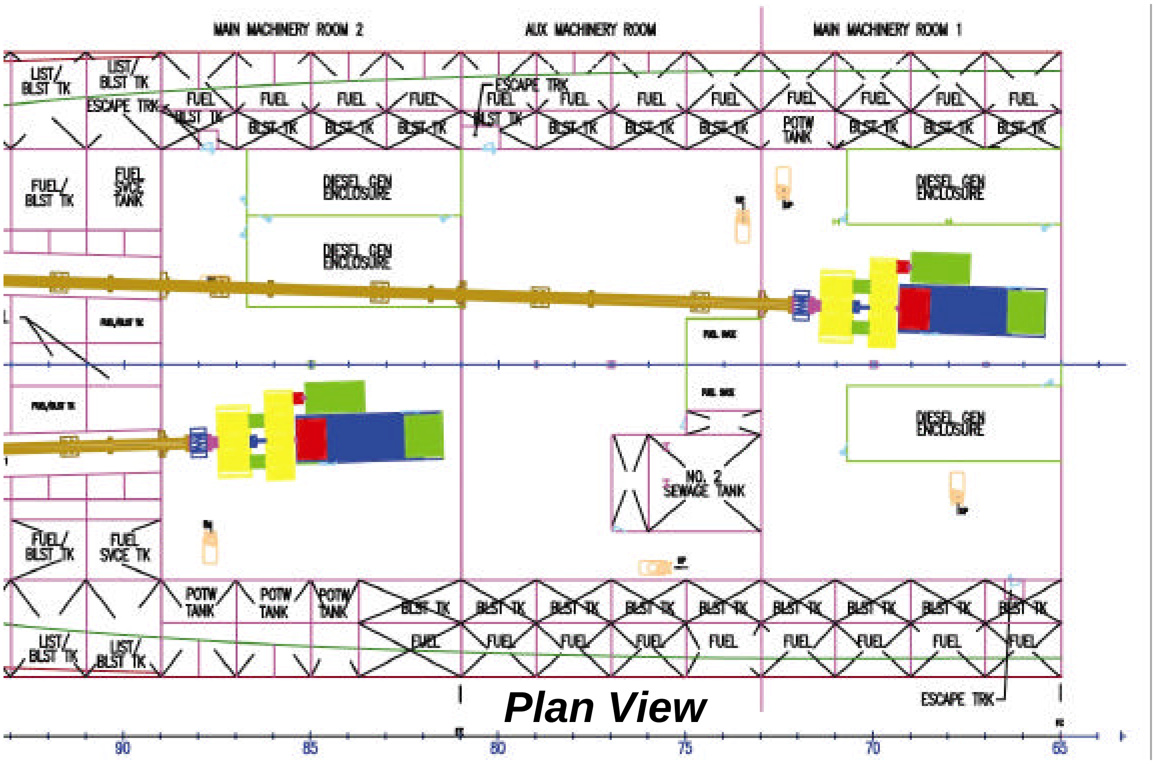


Figure 6 – Baseline Machinery Arrangement (LHD-8)

2.2.2 Purple Mission Spaces

This study considered alternatives to increase area designated as Joint Spaces (designated Purple) to include C4I (Joint), office spaces, mission planning and berthing to support Small Scale Contingency (SSC) JTF or, if designated by the Operational Commander, MEB/CPG staff (135 total staff billets). Its intent was to designate these spaces as separate and distinct from those used routinely by embarked PHIBRON/MEU staff.

2.2.3 'Bomb Farm' Alternatives

The purpose of this study was to define the feasibility and impacts of locating an aviation weapons staging area below the flight deck. Issues included: preliminarily locating and sizing of a handling and stowage area, and identifying flow routes between magazines, bomb farm and flight deck (Figure 7).

Figure 7 – Hangar Deck and Flight Deck Bomb Farms (CVN)

2.2.4 Increased Vehicle Square and Cargo Cube

The purpose of this study was to determine vehicle square and cargo volumetric threshold and objective goals, and select preferred options. Preliminary results were as follows:

- Threshold:
  - Vehicles: USS TARAWA Class (25,400 SQFT)
  - Cargo: USS WASP Class plus allowance increase for MV-22 & JSF (140,000 cubic feet)
- Objective:
  - Vehicles: 30,000 SQFT with optimal cargo flow
  - Cargo: Sufficient capacity for ACE and GCE for 15 days operation
- Drivers:
  - Notional Vehicle Load
  - Proposed Air Wing Load (15 days operation)
- Impacting Studies:
  - Selective Offload (Trade Study 6)
  - Key Mission Loads Definition (Trade Study 8)
  - Longitudinal Bulkhead Location (Trade Study 11)
  - Bomb Farm

2.2.5 Distributed vs. Consolidated Galley

The objective of this study was to identify efficient alternate galley configuration(s) by evaluating the Consolidated and Distributed Galley arrangements. The following options were considered:

- Consolidated Galley (AoA Design)
- Distributed Galley (PD-1 Baseline Design)
- Alternative Distributed Galley Option 1: Separate Crew/Troop Galley, consolidated WR/CPO/SNCO Galley.
- Alternative Distributed Galley (ADG) Option 2: Relocate Wardroom food service complex, separate CPO/SNCO Galley, consolidated WR/Crew/Troop Galley.

Alternative Distributed Galley Option 1 included the following:

- Wardroom Food Service Complex unchanged -
  - Consolidates Wardroom Galley with CPO/SSNCO Galley on Main Deck.
  - Wardroom food prepared in CPO/SSNCO Galley, dumbwaiter used to transport food up to Wardroom Serving Annex.
  - Retention of griddles in Wardroom Serving Annex for “cook to order” foods.
- Crew Mess Area changes -
  - E-6 Messroom starboard, relocated to messing area port side Fr 49B, becomes unassigned space.
  - Relocate Conveyor trunk No. 3, Fr 61 starboard
  - Unassigned space, port side Fr 57, designated as Crew Messroom/Multi-purpose Room.
- CPO/SNCO Mess Area changes -
  - WR/CPO/SSNCO Galley and Scullery relocated forward for easy access.
  - Bread Room combined/relocated into Bakery. CPO and SSNCO lounge moved outboard to compartment vacated by Bread Room.

ADG Option 2 was the same as ADG Option 1 but with Senior Officer Quarters located in a CPS zone.

2.2.6 Dedicated Troop Training and Muster Space

The need for this study was driven by a USMC Requirements letter which specified the following requirements, preferences and deficiencies:

- Dedicated training space is required for 200 Troops (Figure 8).
- The existing LHA/LHD training and marshaling space is utilized as exercise/weight room for ship’s crew and embarked troops. There is no large dedicated training space available for marines.
- The hangar bay is used for troop muster or marshaling area. A dedicated space would be preferable.
- Multi-mission spaces are not suitable for dual uses as Troop training spaces and Troop marshaling spaces.

The study objective was to determine the requirement for a large, dedicated troop training space or a large multi-purpose space, possibly used for training, troop muster, recreation or other purposes. The following options were considered:

- Option 1: Relocate exercise/weight room equipment to unassigned spaces and return Troop Training and Marshaling space to original purpose. Located forward on 02 Level.
- Option 2: Design a dedicated multipurpose space located on 01 level adjacent to Medical and cargo elevators to be utilized by Ship's Company/Embarked Personnel. Proposed area located on 01 Level adjacent to Medical and cargo elevators.
- Option 3: Redesign current Ship Training Area (4-30-0-Q) and include canvas and bunting shop, relocate CBR store room and crew baggage store room.

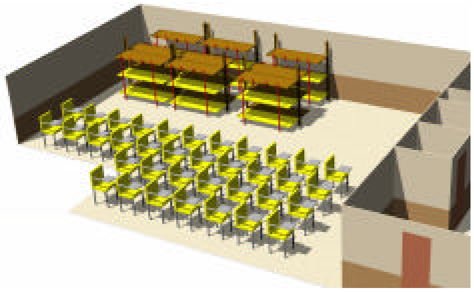


Figure 8 – Notional Training Space

2.2.7 Boat Stowage and Handling

The goals of this study were to:

- Assess volume impact of various Stern Launch arrangements on LHA(R)
- Assess major space impacts of Stern Launch options

The approach included the following steps:

- Determine LHA(R) minimum boat requirements
- Determine volume of legacy ship boat volumes and mix (Table 2)
- Identify Stern Launch arrangement concept options (Figure 9 and Figure 10)
- Project concept options onto the LHA(R) General Arrangement drawings
- Identify volume requirements and space impacts

Table 2 - BOAT MIX – LEGACY vs LHA(R)

TYPE	PERS	MISSION	LHD 7/8	LPD 17	LHA(R)
7M RIB	6	Rescue	1	2	1
36' LCPL	17	Amphibious Control Ops/ Liberty Boat	1-Davit (2-Dolly)*	0	0
11M Navy Standard RIB **	26	Logistics/ Liberty	0	1	2
11M NSW RIB	3 Crew 8 Mission	Special Ops	0	0	1
50' UB	142	Logistics/ Liberty	2	0	0

* LHD capable of accommodating 2 additional LCPL – stacked on UB

** Standard Navy 11 Meter RIB, under development – larger than NSW RIB

Figure 9 - LHD Transom-Stern Gate

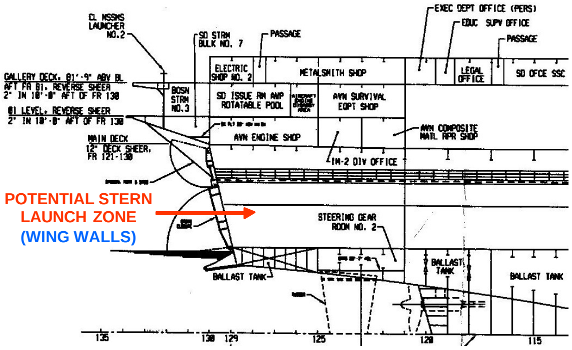


Figure 10 – Stern Launch Zone

Possible stern launch configurations included:

- Well with fixed Ramp (Figure 11)
  - Inclined Ramp allows gravity launch (and recovery)
  - Low slope will require either mechanical assist for launch/recovery
  - Above water line well flooded for boat launch/ recovery using ship's ballasting system
- Extending-Hinged Ramp
  - Requires mechanical system
  - Does not require ballasting down for boat launch/ recovery
  - Could avoid use of ballast tanks for Stern Launch system
- Well with two boats in tandem
- Inclined Ramp with two boats in tandem
- Boats stacked in Wing Walls, with Hoist System for handling upper boat to/from Launching Well

The preliminary conclusions of this study were:

- Incorporating Stern Launch to extent needed to accommodate all boats (less 7M Rescue Boat) will have major impact on LHA(R)
- Volume requirements not much different from legacy volumes devoted to boats
- Using Starboard wingwall appears more feasible than Port, because of main Stern Gate Machinery Room on Port Side
- "Ballast down" Stern Launch options are simpler and would provide for more boats, but require more dynamic modeling to assess effects in a seaway
- Inclined and Extending Ramp options are more predictable, but are more complex and would provide fewer boats
- 7M RIB must be launched & recovered from Davit because Rescue Boat is required to be ready at all times
- 11M RIBs can be launched & recovered by Stern Launch
- Landing Force Special Ops Craft will be embarked and handled as Combat Load via Well Deck or HELO lift

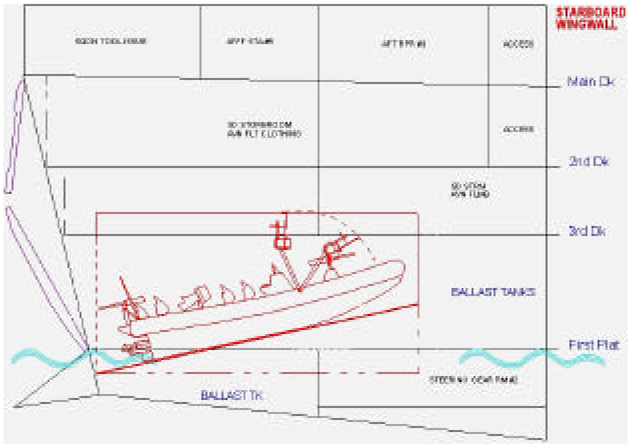


Figure 11 – Well with Fixed Ramp

2.3 Design Space Summary and Ship Impact

Alternatives for improvement of LHA(R) were identified during the US Navy trade studies. Table 1 lists a subset of these trades and options available for each trade as revisited in this study. In the design optimization, each study is assigned a design variable that can assume discrete values equal to the options considered in that trade study. Selection of a particular option results in a specific value of performance (VOP) determined by the panel of experts and applied in the Overall Measure of Effectiveness (OMOE), and in ship impacts on arrangeable area, weight, change in KG and cost. Table 4 lists these impacts. Only limited cost impacts were made available.

