Revisiting DDGX/DDG-51 Concept Exploration

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Abstract

This study revisits concept exploration for DDG-51 using reconstructed 1978–1979 DDX and 1979–1980 DDGX requirements and options, and 2005 tools. The goal of this study is to assess and highlight the benefits of current tools and processes for concept exploration by comparison with a well-known design that did not use these tools. This case study was completed in a summer and fall ship design project at Virginia Tech. In 1979, the acquisition and design process did not begin with a Mission Need Statement, Analysis of Alternatives or Integrated Capabilities Document as is required today. It began with studies, Tentative Operational Requirements, and Draft Top Level Requirements. In this study, we revisit the 1978–1980 DDG-51 (DDX/DDGX) concept exploration based on the guidance, goals, and constraints of the DDX and DDGX studies, using a notional mission statement, concept of operations, and list of required capabilities. The design space is defined to include many of the same design alternatives that were considered in the DDX and DDGX studies. A multiple-objective genetic optimization (MOGO) based on military effectiveness, cost, and risk is used 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 in a series of non-dominated frontiers. Concepts for further study and development are chosen from this frontier and a comparison with DDG-51 is made based on these results.

Motivation and Introduction

The traditional approach to ship design is largely an "ad hoc" process. Experience, design lanes, rules of thumb, preference, and imagination guide the selection of design concepts for assessment. Often, objective attributes are not adequately synthesized or presented to support efficient and effective decisions. This case study uses a total system approach for the design process, including a structured search of the design space based on the multi-objective consideration of effectiveness, cost, and risk (Brown and Thomas 1998; Brown and Salcedo 2003).

The scope of this study includes only the first phase in the ship design process, concept, and requirements exploration. The concept exploration process followed in this study is shown in **Figure 1**. The first step in this process is to develop a clear and precise mission definition and list of required operational and functional capabilities starting with a Mission Need Statement and Acquisition Decision Memorandum, or an Integrated Capabilities Document. This process should not begin by jumping into specific requirements or design characteristics. These should be products of concept exploration, not initiating constraints. Requirements and design characteristics cannot be rationally specified without a thorough understanding of their impact on total ship cost, risk, and effectiveness. Refinement of the mission definition typically

Nomenclature:

AAW: Anti-air warfare

AHP: Analytical hierarchy process

AOA: Analysis of alternatives

ASN(S&L): Assistant Secretary of the Navy for Systems and Logistics

ASROC: Anti-submarine rocket

ASUW: Anti-surface warfare

ASW: Anti-submarine warfare

BHP: Brake horsepower

CAS: Combined antenna system

CBG: Carrier battle group

CCC: Command, control, communication

CIWS: Close-in weapon system

CODAG: Combined diesel and gas turbine

COGAG: Combined gas turbine and gas turbine (Cruise/Boost)

COGAS: Combined gas turbine and steam

CONOP: Concept of operations

CPP: Controllable pitch propeller

CPS: Collective protection system

DNSARC: Department of the Navy Systems Acquisition Review Council

DV: Design variable

DOE: Design of experiments

ECM: Electronic countermeasures

FCS: Fire control system

FPP: Fixed pitch propeller

GFCS: Gun fire control system

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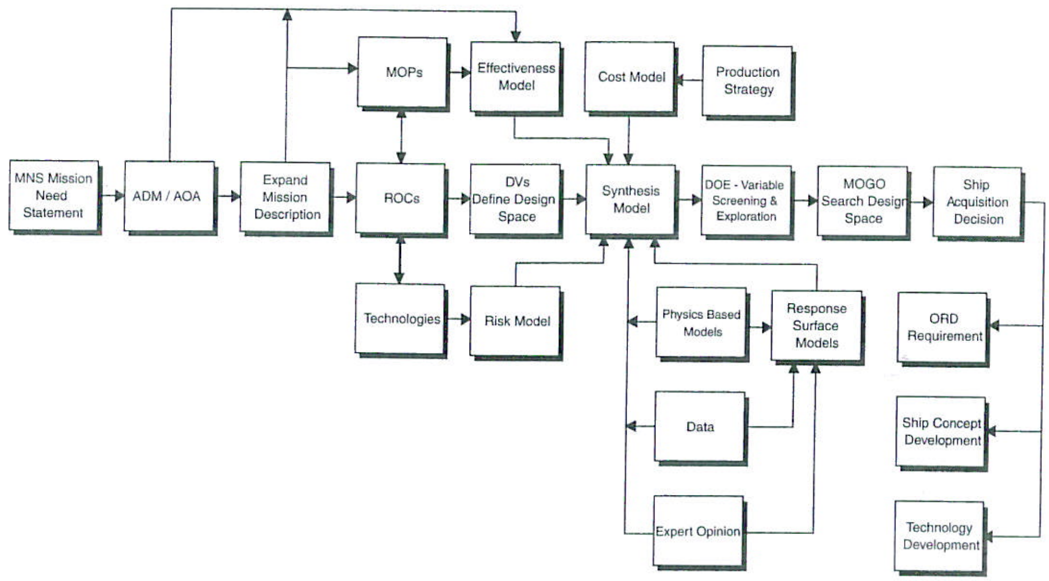
Figure 1: *Concept Exploration Process (Brown 2005)*



GM: Metacentric height above center of gravity

IED: Integrated electric drive

IR: Infrared

KG: Height of center of gravity

LAMPS: Light airborne multi-purpose system

MAVT: Multi-attribute value theory

MD: Mechanical drive

MFCS: Missile fire control system

MOGO: Multi-objective genetic optimization

MOP: Measure of performance

NBC: Nuclear, biological, chemical

NCO: Non-combatant operations

NDF: Non-dominated frontier

NSFS: Naval surface fire support

OMOE: Overall measure of effectiveness

OMOR: Overall measure of risk

ORD: Operational requirements document

includes a concept of operations (CONOPs), projected operational environment and threat, specific missions and mission scenarios, and required operational capabilities (ROCs).

Next, the design space is defined using available or developing technology necessary to provide required capabilities. In this case study, this includes most of the design alternatives that were considered in the DDX and DDGX studies. Concept exploration needs to consider only those requirements and design parameters that have a significant impact on ship balance, military effectiveness, cost, and risk. Cost, risk, and effectiveness models must be developed consistent with mission requirements and the alternative technologies. A simple ship synthesis model is used to balance the designs, assess feasibility, and calculate cost, risk, and effectiveness.

Finally, a multiple-objective genetic optimization (MOGO) is used to search the design space for non-dominated feasible designs using the synthesis and objective attribute models (Shahak 1998; Salcedo 1999). Feasible designs are ranked by cost, risk, and effectiveness, and presented as a series of non-dominated frontiers (NDFs). An NDF represents ship designs in the design space that have the highest effectiveness for a given cost and risk. Concepts for further study and development are chosen from this frontier and a comparison with DDG-51 is made based on these results.

This optimization requires mathematically defined objective functions for effectiveness, cost, and risk. 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. Preferred designs must always be on the NDF. 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. Overall measure of effectiveness (OMOE; Demko 2005; Brown and Demko 2006) and overall measure of risk (OMOR; Mierzwicki 2003; Mierzwicki and Brown 2004) objective functions are developed using the analytical hierarchy process (AHP), multi-attribute value theory (MAVT), and expert opinion (Belton 1986; Saaty 1996). Acquisition and life-cycle cost are calculated using a modified weight-based cost model.