Table 3 - Description of the Design Variables

Design variable	Options	Option Description
Hangar length and High Hats	Option 1	Consume "Composite Shop" and space above into Hangar.
	Option 2	Increase High Hat length by 2 frames on aft end.
	Option 3	Consume "Composite Shop" and space above into Hangar + Additional 5-frame High Hat starting at frame 122.
	Option 4	Combination of 2 + 3
	Option 5	Baseline
Aviation Maintenance and Stowage	Option 1	Find alternative location - new stores - for "Supply Mountain" equipment and spares.
	Option 2	New spaces for projected requirement for 11,556 cubic feet and 40 lton for new ACE (over legacy ACE) plus 2,700 cubic feet shortfall from legacy ACE.
Increased Cargo Cube	140 k Sq. ft.	Baseline
	150 k Sq. ft.	
	160 k Sq. ft.	
	170 k Sq. ft.	Additional stowage space located FWD of well under ramp on 1st plat for small arms/inert cargo - no ballistic protection.
Increased Vehicle Square	25400 Sq. ft.	Baseline
	26000 Sq. ft.	Relocated Gas Turbine exhaust high hat impinging on 1st platform vehicle stowage. Contingent on results of 22 know machinery study. Approx. 800 sq. ft. gross returned to vehicle square.
	26500 Sq. ft.	Optimize arrangements in upper vehicle deck. Relocate ICE, etc.
	27000 Sq. ft.	Both Changes Made
Galley	Option 0	Distributed Galleys
	Option 1	Consolidated WR/CPO/SSNCO Galley
	Option 2	Consolidated WR/Crew/Troop Galley
Dedicated Troop Training and Muster Spaces	Option 0	LHD-8 Baseline
	Option 1	Relocate exercise equipment and utilize existing troop training and muster space as such.
	Option 2	Design dedicated space on 01 Level or 02 level, potentially use existing space, and relocate exercise equipment - distributed exercise rooms.
	Option 3	Redesign current ship training area, adjacent shops/STRMs
Boat Stowage and Handling	External	Install additional fixed overhanging davit for 11M, retain existing LCPL davit
	Internal	Internal stowage for both 11m RIB with fixed launching/recovering system.

Design variable	Options	Option Description
Medical	Baseline	PD-2 Medical capabilities - 6 OR's, 2 dental OR's, 23 ICU beds, 65 ward beds (Level II)
	Option 1	Reduced medical capability.
Damage Tolerance 1: Plating	Option 2b	TSS Preferred Option - Just less than best performance
	Option 3	Best Performance
Damage tolerance 2: DAPS	Option 0	Remove DAPS.
	Option 1	TSS Preferred Option - best performance
	Option 2	
	Option 3	Negotiated Option
	Option 4	
	Option 5	
	Option 6	Worst Performance
Damage tolerance 3: UNDEX	Option 1(HSLA 65)	TSS Preferred Option, HSLA 65
	Option 2 (HSS)	HSS Option, ~same performance
IR Signatures	IR 3	LHD-8 Baseline
	IR 2	Midline Option
	IR 1	ESS and EMS, fore and aft
Acoustic Signatures	Tech 2	Remove Tech 1
	Tech 1	Remove Tech 2
	Tech 1+2	Technology 1 & Technology 2,Included in baseline PD-2
Purple Mission Spaces	Option 1	Minimum compliance with MEB/JTF ref. docs.
	Option 2	Moderate compliance with MEB/JTF ref. docs.
	Option 2.1	Flexible spaces with moderate compliance with MEB/JTF ref. docs.
	Option 3	Maximum compliance with MEB/JTF ref. docs.
Bomb Farm Alternatives	External	Bomb Farm on Flight Deck
	Internal	Internal Bomb Farm on Main Deck adjacent to Elev 1 & 3. Min. protection.
Machinery	Option A	LHD 8 mechanical drive system
	Option B	"Flipped Shaft" new mechanical drive system
	Option C	New mechanical drive system
	Option E	Combined GT & APS drive system
	Option F	Mechanical drive system w/de-rated MT-30

Table 4 - Impact of Design Variable Options on Area, Weight, KG and Cost

Design variable	Option	Significant Impact on					
		Area, sq.ft.	**Weight, LT**	**KG, feet**	**Cost**	**Sustained Speed**	**RCS**
Hangar length and high hats	Option 1	3,800	0				
	Option 2	1,120	0				
	Option 3	6,500	7	-0.01			
	Option 4	7,620	7	-0.01			
	Option 5	0	0	0			
Aviation Maintenance and stowage	Option 1	400	0	0			
	Option 2	2,100	40	0			
Increased cargo cube	140 k	0	0	0			
	150 k	800					
	160 k	1600					
	170 k	2,400					
Increased vehicle square	25400	0					
	26000	600					
	26500	1100					
	27000	1600					
Galley	Option 0	0					
	Option 1	-540					
	Option 2	-540					
Dedicated troop training and muster spaces	Option 0	0					
	Option 1	3400					
	Option 2	3000					
	Option 3	3670					
Boat stowage and handling	External	0	15				Increase RCS
	Internal	3000					Decrease RCS
Medical	Baseline	0					
	Option 1	-1400					
Damage tolerance 1: Plating	Option 2b		108				
	Option 3		428				
Damage tolerance 2: DAPS	Option 0	0	0				
	Option 1	5,880	261				
	Option 2	4,900	225				
	Option 3	3,920	189				
	Option 4	2,940	151				
	Option 5	1960	117				
	Option 6	980	83				

Design variable	Option	Significant Impact on					
		Area, sq.ft.	Weight, LT	KG, feet	Cost	Sustained Speed	RCS
Damage tolerance 3: UNDEX	Option 1(HSLA 65)		550				
	Option 2 (HSS)		1000				
IR Signatures	IR 3		0				
	IR 2		-2		1.3M		
	IR 1		-4		1.3M		
Acoustic signatures	Tech 2		-20				
	Tech 1		100				
	Tech 1+2		0				
Purple mission spaces	Option 1	545					
	Option 2	3,413					
	Option 2.1	2,400					
	Option 3	6,272					
Bomb Farm alternatives	External	0	0	0			
	Internal	2,000	117	0.05			
Machinery	Option A	0	0	0.00			
	Option B		-74	0.07			
	Option C		-74	0.07			
	Option E	0	-35				
	Option F	0	-20				

3 Developing an Overall Measure of Effectiveness (OMOE) for LHA(R)

3.1 OMOE Process

This multi-objective ship design optimization requires quantitative objective-attribute metrics and functions for cost and overall mission effectiveness. Important terminology used in describing effectiveness 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
- 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.
- Design Variables (DVs) – Ship physical characteristics controlled by the designer; used to define a ship design at a level of detail appropriate for a particular design stage.

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 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. This can be structured as a multi-attribute decision problem. Two methods for structuring these problems dominate the literature: Multi-Attribute Utility Theory (Keeney and Raiffa 1976) 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 (Belton, 1986). This approach is adapted here for deriving an OMOE.

The analytical hierarchy process (AHP) is a tool developed by Saaty (1996) for solving multi-attribute decision problems. It uses a hierarchical structure to abstract, decompose, organize and control the complexity of decisions involving many attributes, and it uses informed judgment or expert opinion to measure the relative value or contribution of these attributes and synthesize a solution. Pair-wise comparison and an eigenvalue approach extract and quantify this relative value. The method allows and measures inconsistency in value measurement, and is able to consider quantitative and qualitative attributes.

A hierarchy is a simplified abstraction of the structure of a system used to study and capture the functional interactions of its attributes, and their impact on total system behavior or performance. It is based on the assumption that important system entities or attributes, which must first be identified, can be grouped into sets, with the entities of one group or level influencing the entities of the neighboring group or level. One can conceptualize a hierarchy as a bottoms-up synthesis of influence on the top level behavior of a system, or as the top down distribution of influence of top level behavior to low level attributes. Alternatives are compared in terms of the lowest level attributes and this comparison is rolled up through hierarchy levels to an assessment of relative overall system behavior or performance.

The first step in building an AHP hierarchy is to identify critical attributes affecting the decision or system behavior. The level of detail of these attributes depends on the decision being made. These attributes are then organized into a hierarchy structure that follows a logical breakdown or categorization. In this application, system measures of effectiveness (MOPs) comprise the bottom hierarchy level.

Next, the relative influence of each attribute on system performance and attribute values for each alternative must be estimated. Saaty recommends a nine level dominance scale for the pair-wise comparison of attribute influence on higher level attributes. This results in a “ratio scale” comparison of attributes. Pair-wise comparison or cardinal values may be used to assign attribute values for each alternative. Pair-wise comparison generates more information than is necessary with individual absolute measurements or estimates. The AHP synthesizes and evaluates the consistency of this redundant information and calculates best-fit relative values.

Although the AHP was developed primarily for comparison of management alternatives, it has also proven to be a robust method for application in MAVT. The AHP provides a structured method for deriving an additive weighted value function, and by careful application can also be used to derive non-linear attribute value or utility without the more cumbersome lottery comparison approach.

The OMOE function must include all important effectiveness/performance attributes, both discrete and continuous, and ultimately be used to assess an unlimited number of ship alternatives. Successful application AHP/MAVT to this problem requires a very structured and disciplined process as follows:

1. **Identify, define and bound decision attributes.** Identify critical mission scenarios. Identify Measures of Effectiveness (MOEs) for each mission scenario. Establish goals and thresholds for all MOEs. Identify ship MOPs critical to mission scenario MOE assessment and consistent with the current design hierarchy level. Set goals and thresholds for these MOPs.
2. **Build OMOE/MOP hierarchy**. Organize MOEs and MOPs into a hierarchy with specific ship MOPs at the lowest level. Association with the performance of a discrete system may define some MOPs. Others are continuous performance variables such as sustained speed.
3. **Determine MOP value and hierarchy weighting factors.** Use expert opinion and pair-wise comparison to determine MOP value and the quantitative relationship between the OMOE and MOPs.

Thresholds represent absolute minimum acceptable performance. Goals typically represent either a point of diminishing marginal value or a technology limitation. The pair-wise comparison is structured to compare the relative value of MOP options to achieve the OMOE.

Once MOP value is determined for all MOPs, pair-wise comparison is used to determine MOP and MOE hierarchy weights. In this case the pair-wise comparison is structured to compare the relative value of achieving the goal in the first MOP or MOE and only the threshold in the second, versus achieving only the threshold in the first MOP and the goal in the second. This pair-wise comparison is accomplished at all levels of the hierarchy. An eigenvalue approach is used to extract and quantify average relative values and an inconsistency measurement. An OMOE function, OMOE = g(MOP), is derived from these weights and from the MOP value functions.

$$OMOE = \sum_i w_i VOP_i\left(MOP_i\right) \tag{2}$$

where w_i represents individual MOP weights and $VOP_i(MOP_i)$ are the VOP functions or values.