Model Center (MC) software is used for the design and optimization environment (Phoenix Integration 2004). Design variables (DVs) are screened and sensitivity is assessed using a Design of Experiments (DOE) in MC.

DDX and DDGX Concept Design History

The design of a new guided missile destroyer equipped with an AEGIS weapon system, and identified as DG-AEGIS, was initiated in April 1972, continued through 17 months of concept exploration, and started into a scheduled 12-month preliminary design in September 1973. A preliminary design baseline was never established, and all effort for the DG-AEGIS design was terminated in May 1974 due to budget constraints (Naval Sea System Command [NAVSEA] 1985).

In 1978, the Navy recognized that the escalating cost of CG-47 and the retirement of existing ships required the commencement of a new surface combatant program. An OPNAV (CNO) DDX Study Group, under the direction of RADM R. K. Fontaine, USN, was formed in May 1978 to update the operational requirements for surface combatants (Riddick 2003). From May 1978 to February 1979, this group studied future threats facing the Navy in the 1990s and beyond (SEA 00D 1980). The group also investigated combat system capabilities required to meet these threats, and evaluated 11 alternative ship concepts identified as DDX variants to provide this capability within certain size and cost parameters. NAVSEA personnel, led by Capt. D. P. Roane, USN, from the Combat System Directorate and Jim Raber from the Ship Design Directorate, participated in the areas of combat capability assessment and ship design alternatives (NAVSEA 1985).

Chief of Naval Operations (CNO), ADM T. B. Hayward, USN, directed the Naval Material Command in 1979 to conduct Feasibility Studies for a DDX concept armed with guided missiles (DDGX) that could meet selected operational requirements from the Fontaine study (SEA 00D 1981). The general guidance included the following:

- The design or designs should support a lead ship authorization in an FY84–85 shipbuilding program.
- Each alternative ship configuration should include schedules for research and development.
- One alternative should be based on low-risk technology. Other concepts should consider innovations, technology developments, modularity, and cost reduction items that would reduce ship size and cost.
- The design should satisfy top-level requirements developed in the DDX studies.
- The design should emphasize combat capability and survivability to the maximum degree possible within limits of affordability.
- Interaction with other class ship modernization and maintenance plans was to be explored.

NAVSEA concluded the initial DDGX feasibility studies in December 1979 with five baseline configurations and 27 excursions or variants. After the DDGX studies were presented to the CNO, the Chief of Naval Material (CNM) immediately recommended concept design based on ship Variant 3A. This configuration was 469 feet long with a displacement of 7,000 tons and a follow-ship cost of $550 million. CNO tasked CNM to continue the development of the DDGX and provided the following additional direction (NAVSEA 1985):

- The DDGX design must be lower in cost and total capability than CG 47.
- Follow-ship acquisition cost should not exceed $500 million (FY 1980).
- The design must be powerful and survivable and must include significant anti-air warfare (AAW) capability.
- The design should support a lead ship authorization in FY84–FY86.

DDGX Concept Design began in February 1980 with a baseline 1,000 tons lighter and $50 million less than DDGX Variant 3A. Concept design was completed in three steps: major trade-off studies between February 1980 and May 1980, trade-off study evaluations and system-level integration between June 1980 and July 1980, and final concept design baseline development between August 1980 and January 1981. Over 30 major trade-off studies were conducted in the hull, mechanical, and electrical and combat systems areas. The most comprehensive study was in propulsion where over 100 different concepts were identified and 33 of these were studied in detail.

Two final concept design baselines, designated as Alternatives 1 and 2, were conceived by January 1981. These designs reflected final decisions that had been developed for combat system areas, two different propulsion plants, and deckhouse configurations. NAVSEA recommended Alternative 1 in February 1981 and presented it to a CNO Executive Board (CEB) that received it well. After the DDGX CEB, CNM appointed an independent senior review panel to examine both alternatives again. The panel, headed by VADM R. S. Salzer, USN (Ret.), after a brief review, made the following comments and recommendations (NAVSEA 1985):

- A valid requirement for DDGX continued to exist and the design program should continue to support a lead ship authorization in FY85, but neither of the proposed baselines should be used. Instead, concept design should continue with a new configuration. (A number of specific recommendations were made by the Salzer Panel such as to add more missiles and make the propulsion plant more similar to the DD 963, i.e., mechanical drive with four LM-2500s. Initial design studies to incorporate the Salzer Panel recommendations indicated that a feasible ship would displace 8,700 tons.)
- The cost constraint for the DDGX, incorporating attributes selected by the panel, increased from $500 million to between $600 and $650 million.
- New subsystems should be developed independent of the ship program.
- An emphasis for the new DDGX was to be on reliability.
- A more conservative approach to design development should be followed. Designs should accommodate fallback to proven systems, reduced development risk, and systems testing using land-based engineering facilities (LBEF) and "at sea" test and evaluation where possible.

In April 1981, a second concept design began. This design was based on new guidelines to establish a more dependable concept. The Salzer Panel recommendations were studied and most were incorporated into DDGX during the summer of 1981 (NAVSEA 1985).

Throughout the DDGX concept design and at briefings to OPNAV the operator's desire for modifications was expressed. The modifications consisted of increasing the ship's range, adding tactical towed array sonar (TACTAS), selecting a 4 MW transmitter for SPY-1D in lieu of a 2 MW, and incorporating OPNAV's new requirement for separate food preparation facilities for officers and enlisted men. These characteristics increased weight, causing OPNAV to raise the ship's displacement ceiling to 8,500 tons. The Department of the Navy Systems Acquisition Review Council (DNSARC) reviewed the DDGX progress in June 1981 and was satisfied, as was the Secretary of Defense.

In the fall of 1981, to meet all of the operator's requirements including energy conservation, endurance range, and sustained speed requirements, the ship's displacement was increased by 600 tons to 9,100 tons. NAVSEA created three more designs options by November. One ship, 8,500 tons, met all the requirements except the desired speed and range; another ship, 9,100 tons, met all operator requirements; and the last ship was an austere configuration at 8,000 tons. In December 1981 the four alternatives were presented to CNM, OP 03, and Assistant Secretary of the Navy for Systems and Logistics (US General Accounting Office 1986).

Based on this meeting, NAVSEA started concept design a third time to develop three additional concepts: one ship with gas turbine generators, and two with diesel generators. After another thorough review of the various configurations, NAVSEA recommended to OPNAV the gas turbine ship of 8,500 tons. By February 1982, the design teams were directed to commence preliminary design of the DDG-51 with a gas turbine baseline. **Table 1** is a summary of the DDX/DDGX concept exploration design events (NAVSEA 1985).

Mission Definition

The concept explored in this study is designated DDGVT to distinguish it from the actual DDG-51 design. The DDGVT mission definition is based on a notional DDGVT Mission Need Statement and DDGVT Acquisition Decision Memorandum. These were derived from the CNO DDX Study (1979–1980) and NAVMAT DDGX Study (1980–1981), with elaboration and clarification obtained by discussion and correspondence, and reference to pertinent documents and web sites (SEA 00D 1980; SEA 00D 1981; Hattenford 2004). The original mission analysis, threat, and requirements remain largely classified, but it is possible to infer mission requirements from these studies, from the ships that DDGX was intended to replace, and from the cold war world situation existing at the time.