3.2 LHA(R) OMOE

As discussed in Section 2.3, each design study is assigned a design variable that can assume discrete values equal to the options considered in that trade study, Table 1. For discrete design alternatives, the option selected is itself a measure of performance (MOP). Selection of a particular option results in a specific value of performance (VOP) determined in this study by a panel of experts (Section 3.3) and applied in the Overall Measure of Effectiveness (OMOE). Sustained Speed, Seakeeping, KG Service Life Allowance (SLA), and Weight SLA are continuous MOPs. VOP functions for each of these MOPs relate a value of performance to a value of these MOPs where VOP = 0 corresponds to the threshold value of a particular MOP and VOP = 1 corresponds to the goal value. The LHA(R) MOPs are organized in an OMOE hierarchy (Figure 12) with mission, mobility, survivability and own-ability as trade/performance categories. Options/MOPs are at the bottom of the hierarchy (Figure 13). Option VOPs and hierarchy weights (Table 7) are determined using AHP and pairwise comparison questionnaires (Table 6).

3.3 Collecting Expert Opinion – LHA(R) Panel of Experts

Dr. Brown facilitated the pairwise comparison meeting. The goal of the meeting was to solicit knowledge about the relative importance of the trade studies from a panel of experts using pairwise comparison of elements in the hierarchy. The panel of experts included professionals identified as having knowledge about the mission requirements and no particular stake in any specific area of the ship design. The participants in the panel of experts and their respective organizations are listed in Table 5.

Participants were briefed on the goal of the meeting and how the OMOE supports the design and requirements process. They were told:

- Not to attempt to manipulate results, high-ball or low-ball to achieve their agenda
- That scores of 9 should be very unusual; with 3s and 5s most common
- To compare only on the basis of perceived effectiveness (performance), not to consider acquisition cost or ship impact. These are accounted for separately.

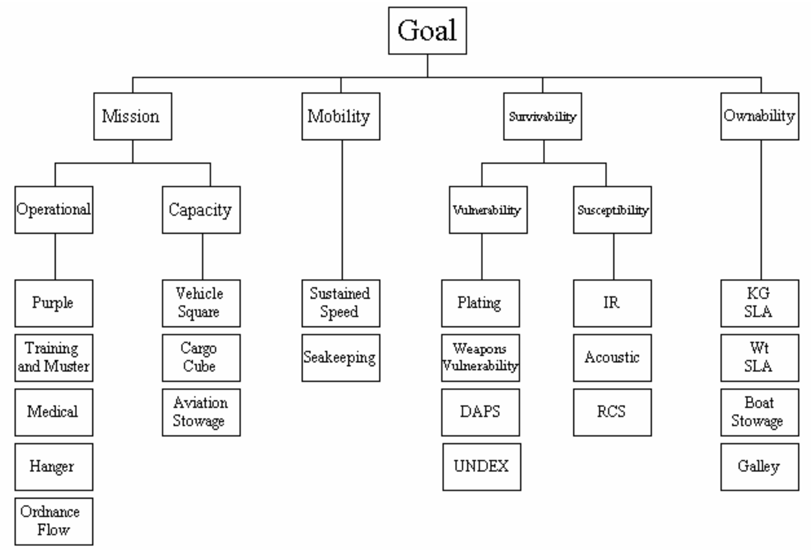
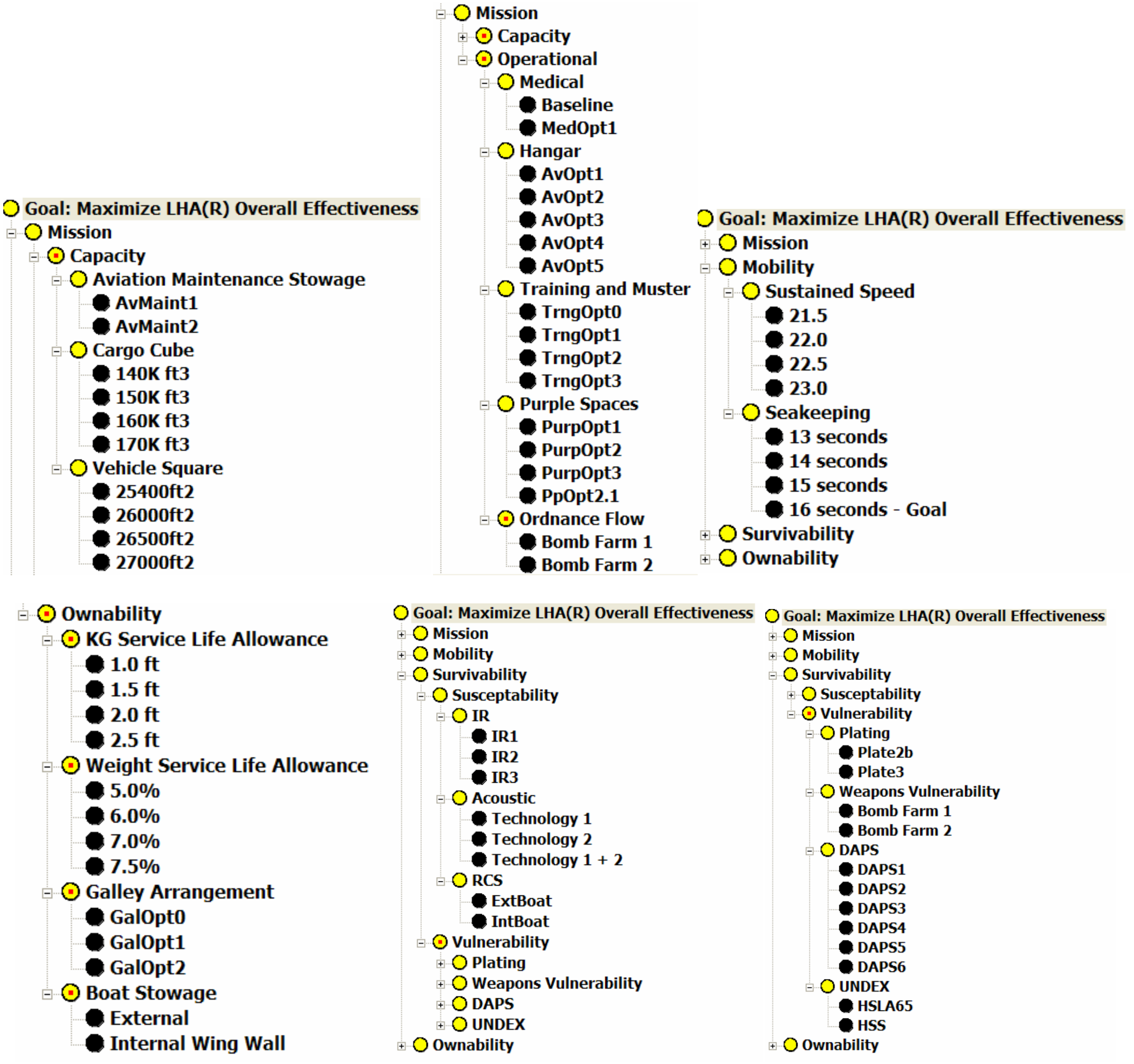


Figure 12 – LHA(R) OMOE Hierarchy



- Goal: Maximize LHA(R) Overall Effectiveness
  - Mission
    - Capacity
      - Aviation Maintenance Stowage
        - AvMaint1
        - AvMaint2
      - Cargo Cube
        - 140K ft3
        - 150K ft3
        - 160K ft3
        - 170K ft3
      - Vehicle Square
        - 25400ft2
        - 26000ft2
        - 26500ft2
        - 27000ft2

- Mission
  - Capacity
  - Operational
    - Medical
      - Baseline
      - MedOpt1
    - Hangar
      - AvOpt1
      - AvOpt2
      - AvOpt3
      - AvOpt4
      - AvOpt5
    - Training and Muster
      - TrngOpt0
      - TrngOpt1
      - TrngOpt2
      - TrngOpt3
    - Purple Spaces
      - PurpOpt1
      - PurpOpt2
      - PurpOpt3
      - PpOpt2.1
    - Ordnance Flow
      - Bomb Farm 1
      - Bomb Farm 2

- Goal: Maximize LHA(R) Overall Effectiveness
  - Mission
  - Mobility
    - Sustained Speed
      - 21.5
      - 22.0
      - 22.5
      - 23.0
    - Seakeeping
      - 13 seconds
      - 14 seconds
      - 15 seconds
      - 16 seconds - Goal
  - Survivability
  - Ownability

- Ownability
  - KG Service Life Allowance
    - 1.0 ft
    - 1.5 ft
    - 2.0 ft
    - 2.5 ft
  - Weight Service Life Allowance
    - 5.0%
    - 6.0%
    - 7.0%
    - 7.5%
  - Galley Arrangement
    - GalOpt0
    - GalOpt1
    - GalOpt2
  - Boat Stowage
    - External
    - Internal Wing Wall

- Goal: Maximize LHA(R) Overall Effectiveness
  - Mission
  - Mobility
  - Survivability
    - Susceptability
      - IR
        - IR1
        - IR2
        - IR3
      - Acoustic
        - Technology 1
        - Technology 2
        - Technology 1 + 2
      - RCS
        - ExtBoat
        - IntBoat
    - Vulnerability
      - Plating
      - Weapons Vulnerability
      - DAPS
      - UNDEX
  - Ownability

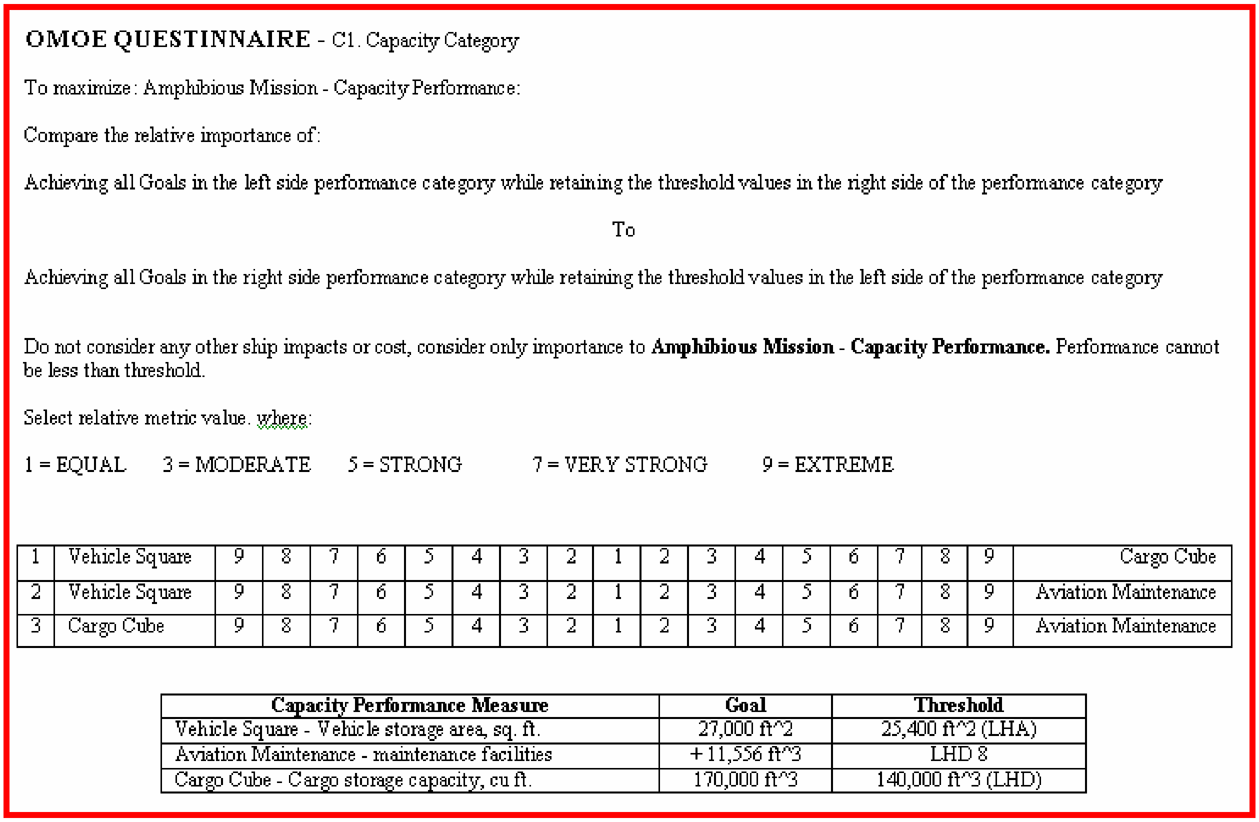
- Goal: Maximize LHA(R) Overall Effectiveness
  - Mission
  - Mobility
  - Survivability
    - Susceptability
    - Vulnerability
      - Plating
        - Plate2b
        - Plate3
      - Weapons Vulnerability
        - Bomb Farm 1
        - Bomb Farm 2
      - DAPS
        - DAPS1
        - DAPS2
        - DAPS3
        - DAPS4
        - DAPS5
        - DAPS6
      - UNDEX
        - HSLA65
        - HSS
  - Ownability

Figure 13 – Trade Study Options/MOPs and Continuous MOPs in OMOE Hierarchy

Table 5 – Panel of Experts

Name	Organization
Brian Bergman	CSC/Design Integration
Martin Pompeo	OPNAV N75
Col Gary Warner	NAVSEA PEO Ships
Maj Jeff Hagan	HQMC/PP+O
Doug Keith	Tech Marine/Program Support
Tom Gorski	Tech Marine
Michael Arnold	PMS377
Earl Cruse	CSC
Jason Reynolds	NAVSEA
Dick Milligan	SEA05D
Doug Haefeli	NAVSEA
Marty Bodrog	T-MB/N75

The experts were given brief descriptions of the trade studies and the alternatives for each study. They were then asked to complete the questionnaires (Table 6), one at a time, with a discussion of the options before completing each questionnaire.



OMOE QUESTINNAIRE - C1. Capacity Category

To maximize: Amphibious Mission - Capacity Performance:

Compare the relative importance of:

Achieving all Goals in the left side performance category while retaining the threshold values in the right side of the performance category

To

Achieving all Goals in the right side performance category while retaining the threshold values in the left side of the performance category

Do not consider any other ship impacts or cost, consider only importance to **Amphibious Mission - Capacity Performance.** Performance cannot be less than threshold.

Select relative metric value. where:

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

1	Vehicle Square	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Cargo Cube
2	Vehicle Square	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Aviation Maintenance
3	Cargo Cube	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Aviation Maintenance

Capacity Performance Measure	Goal	Threshold
Vehicle Square - Vehicle storage area, sq. ft.	27,000 ft^2	25,400 ft^2 (LHA)
Aviation Maintenance - maintenance facilities	+11,556 ft^3	LHD 8
Cargo Cube - Cargo storage capacity, cu ft.	170,000 ft^3	140,000 ft^3 (LHD)

Table 6 – Single Page from VOP Questionnaire

3.4 AHP Results – OMOE Function

The questionnaires were collected and the data was input into an excel spreadsheet. The standard deviation of the response for each pairwise comparison was calculated to determine consistently. The standard deviation for each hierarchy element is listed in Figure 14 where the number by each element is the standard deviation of the pairwise comparison of the elements one level below the current level. Good values are less than 2. Acceptable values are less than 3. Higher values indicate a strong difference of opinion or indifference. The values in this study indicate reasonable convergence, but time permitting; the process should have been repeated after discussion. This usually results in significant improvement.

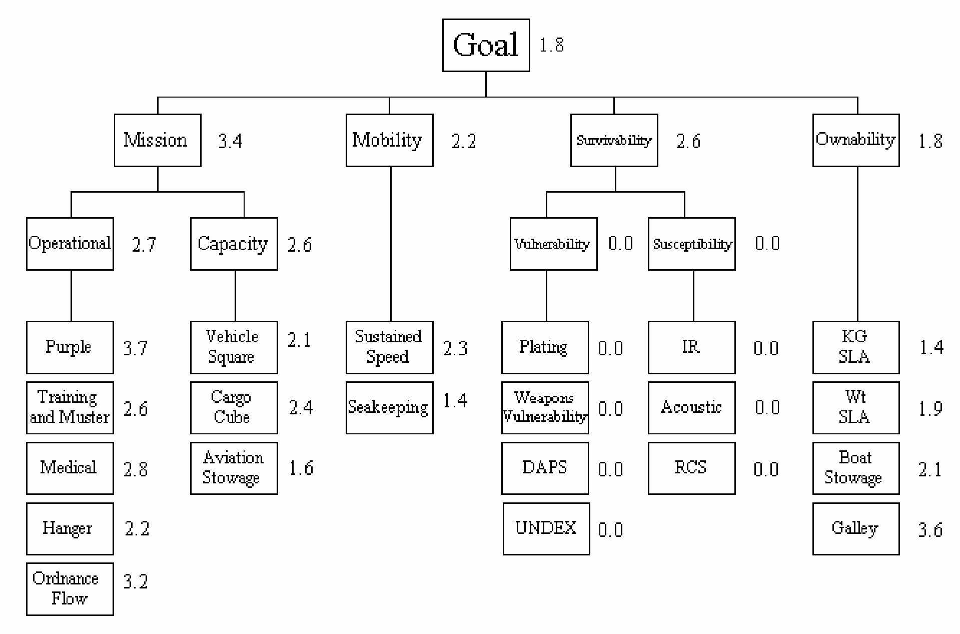


Figure 14 – OMOE Hierarchy with Standard Deviations

AHP was used to calculate MOP weights and option VOPs (Equation 2, Table 7 and Figure 15).

Table 7 - Design Variable Alternatives and their Value of Performance

	Design Variable	Design Variable Weight	Alt-1 VOP	Alt-2 VOP	Alt-3 VOP	Alt-4 VOP	Alt-5 VOP	Alt-6 VOP	Alt-7 VOP
1	Hangar	0.197	0.241	0.224	0.484	1	0.091		
2	Aviation maintenance stowage	0.066	0.2	1					
3	Cargo Cube	0.020	0.8	0.9	0.95	1			
4	Vehicle Square	0.036	0.827	0.827	0.904	1			
5	Galley Arrangement	0.018	0.5	0.5	1				
6	Training and Muster spaces	0.055	0.5	1	0.707	0.707			
7	Boat Stowage	0.018	0.9	1					
8	Medical	0.028	1	0.8					
9	Plating	0.110	0.143	1					
10	DAPS	0.020	1	0.655	0.417	0.263	0.168	0.112	0.0
11	UNDEX	0.046	1	0.143					
12	IR	0.005	1	0.395	0.094				
13	Acoustic	0.037	0.237	0.094	1				
14	Purple spaces	0.065	0.284	0.333	0.403	1			
15	Ordnance Flow	0.080	1	1					
16	Weapons Vulnerability	0.032	1	1					
17	RCS	0.022	1	0.0					

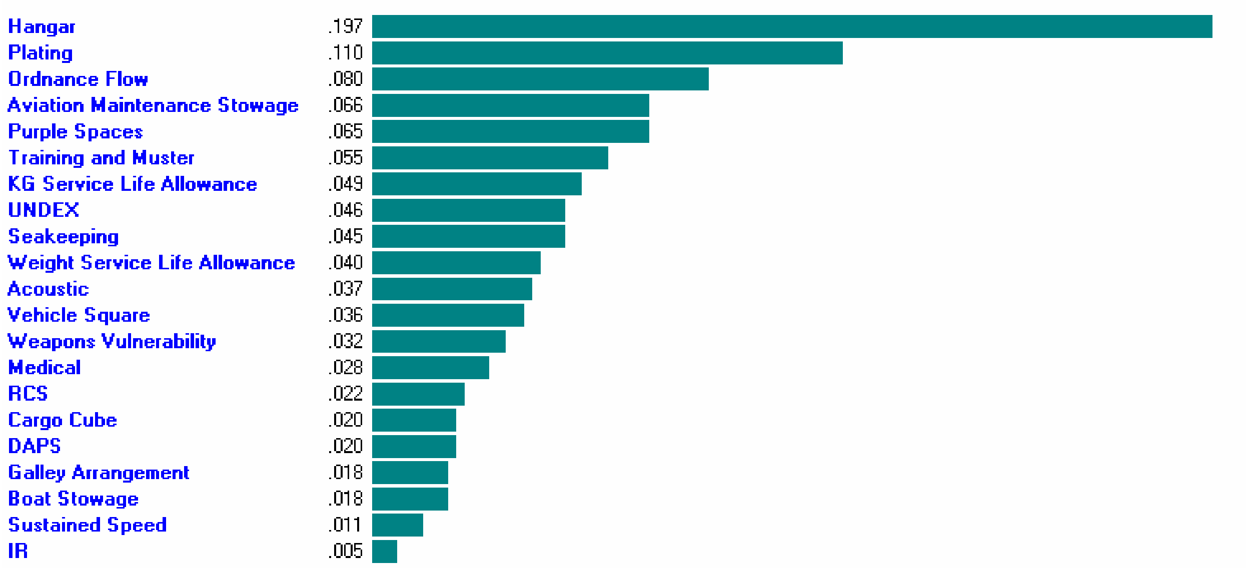


Figure 15 – MOP Weights

4 Multi-Objective Genetic Optimization (MOGO)

As discussed in Chapter 1, a multi-objective genetic optimization (MOGO) was performed using Model Center as the design environment, DARWIN as the MOGO optimizer in Model Center, ASSET as the ship synthesis model, the OMOE function developed as discussed in Chapter 3, design variables listed in Table 3, and a weight-based cost model. A baseline ship in ASSET, similar to PD-2 was provided by the Naval Surface Warfare Center, Carderock Division (NSWCCD). New designs are generated in ASSET by applying the impact of the various trade study option combinations (design variables) to the baseline ship. The feasibility of each of these new designs is evaluated using ASSET. The OMOE and cost of feasible designs are used as objective attributes in DARWIN. The process of generating new designs is repeated until no improvement is made after some number of generations or the maximum number of generations is reached.

4.1 Ship Synthesis Model – ASSET MonoCV

The Advanced Surface Ship Evaluation Tool (ASSET) is a family of interactive computer programs developed primarily by NSWC Carderock for use in the early stage design of naval surface ships. The primary purpose of ASSET is to perform the initial prediction of ship physical and performance characteristics based on mission requirements with sufficient fidelity that the total ship implications of subsystem level design and technology decisions are evident. In this study we use the MonoCV (Monohull Aircraft Carrier) version of ASSET. MonoCV includes an Aviation Support Module. This module addresses those characteristics unique to aircraft carriers including flight deck, catapults, arresting gear, hangars, sponsons, aircraft, weapons, and cargo elevators, aircraft complement and support requirements, magazines and protection systems.