The DDGX study began with a request by the CNO to define a surface ship capable of replacing the retiring fleet of cruisers and destroyers. Specifically, DDGX must replace DLG-37,

TABLE 1: DDX/DDGX Timeline NAVSEA (1985)

Date	Event
May 1978	OPNAV Study Group formed to conduct DDX requirements study
February 1979	DDX requirements study completed by OPNAV Study Group
August 1979	CNO directed CNM to conduct Feasibility Studies of DDX concepts with guided missiles. NAVSEA initiated DDGX Feasibility Studies
December 1979	DDGX Feasibility Studies concluded
January 1980	CNM recommended to CNO that a 7,400 ton concept, "Notional Ship 3A," be selected as baseline for Concept Design
February 1980	CNO directed CNM to start Concept Design with Notional Ship 3A and a goal to reduce acquisition cost. DDGX Concept Design was initiated with Notional Ship 3A as baseline concept
January 1981	DDGX Concept Design completed with two lower cost alternative concepts for OPNAV review
February 1981	NAVSEA recommended to CNO's Evaluation Board (CEB) that a 7580 ton RACER-equipped concept, Alternative 1, be selected as baseline for Preliminary Design. CNM directed the establishment of senior design review panel (Salzer Panel) to review the concepts. The Salzer Panel recommended that a more conservative concept be developed to serve as the baseline for Preliminary Design
April 1981	DDGX Concept Design was re-instituted to develop some "Salzer" concepts
June 1981	DDGX Program reviewed by DNSARC. Draft TLR issued by OPNAV
November 1981	Four more conservative concepts were presented for OPNAV review
December 1981	NAVSEA presented 8,500 ton concept as recommended baseline and 9,100-ton concept as alternative concept to CNM, OP 03 and ASN (S&L). Neither concept was found acceptable
January 1982	DDGX Concept Design was again reinstated and three additional concepts one with gas turbine generators and two with diesel generators, were developed
February 1982	NAVSEA presented the recommended concept, an 8,500-ton gas turbine ship, to CNM and OP 03. OPNAV requested NAVSEA to work on increasing ship's range and speed while reducing beam, but authorized initiation of Preliminary Design. COMNAVSEA directed SEA 05 to initiate Preliminary Design with the 8,500–ton gas turbine concept as baseline. DDGX redesignated DDG-51. This may be considered the official end of Concept Exploration and Development

For abbreviations please see nomenclature.

CG-16, and CG-26 class ships, and in a later flight, DD-963 class ships. DDGX must be interoperable with the CG-47 class or operate independently. It must complement AEGIS-equipped ships in battle force operation against a sophisticated missile threat, emphasizing: rapid reaction, increased firepower, high-target handling capacity, electronic countermeasures (ECM) resistance, and potential for force AAW coordination. DDGX minimum requirements were to replace existing (1980) capabilities one for one with additional capabilities in a Strike Mission to support Tomahawk cruise missiles. The DDGX design must also address shortcomings in existing (1980) ships including steam plant limitations, habitability, aluminum superstructure vulnerability, lack of fragment armor, blast resistance, service life reserves, and lack of signature control (SEA 00D 1981).

DDGVT is required to function as a multi-mission guided missile destroyer, designed to operate as an integral element in a carrier battle group, independently, or as an amphibious, logistics force or mine counter measures group escort, in multi-threat environments that include air, surface, and subsurface threats. It will have tactical employment in contingency and wartime operations. Primary missions include the following:

- CBG—Protect the carrier. Flexibly perform AAW, ASUW, and ASW operations, as required, to counter a multi-dimensional Soviet attack against the carrier and CBG. Because individual units may be required to operate as an integral part of a battle group or independently, this implies both multi-purpose and specialized (complementary to other existing or planned combatants) capabilities. New combatants must ultimately perform the missions of ship classes to be replaced.
- Escort—Protect sea lines of communication including commercial shipping and military transport of cargo, personnel, and amphibious forces, and special-purpose task groups such as mine countermeasures and at-sea replenishment.
- SAG—Independent/Surface Action Group—Function as independent forward-deployed naval forces and the first military forces on-scene, having "staying and convincing" power to promote peace through deterrence. Ships must be at-sea sustainable with endurance, prepared for crisis without warning.
- Non-combatant operations (NCO)—Support NCO in conjunction with national directives. Ships must be flexible enough to support a peacetime presence mission yet be able to provide instant wartime response should a crisis escalate.

Additional requirements include:

- Deal decisively with Soviet submarine, air, and surface threats without warning. This implies multi-purpose, not single-purpose capabilities.
- Project power—Able to supplement the US nuclear and conventional tactical reserve and provide deterrence. Power projection requires the execution and support of flexible strike missions and the support of naval amphibious operations. This includes gunfire support, protection to friendly forces from enemy attack, unit self-defense against AAW, ASW, and ASUW threats and area defense.
- Maintain battle space dominance, including: command/control/communications and intelligence operations beyond weapons range.
- Possess sufficient mobility and endurance to perform all missions on extremely short notice, at locations far removed from homeport.

Possible mission scenarios include:

- Support of a three-carrier force assigned to perform quick air and Tomahawk anti-ship missile (TASM) or Harpoon strike(s) in the North Atlantic versus Soviet threats. This scenario is intended to depict an operation of a short duration with surface forces performing in a multi-mission battle force environment.
- Support of a four-carrier force assigned to perform air and TASM or Harpoon strike(s) in the Northern Pacific versus Soviet or Chinese

threats similar to the three-carrier scenario. This scenario requires operations of extended duration, which are intended to test re-supply through underway replenishment. DDGVT involvement may include CBG or underway replenishment escort operations.
- Deployment as part of an SAG assigned to perform air and TASM or Harpoon strike(s) in Southeast or Southwest Asia using surface combatants only, without the support of an aircraft carrier's embarked airwing.
- A protection of shipping scenario protecting a convoy crossing the Atlantic to re-supply Europe.

Required Operational Capabilities (ROCs) were developed from this mission description and used as a comprehensive list of required DDGVT capabilities. Most require a specific system or technology to provide the capability. Some are required with an equal level of performance for all designs. Others must be assessed for different designs using measures of performance (MOPs) with goal and threshold values. These MOPs are included in the effectiveness (OMOE) calculation.

DDGX Design Alternatives and Technology

The following additional minimum requirements were specified by the original NAVMAT study group:

- minimum sustained speed of 28 knots,
- minimum endurance range of 5,000 nm at 18 knots or 3,500 nm at 20 knots,
- appropriate passive protection,
- hull-mounted sonar capable of long-range operations (1st convergence zone active and passive, if possible),
- facilities for light airborne multi-purpose system (LAMPS) operation, or future vertical take-off and landing,
- long range surface-to-surface missile system capable of attacking ships and targets ashore with conventional and nuclear warheads, and
- advanced phased array radar AAW system that will supplement AEGIS-equipped ships in battle force operation against a sophisticated missile threat, emphasizing rapid reaction, increased firepower, high target handling capacity, ECM resistance, and potential for force AAW coordination.

TABLE 2: 1981–1982 DDGX Variants

Ship Number	Type/Description
DDGX Variants 1A–1P	Cruiser-like
DDGX 2	Advanced electric drive (not followed up)
DDGX Variants 3A–3H	Mid-size destroyer
Ship 4	Not followed up
DDGX Variants 5A–5C	VLS frigate

The study identified five baseline configurations listed in **Table 2** (SEA 00D 1981).