Figure 16 shows the flow chart for the individual modules in ASSET. ASSET balances a design by the combined function of multiple individual modules rather than by a global algorithm. Each individual module modifies the current model in ASSET. For example, depending on how ASSET is configured by the user (switch settings): the hull geometry module adjusts beam, depth and draft to provide adequate stability, space, balance weight and displacement and provide sufficient height of the machinery room space; the deckhouse module adjusts deckhouse size to provide sufficient deckhouse area; the machinery module computes fuel requirements which drives ship weight and volume; and many modules perform analyses that change weight, area, power and stability. Modules also supply default and temporary values to the current model when not provided by the user or before other modules have been run to calculate these values. Individual modules are run consecutively until convergence. The input and output connectivity between modules is not entirely consecutive, and multiple iterations are required to achieve consistent input and output across all modules. Convergence in ASSET occurs when two iterations through the synthesis loop produce sufficiently identical designs.

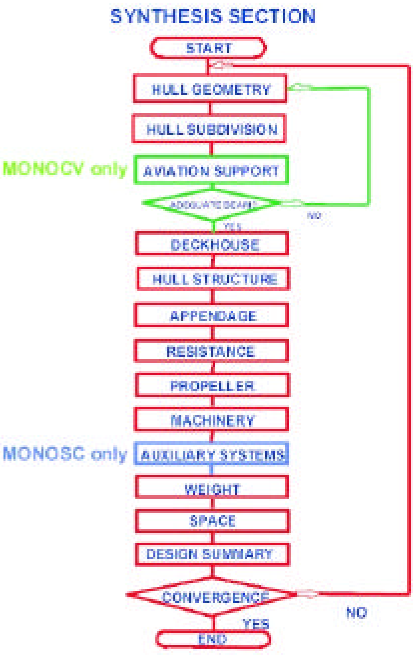
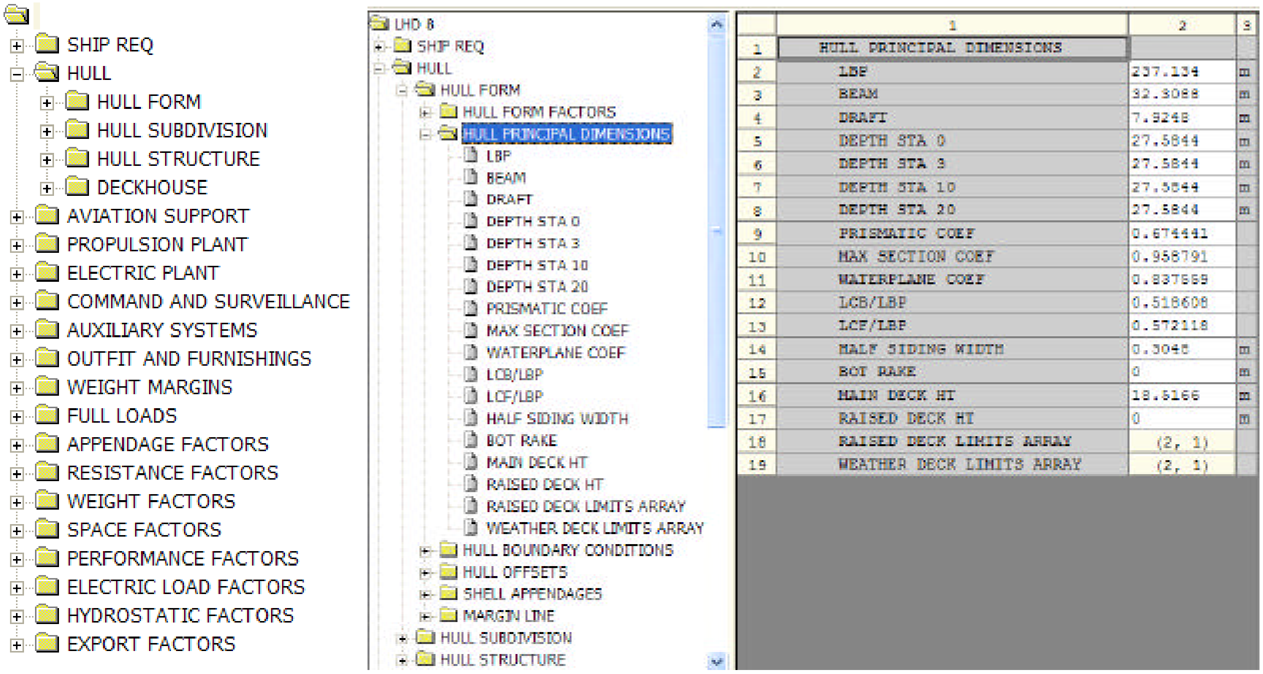


Figure 16 – ASSET Flow Chart

Ship design data in ASSET are stored in databanks using a multi-level, tree-type hierarchy as illustrated in Figure 17. The list of these parameters is called the model parameter list (MPL). In this study, the databank for the baseline ship and all the trade study options were provided by the Naval Surface Warfare Center, Carderock Division (NSWCCD). The databank can be edited in ASSET using either the edit tool or the command line. A continuous block of data (data that occupies contiguous blocks in the MPL) can be stored, edited and inserted in a databank as a single component. Instead of sending individual commands editing each of the parameters in a block, a single command can be used to insert an entire component. The impact of a number of the options in this study was implemented using components. ASSET has tabular and graphical displays which are used to describe and present a particular design as defined by the MPL data (Figure 18 and Table 8).

A single design is used and identified in ASSET as the "current" design. All changes, synthesis operations and data displays operate on the current design data. The current design is stored separately from the main databank and must be saved in the main databank before exiting or operating on a new current design.



	1	2	3
1	HULL PRINCIPAL DIMENSIONS		
2	LBP	237.134	m
3	BEAM	32.3088	m
4	DRAFT	7.9248	m
5	DEPTH STA 0	27.5844	m
6	DEPTH STA 3	27.5844	m
7	DEPTH STA 10	27.5844	m
8	DEPTH STA 20	27.5844	m
9	PRISMATIC COEF	0.674441	
10	MAX SECTION COEF	0.958791	
11	WATERPLANE COEF	0.837869	
12	LCB/LBP	0.518608	
13	LCF/LBP	0.572118	
14	HALF SIDING WIDTH	0.3048	m
15	BOT RAKE	0	m
16	MAIN DECK HT	18.5166	m
17	RAISED DECK HT	0	m
18	RAISED DECK LIMITS ARRAY	(2, 1)	
19	WEATHER DECK LIMITS ARRAY	(2, 1)	

Figure 17 – ASSET Databank

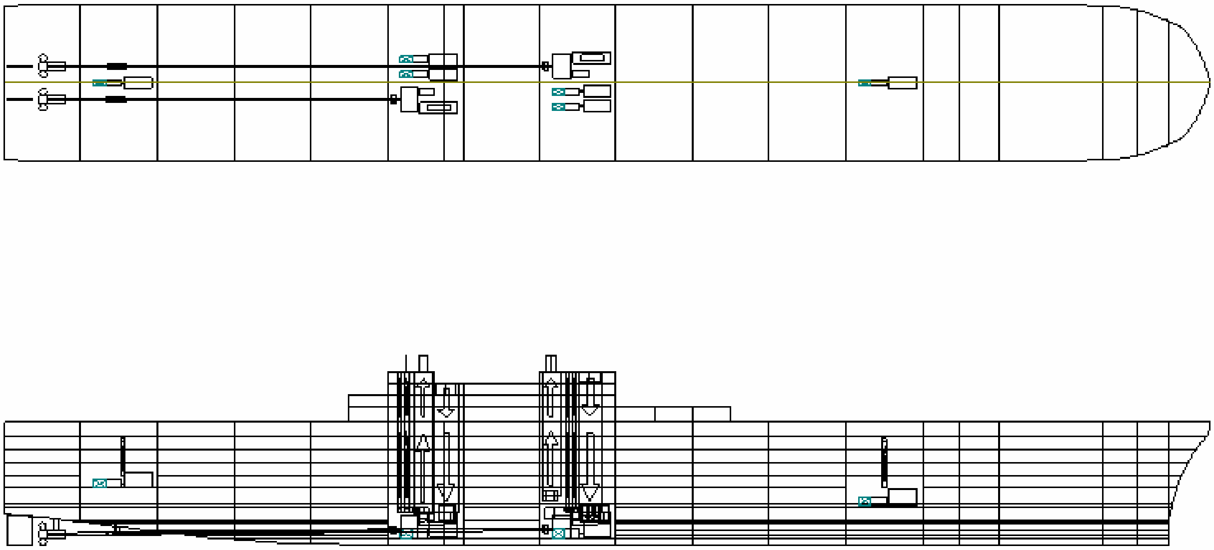
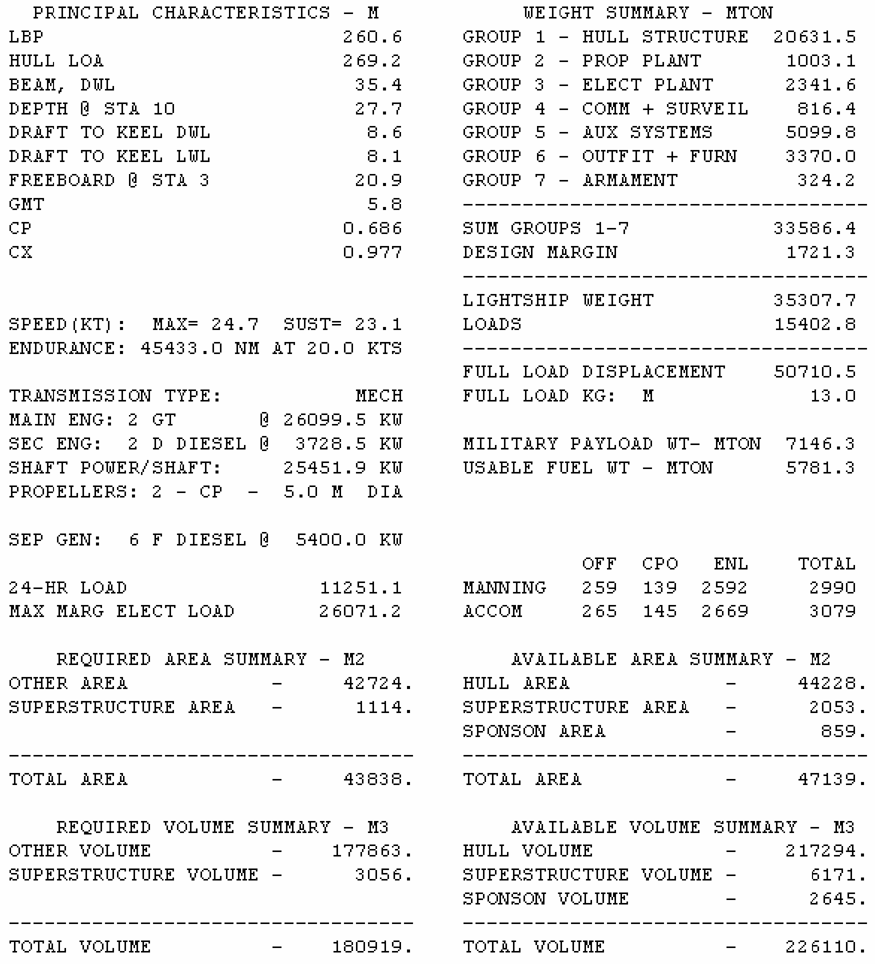


Figure 18 – LHA(R) Baseline Design in ASSET (Machinery Profile)