Ultimately, the DDGX study recommended Ship 3A. However, according to Stocker (1981), characteristics of the cruiser and frigate-like ships were still to be considered. Ship 3A included two vertical launch system (VLS) standard ship systems engineering standards (SSES) modules (32-cell and 64-cell).

The development of the hull engineering system involved, in part, consideration of the following technical issues:

- HSLA80 versus HY80 (high strength steels) for the hull girder,
- deckhouse material of steel or aluminum,
- deck height dimensions,
- radar cross section impact on hull form,
- collective protective system (CPS)—full/partial,
- habitability/living Spaces,
- office requirements,
- single versus dual passageways,
- use of a compensated fuel system, and
- clean salt water ballast.

A variety of propulsion options were considered during the DDGX studies, including fixed pitch versus controllable pitch propellers, reversing versus non-reversing reduction gears, various other gear configurations, one or two Rankine cycle energy recovery (RACER) systems, and machinery box tightness. Many variants incorporated a RACER system for energy conservation. Extensive effort was placed on RACER, which was still in development (Baskerville, Quandt, and Donovan 1984). Selecting an upgraded LM-2500, incorporating one RACER system, and choosing the reverse reduction gear/fixed pitch propeller for the baseline provided an increase from 80,000 to 97,000 shaft horsepower (SHP; NAVSEA 1985).

In summary, the development of the propulsion system, auxiliary systems, and deck machinery systems involved consideration of many technical issues, including the following (NAVSEA 1985):

- fixed pitch propeller (FPP)/reverse reduction gear (RRG) versus controllable pitch propellers (CRP),
- 40,000 versus 50,000 SHP shaft output,
- RACER,
- machinery box tightness and length,
- lowering and centerlining engines,
- propeller shaft splay versus tip-to-tip clearance,
- endurance requirements and calculation methods,
- three versus four generators,
- electrical margins,
- uninterruptible power source,
- all electric auxiliaries,
- centralized versus distributed seawater systems,
- compensated fuel versus clean ballast system, and
- all electric auxiliaries versus auxiliary boilers or waste heat boilers.

DDGVT Technologies and DVs

Available technologies, systems, and concepts, based on those considered in the 1979–1981 studies, that are necessary to provide required operational capabilities were identified and defined in terms of performance, cost, risk, and ship impact (weight, area, volume, power). Trade-off studies were performed using technology and concept design parameters to select trade-off options in a MOGO for the total ship design. Alternative ship designs are described using 25 DVs listed in **Table 3**. Design-variable values are selected by the optimizer from the range indicated and input into the ship synthesis model. The ship is then balanced, checked for feasibility, and ranked based on risk, cost, and effectiveness.

The ranges for principal characteristics (LWL, B, T, D_{10}, C_p, C_x, and C_{rd}) were selected based on the earlier studies and typical cruiser/destroyer design lanes (Schaffer, Byers, and Slager 1983). Propulsion engines must be non-nuclear, grade A shock certified, and Navy qualified. The machinery system alternatives must span a total power range of 40,000–100,000 SHP with ship service power >3,000 kW. Three propulsion system type alternatives were considered in the DDGVT propulsion trade-off study. These are shown in **Figure 2**. Propulsion system type alternatives 1 and 3 are mechanical drive systems, system type 1 with a CRP, and system type 3 with an RRG and FPP. System type 2 uses integrated electric drive (IED) with a fixed pitch propeller. The propulsion power requirement is satisfied with two to four main engines. The IED system has two propellers, and the mechanical drive systems may have one or two propellers. The COGAS with the RACER option considered in 1981 was originally a favored choice because of its fuel efficiency. At the time, RACER and IED were new technologies with significant development risk. Gas turbine and diesel generator sets were both considered, including DDA 501-K17, DD 16V149TI, and FM 12V.

Ship Synthesis Model

A ship synthesis model is required to balance and assess designs selected by the optimizer. Modules in the synthesis model were developed using FORTRAN, and the model is integrated and executed in MC. The multi-objective genetic optimization is run in MC using the MC Darwin optimization plug-in. **Figure 3** shows the synthesis model in MC. MOPs are calculated based on the design parameters and their predicted

TABLE 3: DDGVT Design Variables (DVs)

DV	Name	Description	Design Space
1	LWL	Waterline length	120–180 m
2	B	Beam	15–18 m
3	T	Draft	5–7 m
4	D10	Depth at Station 10	10–13 m
5	Cp	Prismatic coefficient	0.55–0.65
6	Cx	Maximum section coefficient	0.7–0.88
7	Crd	Raised deck coefficient	0.6–1.0
8	VD	Deckhouse volume	4,000–6,000 m^3
9	Cdhmat	Deckhouse material	1 = steel, 2 = aluminum
10	BALtype	Ballast/fuel system type	0 = clean ballast, 1 = compensated fuel tanks
11	PSYS	Propulsion system alternative	Option 1: MD, CPP, 1 Shaft, 2×LM2500/COGAS (RACER)
			Option 2: MD, CPP, 1 Shaft, 2×LM2500
			Option 3: MD, CPP, 2 Shaft, 4×LM2500
			Option 4: MD, CPP, 2 Shaft, 2×LM2500, 2×LM500/COGAG
			Option 5: MD, CPP, 2 Shaft, 2×LM2500,2×PC2/16-DD/CODAG
			Option 6: MD, CPP, 2 Shaft, 2×LM2500
			Option 7: MD, CPP, 2 Shaft, 2×LM2500, 2×LM2500/COGAS(RACER)
			Option 8: MD, RRG, FPP, 1 Shaft, 2×LM2500/COGAS (RACER)
			Option 9: MD, RRG, FPP, 1 Shaft, 2×LM2500
			Option 10: MD, RRG, FPP, 2 Shaft, 4×LM2500
			Option 11: MD, RRG, FPP, 2 Shaft, 2×LM2500, 2×LM500/COGAG
			Option 12: MD, RRG, FPP, 2 Shaft, 2×LM2500, 2×PC2/16-DD/CODAG
			Option 13: MD, RRG, FPP, 2 Shaft, 2×LM2500
			Option 14: MD, RRG, FPP, 2 Shaft, 2×LM2500, 2×LM2500/COGAS(RACER)
			Option 15: IED, 2 Shaft, FPP, 2×LM2500
			Option 16: IED, 2 Shaft, FPP, 3×LM2500
			Option 17: IED, 2 Shaft, FPP, 4×LM2500
12	GSYS	Ship service generator system alternative	Option 1: 3×3000 kw Allison 501-K17, SSGTG
			Option 2: 4×3000 kw Allison 501-K17, SSGTG
			Option 3: 3×1053 kw DD 16V149TI, SSDG
			Option 4: 4×1053 kw DD 16V149TI, SSDG
			Option 5: 5×1053 kw DD 16V149TI, SSDG
			Option 6: 3×1566 kw FM 12V, SSDG
			Option 7: 4×1566 kw FM 12V, SSDG
			Option 8: 5×1566 kw FM 12V, SSDG
13	T_s	Provisions duration	45–60 days
14	N_{cps}	Collective protection system	0 = none, 1 = partial, 2 = full
15	N_{degaus}	Degaussing system	0 = none, 1 = degaussing
16	C_{man}	Manning reduction factor	0.95–1.0
17	AAW	AAW system alternative	Option 1(DDGX1A): 2×SPY-1B, SPS-49, 2×SPG-62, AEGIS Combat System, MK99 FCS
			Option 2 (DDX 2,5,6): 1×SPY-1B, SPS-49, 4×SPG-62, AEGIS Combat System, MK99 FCS
			Option 3 (DDG-51): 1×SPY-1D, 3×SPG-62, AEGIS Combat system, MK99 FCS
			Option 4 (DDX 7): 1×SPY-1B, SPS-49, AEGIS Combat System, MK99 FCS
			Option 5 (CG-47/DDGX1G): 2×SPY1A, SPS-49, 4×SPG-62, AEGIS Combat System, MK99 FCS
			Option 6 (DDX 3/4): SPS-48, SPS-49, MK 74 MFCS
			Option 7 (DD993): SPS-48, SPG-60, MK 74 MFCS
			Option 8 (DDX 1/FFG-7): SPS-49, SPG-60, MK 92 MFCS/STIR/CAS
			Option 9 (DDGX3E): SPS-49, MK 92 MFCS/STIR/CAS
			Option 10 (DD-963): SPS-40, SPG-60, MK91 MFCS

Table 3. (Continued).

DV	Name	Description	Design Space
18	ASUW	ASUW system alternative	Option 1 (DDG-51): SPS-67, SPS-64, MK 160/34 GFCS, Harpoon WCS SWG-1, Small Arms
			Option 2 (CG-47/DD-963/993): SPS-55, SPQ-9, MK 86 GFCS, Harpoon WCS SWG-1, Small Arms
			Option 3 (DDX 6&7): SPS-55, SPS-64, Harpoon WCS SWG-1, Small Arms
			Option 4 (DDX 1-5/FFG-7/DDGX-A): SPS-55, Harpoon WCS SWG-1, Small Arms
19	ASW	ASW system alternative	Options 1 and 2 (DDX 1/DDG-51/DDX3&4): SQS-53C, SQR-19 TACTAS, Nixie, 2×MK 32 Triple Tubes, SQQ 89 ASW System, MK 116 UWFCS
			Option 3 (DDX-2): SQS-53C, Nixie, 2×MK 32 Triple Tubes, SQQ 89 ASW System, MK 116 UWFCS
			Option 4 and 6 (DD-963/993/CG-47): SQS-53B, SQR-19 TACTAS, Nixie, 2×MK 32 Triple Tubes, SQQ 89 ASW System, MK 116 UWFCS
			Option 5 and 7 (DDGX-1E/FFG-7): SQS-56, SQR-19 TACTAS, Nixie, 2×MK 32 Triple Tubes, MK 309 Torpedo FCS, SQQ 89 ASW System
			Option 8 (DDX-7): SQS-56, Nixie, 2xMK 32 Triple Tubes, MK 309 Torpedo FCS, SQQ 89 ASW System
			Option 9 (DDX 5&6): Nixie
20	NSFS	NSFS system alternative	Option 1: 5″ 54 caliber MK 45 gun
			Option 2: 76 mm MK 75 gun
21	CCC	CCC system alternative	Option 1: CG 47; Option 2: DDG 51; Option 3: DD 993; Option 4: DD 963; Option 5: FFG 7
22	SEW	Signal and electronic warfare system alternative	Option 1: ECM SLQ-32-V3, MK 36 SRBOC
			Option 2: ECM SLQ-32-V2, MK 36 SRBOC
23	LAMPS	LAMPS/helo system alternative	Option 1: Embarked LAMPS w/Hangar; Option 2: LAMPS haven (flight deck); Option 3: in-flight refueling
24	SDS	Self-defense systems	Option 1: 1×CIWS,1 RAM; Option 2: 2×CIWS; Option 3: 1×CIWS
25	GMLS	Guided missile launching system alternative	Option 1 (DDG-X1A/DDX2&3): MK 41 VLS 128 cell, AN/SWG-3A Tomahawk WCS, MK 141 Harpoon Box Launcher
			Option 2 (DDX5-7/DDG-51): MK 41 VLS 96 cell, AN/SWG-3A Tomahawk WCS, MK 141 Harpoon Box Launcher
			Option 3 (DDX1): MK 41 VLS 64 cell, MK 13 GMLS, AN/SWG-3A Tomahawk WCS
			Option 4 (DDX 4): MK 41 VLS 64 cell, AN/SWG-3A Tomahawk WCS, MK 141 Harpoon Box Launcher
			Option 5 (CG-47/DD993): 2×MK 26 GMLS, MK 141 Harpoon Box Launcher
			Option 6 (FFG-7): MK 13 GMLS
			Option 7 (DD 963): MK29 GMLS, MK143 Launcher, AN/SWG-3A Tomahawk WCS, MK141 Harpoon Box Launcher, ASROC

For abbreviations please see nomenclature.

performance in a balanced design. VOPs, an OMOE, OMOR, and life-cycle cost are also calculated by the synthesis model.

The ship synthesis model is organized into modules as shown in Figure 3:

- Input Module—inputs the DV vector and other design parameters that are constant for all designs. Provides this input to the other modules.
- Combat Systems Module—retrieves combat systems data from the combat systems data base as specified by the combat system DVs. Calculates payload SWBS weights, vertical centers of gravity (VCGs), areas, and electric power requirements and assesses performance for the total combat system.