Table 8 – LHA(R) Baseline ASSET Design Summary



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  PRINCIPAL CHARACTERISTICS - M            WEIGHT SUMMARY - MTON
LBP                         260.6     GROUP 1 - HULL STRUCTURE  20631.5
HULL LOA                    269.2     GROUP 2 - PROP PLANT       1003.1
BEAM, DWL                    35.4     GROUP 3 - ELECT PLANT      2341.6
DEPTH @ STA 10               27.7     GROUP 4 - COMM + SURVEIL    816.4
DRAFT TO KEEL DWL             8.6     GROUP 5 - AUX SYSTEMS      5099.8
DRAFT TO KEEL LWL             8.1     GROUP 6 - OUTFIT + FURN    3370.0
FREEBOARD @ STA 3            20.9     GROUP 7 - ARMAMENT          324.2
GMT                           5.8     ----------------------------------
CP                          0.686     SUM GROUPS 1-7            33586.4
CX                          0.977     DESIGN MARGIN              1721.3
                                      ----------------------------------
                                      LIGHTSHIP WEIGHT          35307.7
SPEED(KT):  MAX= 24.7  SUST= 23.1     LOADS                     15402.8
ENDURANCE: 45433.0 NM AT 20.0 KTS     ----------------------------------
                                      FULL LOAD DISPLACEMENT    50710.5
TRANSMISSION TYPE:           MECH     FULL LOAD KG:  M             13.0
MAIN ENG: 2 GT       @ 26099.5 KW
SEC ENG:  2 D DIESEL @  3728.5 KW     MILITARY PAYLOAD WT- MTON  7146.3
SHAFT POWER/SHAFT:     25451.9 KW     USABLE FUEL WT - MTON      5781.3
PROPELLERS: 2 - CP  -  5.0 M  DIA

SEP GEN:  6 F DIESEL @  5400.0 KW
                                                OFF  CPO   ENL    TOTAL
24-HR LOAD                11251.1     MANNING   259  139  2592     2990
MAX MARG ELECT LOAD       26071.2     ACCOM     265  145  2669     3079

    REQUIRED AREA SUMMARY - M2            AVAILABLE AREA SUMMARY - M2
OTHER AREA            -     42724.    HULL AREA             -     44228.
SUPERSTRUCTURE AREA   -      1114.    SUPERSTRUCTURE AREA   -      2053.
                                      SPONSON AREA          -       859.
----------------------------------    ----------------------------------
TOTAL AREA            -     43838.    TOTAL AREA            -     47139.