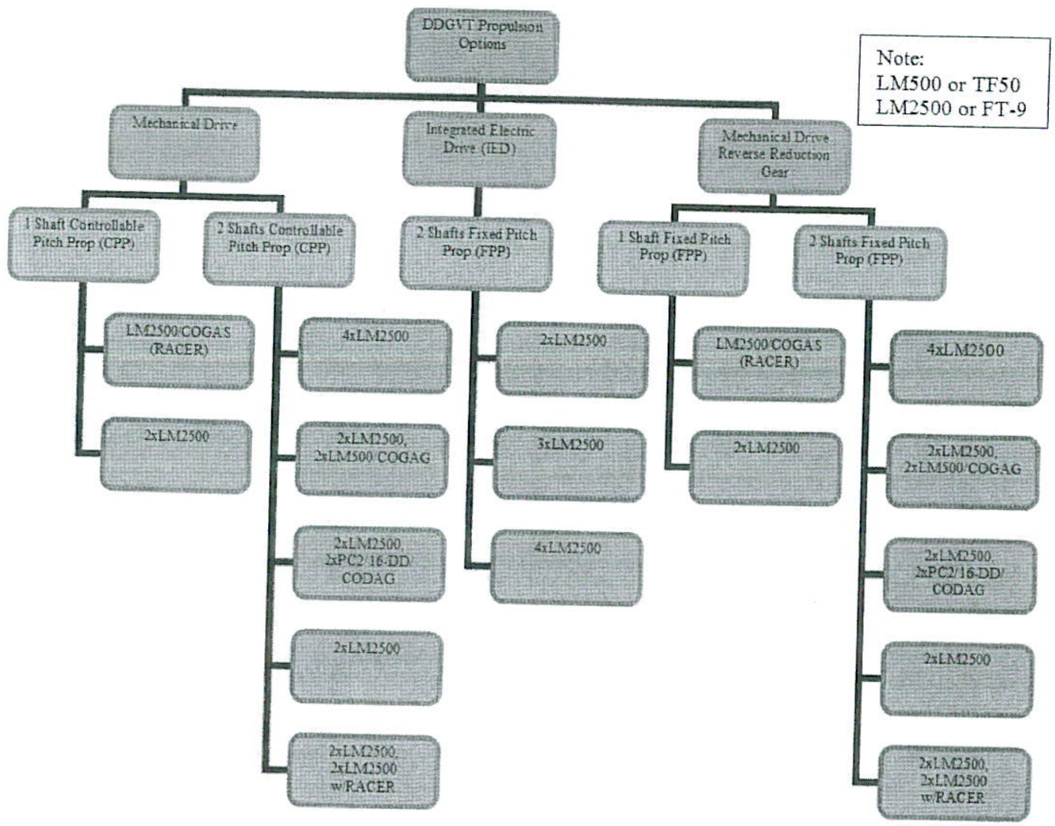


Figure 2: *DDGVT Machinery Alternatives*

- Hull Form Module—calculates hull form principal characteristics and supplies them to other modules.
- Propulsion Module—retrieves propulsion system and ship service power system data from the Propulsion and Power System Data Base as specified by the propulsion system and generator system DVs.
- Space Available Module—calculates available volume and area, minimum depth required at amidships, cubic number, CN, and the height and volume of the machinery box.
- Resistance Module—calculates hull resistance, required shaft horsepower at endurance speed and sustained speed. Resistance is calculated using the Holtrop and Mennen (1982) regression-based method. Propulsive coefficient is approximated. Sustained speed is calculated based on total brake horsepower (BHP) available with a 25% margin.
- Electric Power Module—calculates maximum functional electric load with margins (KW_{MFLM}), required generator power (KW_{GREQ}), required average 24-hour electric power (KW_{24AVG}), and required auxiliary machinery room volume (V_{AUX}). It estimates system power requirements using known values and parametric equations, sums and applies margins, assumes one ship service generator is unavailable, uses a power factor of 0.9, and uses the electric load analysis method from DDS 310-1 (NAVSEA 1980).
- Weight and Stability Module—calculates single-digit SWBS weights, total weight, fuel weight, and metacentric height above center of gravity (GM)/B ratio. The module uses a combination of known weights and parametric equations to calculate the SWBS weights. Height of center of gravity (KG) is calculated from single digit weights and VCGs, estimated using parametric equations. Fuel weight is calculated as the difference between displacement and the sum of all other weights (less fuel).
- Tankage Module—calculates tankage volume requirements based on fuel weight and para-

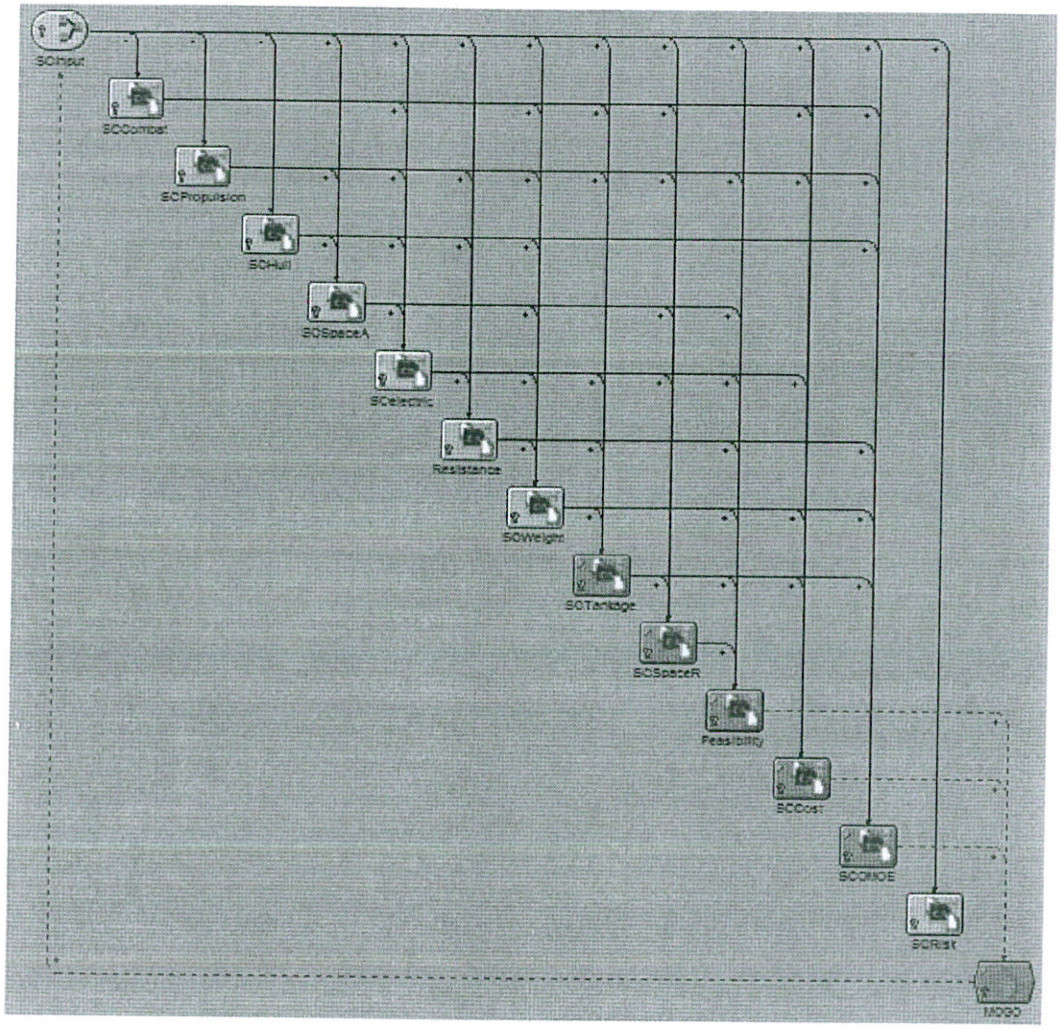


Figure 3: *SC Ship Synthesis Model in Model Center (MC)*

metric equations. It uses a number of input variables including fluid specific volumes, ballast type, transmission efficiency, fuel consumption at endurance speed, average generator engine fuel consumption, average electric load, endurance speed, total propulsion engine BHP, potable water weight, and lube oil weight. It uses parametric equations for various tank volumes and design data sheet DDS-200-1 for endurance fuel calculations. It outputs total required tankage volume, fuel tank volume and endurance range.

- Space Required Module—calculates deckhouse arrangeable area required and available, and total ship area required and available using parametric equations. Inputs include number and type of personnel, cubic number, known area requirements, hull and deckhouse volumes, large object volumes, average deck height, beam, and stores duration.

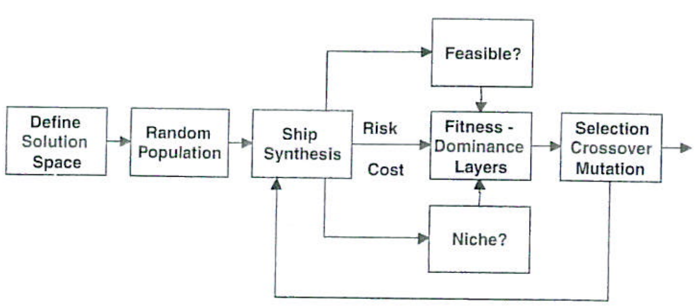


Figure 4: *Multi-Objective Genetic Optimization*

- Feasibility Module—assesses the overall design feasibility. It compares available with required characteristics including total arrangeable ship area, deckhouse area, sustained speed, electrical plant power, minimum and maximum GM/B ratios, endurance range, and sustained speed.
- Cost Module—calculates lead-ship acquisition, follow-ship acquisition, and life-cycle cost using weight-based parametric equations modified for complexity and producibility.
- Effectiveness Module—calculates VOPs for all MOPs. Calculates the OMOE using these VOPs and their associated weights.
- Risk Module—calculates a quantitative OMOR for a specific design considering performance risk, cost risk, and schedule risk.