    REQUIRED VOLUME SUMMARY - M3          AVAILABLE VOLUME SUMMARY - M3
OTHER VOLUME          -    177863.    HULL VOLUME           -    217294.
SUPERSTRUCTURE VOLUME -      3056.    SUPERSTRUCTURE VOLUME -      6171.
                                      SPONSON VOLUME        -      2645.
----------------------------------    ----------------------------------
TOTAL VOLUME          -    180919.    TOTAL VOLUME          -    226110.
```

4.2 Design Environment - Model Center

The process integration environment used in this project is Phoenix Integration's commercial software ModelCenter® (MC). MC provides a flexible integration platform for engineering analysis codes written in a variety of programming languages. Different applications (processes) can be run in coordination to form a model. Processes are represented by components in Model Center. A component can be thought of as a black box that takes the input, follows instructions and generates output. Advantages of the MC environment for this purpose include: (1) a user-friendly graphical interface that enables users to visualize the connectivity, input/output variables, and dependencies of individual modules, (2) the ability to easily replace one module or component with another and to modify module connectivities, (3) the ability to automatically run each module when the values of its input values are modified (by the user or another module), (4) the ability to securely integrate modules that reside in different locations on a computer network, (5) a suite of design exploration tools (optimization, parametric studies, design of experiments, response surface models).

The link editor in Model Center provides a means to link the output from one component to the input of another component. Links can be created, edited, suspended and broken. The link editor is activated by dragging a line from one component to another. Once all the components in the model are linked in the required fashion the model is ready to run. The order of running these components is determined by the scheduler.

The scheduler is responsible for knowing which components need to be run and when. Model Center supports different schedulers. They are backward scheduler, forward scheduler, mixed mode scheduler, script scheduler. In this project the forward scheduler is used. In forward scheduling, as soon as an input value is changed, all downstream components are immediately run. Model Center maintains two states for all output variables: valid and invalid. The valid state is displayed as a box with an arrow pointing out of it and the same icon with red X through it indicates the invalid state (requires update).

ASSET is "wrapped" for use in the MC environment. "Wrapping" is the process of preparing a module or program for use in the MC environment, and involves specifying: (1) the input and output variables that will be exposed to the user, (2) where the module is located on the network, (3) how to run the module. Script Wrappers are ideal for integrating software codes that implement a Component Object Model (COM) interface. Script Wrappers are simple to create and require anywhere from a few hours to a few days to develop depending on the complexity of the program being wrapped. Each Script Wrapper may be written using one of several types of scripting languages, such as VBScript, JScript, Perl, etc. MC provides several different methods for wrapping modules. Components are created using a script component editor. The script component editor has two segments. One for defining input and output variables and the other for writing the script that does all the required calculations. Defining a variable includes specifying its properties such as units, type (Integer, Real, Array, etc.), description, lower bound, upper bound, etc. The scripting language used in this project is VBScript.

In this study it was decided to call individual ASSET modules in MC by executing the appropriate ASSET command line with ASSET running in the background. MC passes input data to ASSET and output data is retrieved by MC. This strategy allows future applications to substitute other models and programs in place of individual ASSET modules. This strategy also allows individual designs to be returned to ASSET to extract a complete set of design parameters, and produce ASSET reports and graphics. The baseline design and groups of design alternatives (machinery, hullform, deckhouse, payloads, etc.) are set up in ASSET for use and modification during the optimization. This includes indicator switches and ASSET design parameters that are not changed by MC.

Figure 19 shows the MC model for LHA(R). The Setup component checks the range of input variables received from MC, and passes them through to the 16 design variable (trade) options components. Figure 20 shows the Machinery Options component. Other options components are similar. Depending on the option selected, ship impacts provided by NSWC Card for this study (Table 4) are applied to the Baseline ASSET model through the ASSET command line. Once the current model in ASSET has been updated consistent with the selected options, MC runs individual ASSET modules in sequence (Hull Geometry, Hull Subdivision, Deckhouse, Hull Structure, Appendage, Resistance, Propeller, Machinery, Weight and Space).

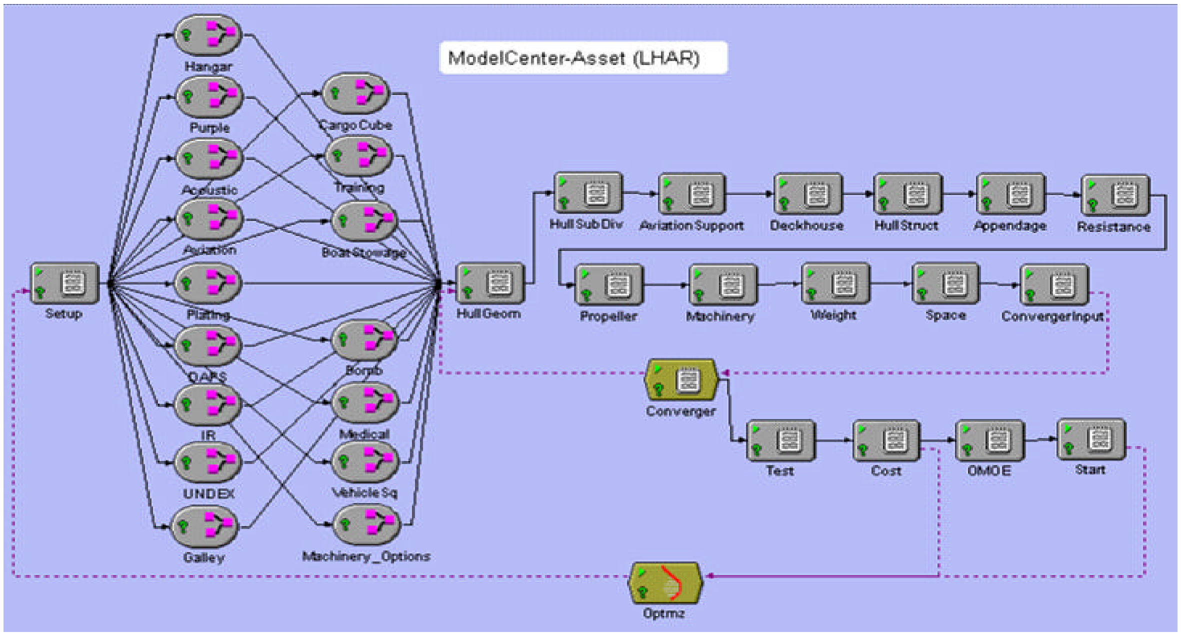


Figure 19 – LHA(R) model in Model Center

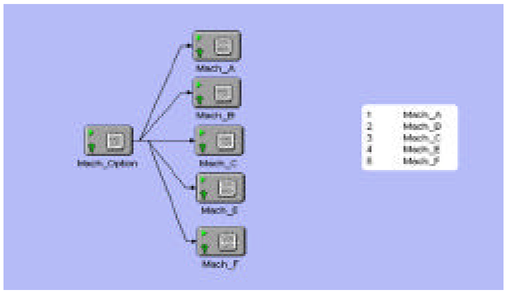


Figure 20 – MC Machinery Options Component

ASSET modules are always run in the above sequence. Objective attributes, effectiveness (OMOE) and cost, are not calculated until the ship synthesis has converged. Characteristics calculated in ASSET or using ASSET output that affect OMOE and cost include: single-digit weights, KG service life allowance, sea-keeping, weight service life allowance and sustained speed. Convergence is required for these parameters. The convergence tolerance value used is 0.1%. The difference between the parameter values in the current and previous runs must be less than the tolerance value for convergence. If the difference is more than the tolerance then the parameters are not converged and the ASSET modules are run again.

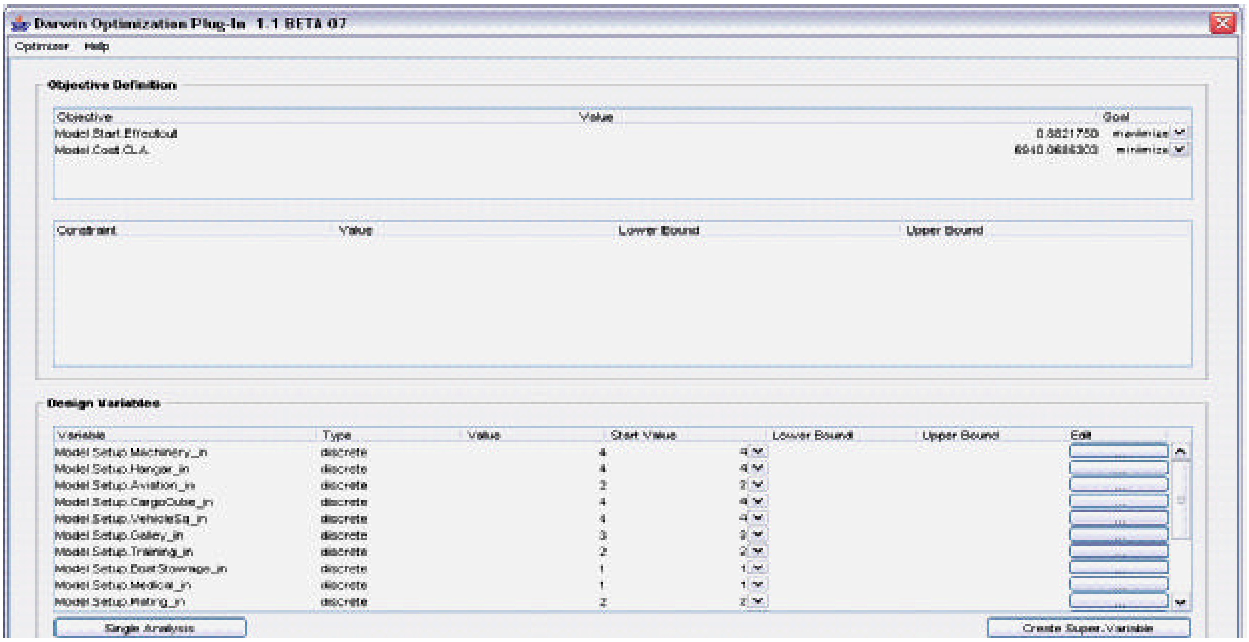
4.3 Optimizer - DARWIN

The genetic algorithm optimization tool used for this project is DARWIN. DARWIN is a standard tool available in MC, but at the start of the project it was only able to perform single objective optimization. In the course of this project, additional capability was added to DARWIN for multi-objective optimization. This study is the first application of this new capability.

Genetic algorithms (GAs) are well suited for designing complex engineering systems because 1) they are capable of working with both discrete and continuously valued design variables, and 2) they implement global search strategies, which allow them to accurately search large nonlinear multi-modal design spaces, 3) they are well suited to performing optimization with more than one objective. The primary drawback to GAs is that they often require large numbers of function evaluations to converge, which can lead to excessively long run times if the underlying analyses are computationally expensive. DARWIN incorporates several features designed to alleviate long run times. These include 1) elitist and multiple elitist selection schemes [5], and 2) an analysis "memory" feature. The memory feature works as follows: after each function evaluation, the result of the analysis (fitness function) is stored in a binary tree. Before running a new analysis for a given design, DARWIN checks the binary tree to determine whether or not that analysis has previously been run or not. If it has, the fitness function is extracted from the binary tree and a new function evaluation is avoided. This feature has resulted in reductions of 20-50% in total optimization run times. Recent research has indicated that additional improvements in GA run times can be achieved using on-the-fly surrogate analysis models.

Optimization problems are defined in DARWIN by dragging and dropping variables, constraints and objective attributes from MC. Two or more MC variables can be put together to create "super-variables". For example, MC variables describing the characteristics of discrete propulsion system choices can be grouped into a single "propulsion system" super-variable. The optimizer will work directly with this high-level super-variable, and not with the individual MC variables.

Figure 21 shows the MC interface for DARWIN. It includes windows for dragging, dropping and defining objectives, constraints and design variables. GA parameters can be modified using the Optimization Parameter interface, Figure 22. Non-dominated frontiers for successive generations are displayed in Figure 23.

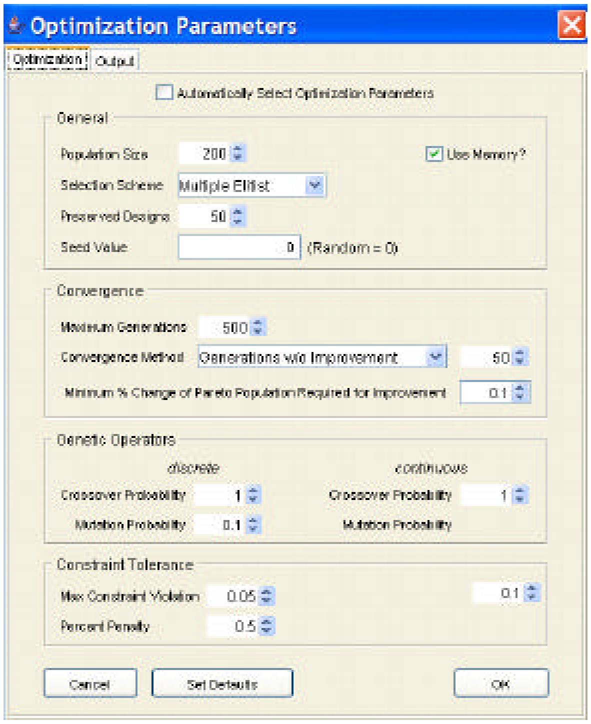


Objective	Value	Goal
Model.Start.Effectout	0.8821750	maximize
Model.Cost.CLA	6940.0686300	minimize

Constraint	Value	Lower Bound	Upper Bound

Variable	Type	Value	Start Value		Lower Bound	Upper Bound	Edit
Model.Setup.Machinery_in	discrete		4	4			...
Model.Setup.Hangar_in	discrete		4	4			...
Model.Setup.Aviation_in	discrete		2	2			...
Model.Setup.CargoCube_in	discrete		4	4			...
Model.Setup.VehicleSq_in	discrete		4	4			...
Model.Setup.Galley_in	discrete		3	3			...
Model.Setup.Training_in	discrete		2	2			...
Model.Setup.BoatStowage_in	discrete		1	1			...
Model.Setup.Medical_in	discrete		1	1			...
Model.Setup.Rating_in	discrete		2	2			...

Figure 21 – MC Darwin Optimization Interface



☐ Automatically Select Optimization Parameters

General
Population Size 200
☑ Use Memory?
Selection Scheme Multiple Elitist
Preserved Designs 50
Seed Value 0 (Random = 0)

Convergence
Maximum Generations 500