MOGO

The optimization is performed in Model Center using the Darwin optimization plug-in. Objective attributes for this optimization are life-cycle cost, risk (technology cost, schedule, and performance risk), and military effectiveness. A flow chart for the MOGO is shown in **Figure 4**. In the first design generation, the optimizer randomly defines 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 DV values. A small percentage of randomly selected DV 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 100+ generations of evolution, the NDF (or surface) of designs is defined. Each ship on the NDF provides the highest effectiveness for a given cost and risk compared with other designs in the design space. The "best" design is determined by the customer's preference for effectiveness, cost, and risk.

To perform the optimization, quantitative objective functions are developed for each objective attribute. Effectiveness and risk are quantified using OMOE and OMOR.

Measures of Performance are selected based on ROCs and DVs. Goal and threshold metric values or options are identified for each MOP.

TABLE 4: DDGVT MOPs

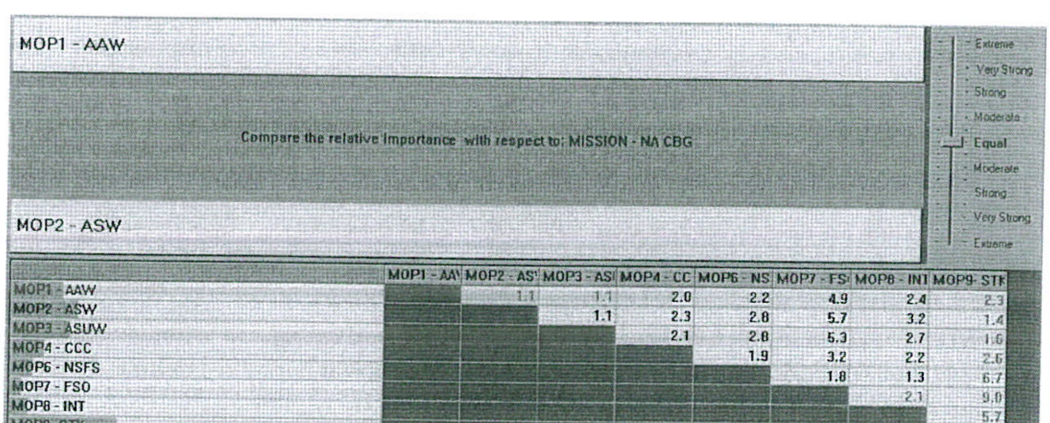
MOP #	MOP	Metric	Goal	Threshold
1	AAW	AAW option	AAW = 1	AAW = 10
		GMLS option	GMLS = 1	GMLS = 7
		SEW option	SEW = 1	SEW = 2
		SDS option	SDS = 1	SDS = 3
		CCC option	CCC = 1	CCC = 5
2	ASW	ASW option	ASW = 1	ASW = 9
		LAMPS option	LAMPS = 1	LAMPS = 3
		GMLS option	GMLS = 1	GMLS = 7
		CCC option	CCC = 1	CCC = 5
3	ASUW	ASuW option	ASuW = 1	ASuW = 4
		LAMPS option	LAMPS = 1	LAMPS = 3
		NSFS option	NSFS = 1	NSFS = 2
		CCC option	CCC = 1	CCC = 5
		SEW option	SEW = 1	SEW = 2
4	CCC	CCC option	CCC = 1	CCC = 5
5	Not used			
6	NSFS	NSFS option	NSFS = 1	NSFS = 2
		CCC option	CCC = 1	CCC = 5
7	FSO	LAMPS option	LAMPS = 1	LAMPS = 3
		CCC Option	CCC = 1	CCC = 5
8	INT	LAMPS Option	LAMPS = 1	LAMPS = 3
		CCC option	CCC = 1	CCC = 5
9	STK	GMLS option	GMLS = 1	GMLS = 7
		CCC option	CCC = 1	CCC = 5
10	Sustained speed	Knots	Vs = 32 knots	Vs = 28 knots
11	Endurance range	Nm	E = 6,500 nm	E = 3,500 nm
12	Stores and provisions	Days	Ts = 60 days	Ts = 45 days
13	Seakeeping	McCreight index	McC = 16	McC = 6
14	Environmental	Ballast option	Clean	Compensated
15	Structure, DH material	Cdhmat	Steel	Aluminum
16	NBC	CPS option	Full	None
17	RCS	Cubic meters	VD = 4,000	VD = 6,000
18	Acoustic signature	PSYStype	FPP, IED	CPP, MD
18	IR signature	PENGtype	RACER	GT
19	Magnetic signature	Degaussing	Degaussing	None

For abbreviations please see nomenclature.

Figure 5: *OMOE Hierarchy*

MOPs are used in the ship synthesis model to calculate the OMOE (Demko 2005; Brown and Demko 2006). MOPs are listed in **Table 4**.

Figure 5 is the OMOE hierarchy for DDGVT derived from Table 4. Separate hierarchies are developed for each type of mission for DDGVT. MOPs are grouped into four categories (mission and active defense, sustainability, mobility, vulnerability, and susceptibility) under each mission. MOP weights are calculated using expert opinion and pair-wise comparison as shown in **Figure 6**. Results are shown in **Figure 7**. MOP weights and value functions are finally assem-



	MOP1 - AA\	MOP2 - AS'	MOP3 - AS	MOP4 - CC	MOP6 - NS	MOP7 - FS	MOP8 - INT	MOP9- STK
MOP1 - AAW		1.1	1.1	2.0	2.2	4.9	2.4	2.3
MOP2 - ASW			1.1	2.3	2.8	5.7	3.2	1.4
MOP3 - ASUW				2.1	2.8	5.3	2.7	1.6
MOP4 - CCC					1.9	3.2	2.2	2.6
MOP6 - NSFS						1.8	1.3	6.7
MOP7 - FSO							2.1	9.0
MOP8 - INT								5.7
MOP9- STK	Incon: 0.01							

Figure 6: *Analytical Hierarchy Process Pair-wise Comparison*

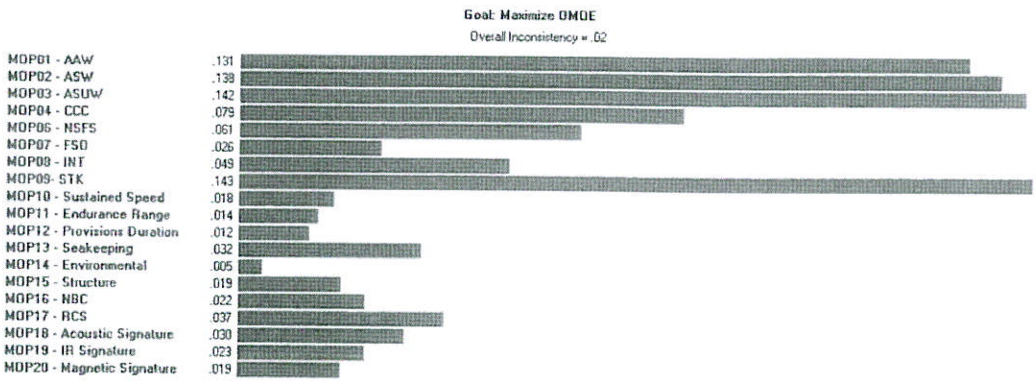


Figure 7: *MOP Weights (See Table 4)*

bled in a single OMOE function:

$$\begin{aligned}\text{OMOE} &= g[VOP_i(MOP_i)] \\ &= \sum_i w_i VOP_i(MOP_i) \qquad (1)\end{aligned}$$

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 technology risk may be necessary to achieve specified performance or cost reduction goals. An OMOR (Mierzwicki 2003; Mierzwicki and Brown 2004) is used as a metric for this risk.