Convergence Method Generations w/o Improvement 50
Minimum % Change of Pareto Population Required for Improvement 0.1

Genetic Operators
discrete
Crossover Probability 1
Mutation Probability 0.1
continuous
Crossover Probability 1
Mutation Probability

Constraint Tolerance
Max Constraint Violation 0.05
Percent Penalty 0.5
0.1

Figure 22 – DARWIN Optimization Parameters

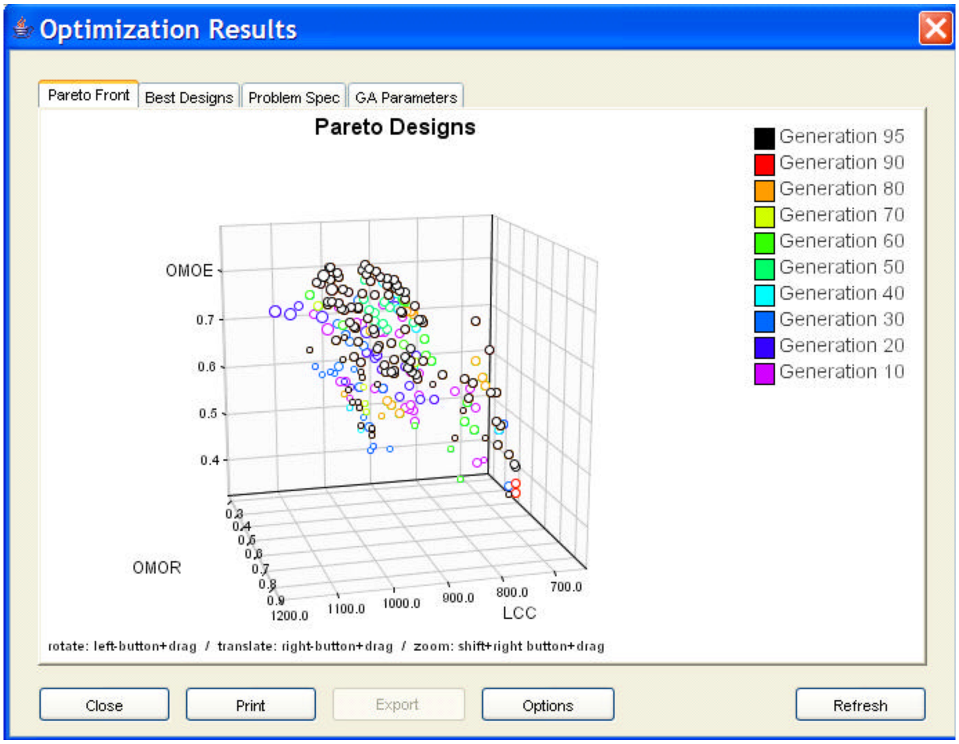


Figure 23 – DARWIN Optimization Results (3 objective)

4.4 Cost

The cost model used in this project is weight-based which is useful for new design concept exploration, but will not provide an accurate estimate of the change in cost for the specific change alternatives considered here. It was the only model available, and it was used primarily to finish the study and assess the process.

Construction costs are estimated for each SWBS group using weight-based equations adapted from an early ASSET cost model and US Navy cost data. Historical costs are inflated to the base year using a 2.3% average annual inflation rate from 1981 data. Figure 24 illustrates total lead ship acquisition cost components calculated in the model. Lead ship costs include detail design engineering and plans for the class (SWBS 800 – Integration and Engineering) and all tooling, jigs and special facilities for the class (SWBS 900 - Ship Assembly and Support). The Basic Cost of Construction (BCC) is the sum of all SWBS group costs. Ship price includes profit. The Total Government Portion is the sum of the cost of Government-Furnished Material (GFM) and Program Managers Growth. The Total End Cost is the Sum of the Total Shipbuilder Portion and the Total Government Portion.

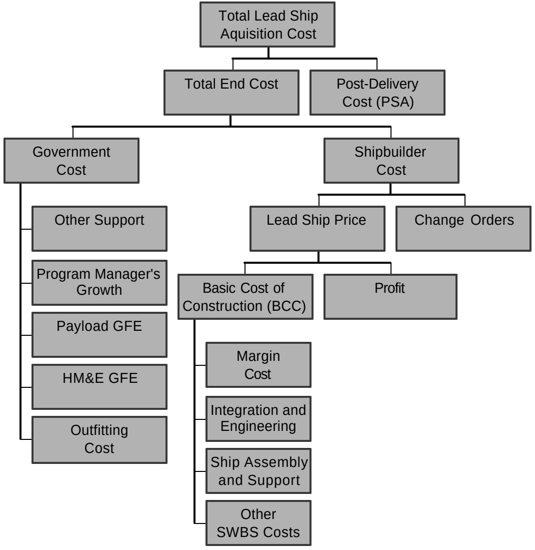


Figure 24 - Acquisition Cost Components

Basic follow-ship costs for SWBS groups 100-600 are equal to lead ship costs, but reduced by a learning factor and inflated to the follow-ship award year. Follow-ships have significantly lower SWBS 800 and 900 costs. Follow-ship construction cost benefits from a learning curve that reduces the cost as the work force becomes more efficient at the various production processes repeated from ship to ship. The learning rate represents the percent cost reduction for every doubling of the number of ships produced. Total follow-ship acquisition cost is the sum of shipbuilder and government portions. A learning rate of 98%, total ship acquisition of 10 and production rate of one ship per year are assumed.

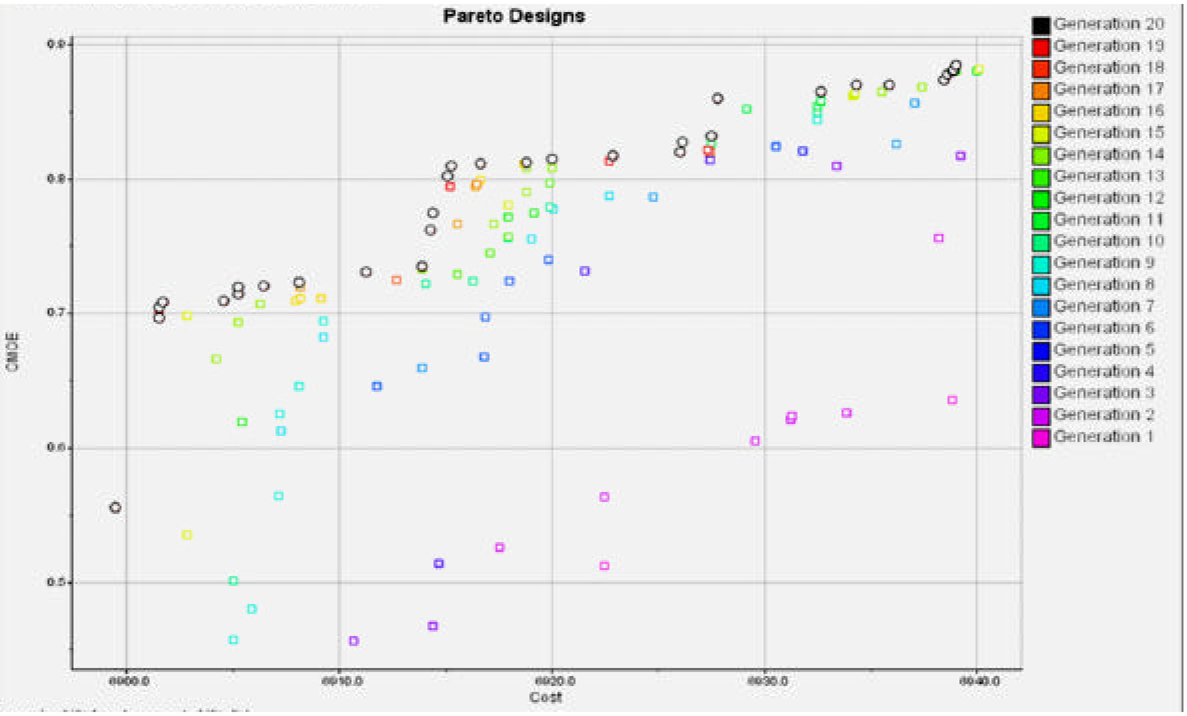


Figure 25 – LHA(R) Design Points Converging to Non dominated Frontier (POP=20, GEN=50)

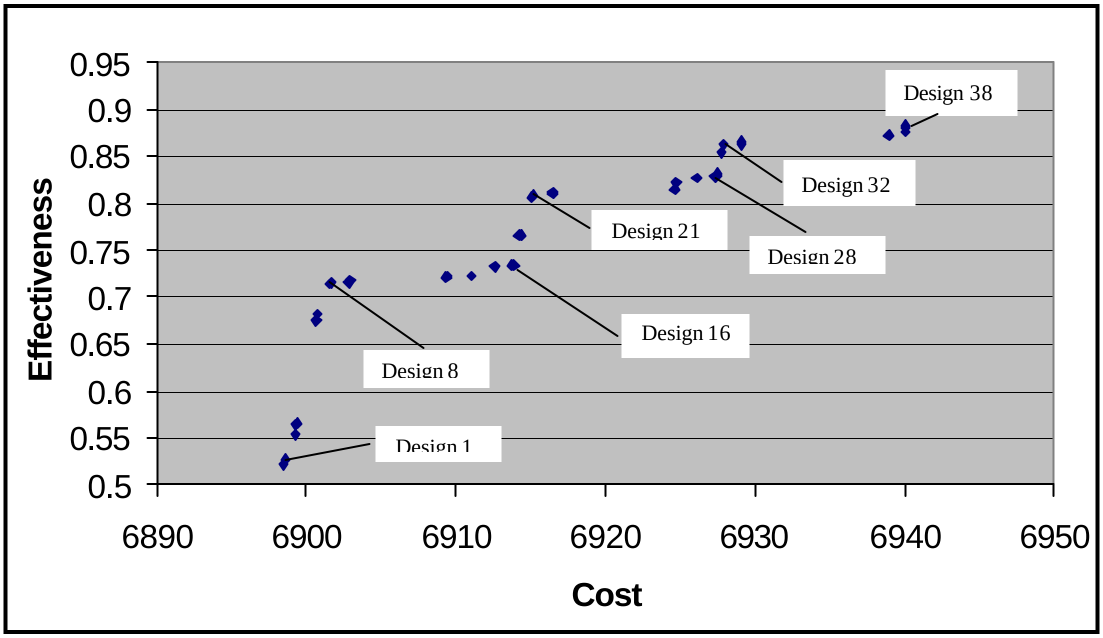


Figure 26 – LHA(R) Non-Dominated Frontier (POP=20, GEN=50)

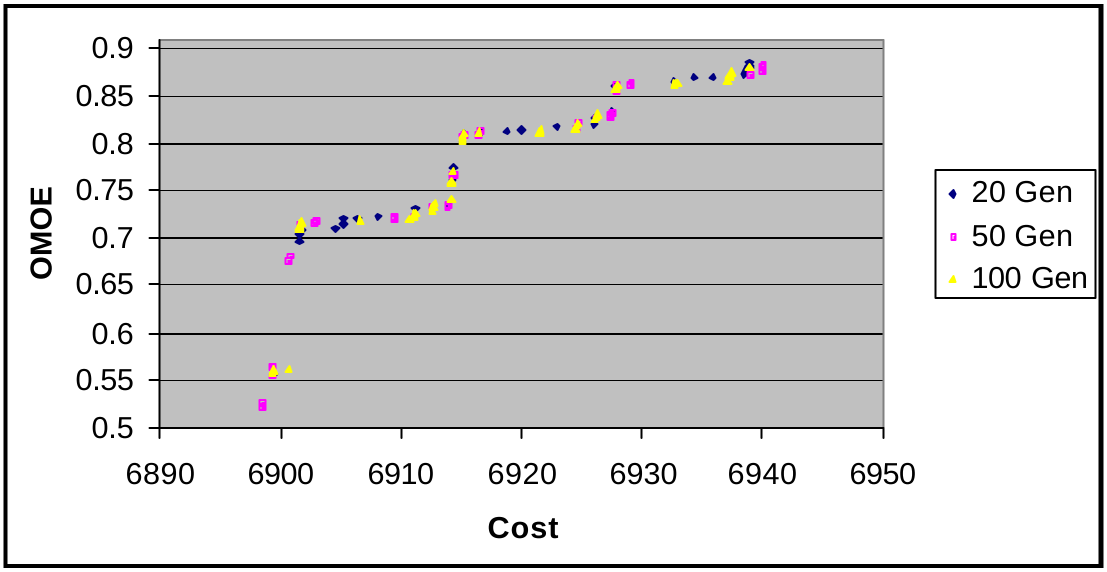


Figure 27 – LHA(R) Non-Dominated Frontier – Various Population Sizes

4.5 Results

Figure 25 shows the non-dominated frontier obtained in MC and DARWIN through 50 generations, using a population size of 20. The Non-dominated Frontier shows good convergence. Figure 26 shows only the non-dominated designs. Very similar results and most of the same designs were obtained using different population sizes and number of generations (Figure 27). The optimization is robust with excellent convergence and consistency.

Designs of interest (knees in the curve) and the high-end design are indicated in Figure 26. Although all non-dominated designs represent the best effectiveness for a given cost, knees are often preferred because they are at the top of a region where effectiveness has increased substantially for a relatively small increase in cost. Table 9 lists the options for designs at the top and bottom of the three knees. Drivers for the selection of particular options in these designs are as follows:

- Machinery - Option 3 weighs 39 ltons less than Option 4 (IPS) and using the weight-based algorithm it is more costly, but Option 4 does provide a slightly higher sustained speed. Sustained speed has a relatively low MOP weight (.011). Option 4 is only selected at the low end of the second knee where weight is less critical.

- Hangar – Hangar Maintenance Improvements has the highest MOP weight (.197) and although Option 4 has significant weight and area impact, it is always selected except in the lowest end option (Option 1).
- Aviation Maintenance and Stowage - Option 2 is 40 ltons heavier and requires more area than Option 1, but also has a relatively high MOP weight (.066) and VOP difference. It was selected for the 3rd knee high end.
- The goal options for Cargo Cube, Vehicle Square, Training, Medical and Purple Spaces were selected consistently because total area impact did not sufficiently constrain their values. Arrangement and local area constraints were not used. These constraints should be implemented. The low area galley option is selected except for the lowest end option (Design 1) where other area requirements were minimal.
- Damage Tolerance Plating - Option 2 is more than 320 ltons heavier, but results in a much higher OMOE because of its very high MOP weight and VOP difference. It is selected at the top of the 2nd knee and above, except where weight is severely constrained by other options.
- Boat Stowage – External boat stowage (Option 1) is selected consistently because of the significant area requirement for internal stowage and the relatively low RCS MOP weight (.022).
- DAPS – Option 1 has a large area and space impact and is only selected when other area and weight requirements are low.
- UNDEX – Option 1, HSLA 65, has a higher VOP and lower weight. It is always selected. Its actual cost and risk are not reflected in these metrics. This should be revisited.
- IR – Option 3 (Goal) is usually selected despite its low MOP weight (.005) because of its low weight and cost impact.
- Acoustic – Goal Option 3 is always selected because of its low weight impact and moderate MOP weight (.037).
- Bomb Farm – Goal Option 2 (internal) is selected consistently because of the relatively high ordnance flow and weapons vulnerability MOP weights. Cost and other arrangement constraints may not be properly represented.

Table 9 - Design variable options of designs forming steps in the Pareto Front

Design variable→ Design ?	MACHINERY	HANGER	AVIATION	CARGOCUBE	VEHICLESQ	GALLEY	TRAINING	BOAT STWG	MEDICAL	PLATING	DAPS	UNDEX	IR	ACOUSTIC	PURPLE	BOMB FARM	Lead Ship Cost ($M)	OMOE
Goal	3	4	2	4	4	1	2	2	1	2	1	1	3	3	4	2		
First Knee																		
Design 1	3	1	1	4	4	1	2	1	1	1	7	1	3	2	4	2	6898.5	0.521
Design 8	3	4	1	4	4	3	2	1	1	1	7	1	3	3	4	2	6901.5	0.713
2nd Knee																		
Design 16	4	4	1	4	4	3	2	1	1	1	1	1	3	3	4	2	6913.8	0.734
Design 21	3	4	1	4	4	3	2	1	1	2	7	1	3	3	4	2	6915.1	0.808
3rd Knee																		
Design 28	4	4	1	4	4	3	2	1	1	2	1	1	3	3	4	2	6927.4	0.828
Design 32	3	4	2	4	4	3	2	1	1	2	7	1	2	3	4	2	6927.9	0.862
High																		
Design 38	3	4	2	4	4	3	2	1	1	2	7	1	3	3	4	2	6941.1	0.880

5 Conclusions and Future Work

This study demonstrates an effective and rational process for concept exploration in a naval ship design. LHA(R) is a modified-repeat design and the design variables in this study are very different from a clean-sheet-of-paper design. In most cases they are simply trade-off alternative selections considering their associated total-ship impact, but with very little flexibility to modify other ship characteristics. This limits the application of a structured design and optimization process, but significant benefit and insights were still obtained:

- The OMOE development process was demonstrated in a real US Navy acquisition setting. The process structured the discussion of alternatives and provided insight to the panel of experts in a way that they noted they had been unable to achieve in a normal unstructured meeting format. The results of the process were also useful and indicated that for LHD(R) the most important improvements are those associated with aviation and aviation maintenance.
- The optimization was successfully linked to ASSET. This is the first time ASSET has been used in this manner, and the benefit for future applications was clearly demonstrated. Individual trade studies cannot begin to search the entire trade space. This structured optimization process in MC can search millions on combinations efficiently and with confidence of convergence.
- A multi-objective optimizer and user interface were developed in Model Center.
- The optimization results showed excellent convergence to a non-dominated frontier. They were consistent and repeatable.

The results of this study are questionable because a number of compromises were made:

- The cost model used in this project was weight-based which is useful for new design concept exploration, but does not provide an accurate estimate of the change in cost for the specific change alternatives considered here. It was the only model available, and it was used primarily to finish the study and assess the process.
- Arrangement-based constraints were not used which caused a number of the design variables to consider only their goal values. They were unconstrained and there was no cost or impact to restrict them.
- Only one OMOE pair-wise comparison session was used. Results would benefit from some improvement to the OMOE hierarchy, and at least one more round of comparisons.

The first two of these deficiencies can corrected with an additional effort to obtain cost impact estimates and establish arrangement constraints. The optimization could then be rerun and more valid results obtained.

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[2] Brown, A.J., Salcedo, J.*, "Multiple Objective Genetic Optimization In Naval Ship Design", *Naval Engineers Journal*, Vol. 115, No. 4, pp. 49-61, Fall 2003.

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