Three types of technology risk events are considered in the DDGVT 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 DVs 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 DVs, required capabilities, cost, and schedule. The risk is calculated for each event and a risk table or register is created. Possible risk events identified for DDGVT are listed in **Table 5**. Performance risk events include the addition of RACER to the LM-2,500, IED, the development of a SPY-1D radar, and the new vertical launch system. Cost and schedule risk events include the new technologies failing, exceeding cost, and/or development schedule estimates. The AHP and expert pair-wise comparison are then used to calculate OMOR hierarchy weights, W_{perf}, W_{cost}, W_{sched}, w_i, w_j, and w_k. The OMOE performance weights calculated previously that are associated with risk events are normalized to a total of 1.0, and reused for calculating the OMOR. Once possible risk events are identified, a probability of occurrence, P_i, and a consequence of occurrence, C_i, are estimated for each event using **Tables 6** and **7**. The OMOR is calculated using these weights and probabilities in the following equation:

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

The OMOR function is used as the third objective attribute in the MOGO.

DDGVT construction costs are estimated for each SWBS group using weight-based equations. **Figure 8** illustrates acquisition cost components calculated in the model. The basic cost of construction (BCC) is the sum of all SWBS group costs including engineering, assembly, and support, which are very large for the lead ship. Ship price includes profit. In naval ships, the total shipbuilder portion is the sum of the projected cost of change orders and the BCC. The total government portion is the sum of the cost of

TABLE 5: DDGVT Risk Register

SWBS	Risk Type	Related DV #	DV Options	DV Descriptions	Risk Event EI				
Event #	PI	CI	RI						
2	Performance	DV11	15,16,17	Integrated electric drive	Does not meet performance TLRs	1	0.5	0.7	0.35
2	Schedule	DV11	15,16,17	Integrated electric drive	Schedule delays impact program	2	0.6	0.5	0.3
2	Cost	DV11	15,16,17	Integrated electric drive	Development and acquisition cost overruns	3	0.7	0.5	0.35
2	Performance	DV11	1,7,8,14	RACER	Does not meet performance TLRs	4	0.8	0.3	0.24
2	Schedule	DV11	1,7,8,14	RACER	Schedule delays impact program	5	0.6	0.5	0.3
2	Cost	DV11	1,7,8,14	RACER	Development and acquisition cost overruns	6	0.6	0.5	0.3
2	Performance	DV11	8,9,10,11,12,13,14	RRG	Does not meet performance TLRs	7	0.7	0.2	0.14
2	Schedule	DV11	8,9,10,11,12,13,14	RRG	Schedule delays impact program	8	0.6	0.2	0.12
2	Cost	DV11	8,9,10,11,12,13,14	RRG	Development and acquisition cost overruns	9	0.6	0.3	0.18
4	Performance	DV17	1,2,3,4	SPY-1B.D	Does not meet performance TLRs	10	0.2	0.3	0.06
4	Schedule	DV17	1,2,3,4	SPY-1B,D	Schedule delays impact program	11	0.25	0.6	0.15
4	Cost	DV17	1,2,3,4	SPY-1B,D	Development and acquisition cost overruns	12	0.25	0.6	0.15
4	Performance	DV18	1	SPS-67	Does not meet performance TLRs	13	0.4	0.1	0.04
4	Schedule	DV18	1	SPS-67	Schedule delays impact program	14	0.3	0.3	0.09
4	Cost	DV18	1	SPS-67	Development and acquisition cost overruns	15	0.3	0.3	0.09
4	Performance	DV19	1,2,3	SQS-53C	Does not meet performance TLRs	16	0.2	0.4	0.08
4	Schedule	DV19	1,2,3	SQS-53C	Schedule delays impact program	17	0.3	0.6	0.18
4	Cost	DV19	1,2,3	SQS-53C	Development and acquisition cost overruns	18	0.3	0.6	0.18
7	Performance	DV24	1	RAM	Does not meet performance TLRs	19	0.8	0.5	0.4
7	Schedule	DV24	1	RAM	Schedule delays impact program	20	0.25	0.3	0.075
7	Cost	DV24	1	RAM	Development and acquisition cost overruns	21	0.25	0.3	0.075
7	Performance	DV25	1,2,3,4	VLS	Does not meet performance TLRs	22	0.1	0.4	0.04
7	Schedule	DV25	1,2,3,4	VLS	Schedule delays impact program	23	0.1	0.5	0.05
7	Cost	DV25	1,2,3,4	VLS	Development and acquisition cost overruns	24	0.1	0.6	0.06

For abbreviations please see nomenclature.

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. DDGVT life-cycle cost as defined in this study includes acquisitions, manning, and fuel costs.

TABLE 6: 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

Results

The non-dominated (ND) frontier results from the optimization are shown in **Figures 9** and **10**. In Figure 9, effectiveness (OMOE) is plotted versus follow-ship acquisition cost (C_{fola}) and risk (OMOR). Colors represent the improvement in non-dominated designs from Generation 1, selected at random, to Generation 107. Bands of non-dominated designs versus OMOR shown in the left view correspond to low-risk designs, medium-risk designs (RACER or IED and VLS

TABLE 7: 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	Cannot achieve key team or major program milestone	>10%

or SQS-53C) and high-risk designs (RAM or significant automation). These bands are plotted in two dimensions in Figure 10 with green points representing low-risk, yellow points representing medium-risk, and red points representing high-risk designs. Results for the actual ships DDG-51, CG-52, and FFG-7 are also plotted for comparison. Designs 17, 18, 33, and 54 are circled for discussion. Specific characteristics for these designs are listed and compared with DDG-51 in **Table 8**.

In general, most designs on the NDF include fuel-efficient propulsion options (RACER or combined diesel and gas turbine [CODAG]). Despite reliability and redundancy impacts, single-shaft systems were often selected even in higher cost ships. This is due to the very substantial total ship impact of a single shaft and main machinery room, and the higher value given to warfighting capabilities. Most high-end ships include the DDG-51 AAW system (SPY-1D) and VLS (96 or 64 cells). Most include a partial or full CPS and degaussing, despite the significant volume and weight impacts of these options. Most include a compensated fuel system to provide valuable volume in volume-limited designs despite an environmental penalty. Most high-end ships include an embarked LAMPS and hangar, despite the fact that, as in 1980, this option was not given a significant performance advantage over flight-deck only. CG-47, FFG-7, and DD-963 class ships were considered to have sufficient task group hangar capacity. However, the fact that LAMPS capability enhances multiple warfighting areas (ASW, ASUW, FSO, INT) and provides excellent ASW capability without the major impact of an SQS-53C sonar and/or TACTAS gave the embarked LAMPS significant leverage over other options. Less-capable ASW systems (SQS-56 w/o TACTAS) are often selected even in higher cost ships. Most of the designs on the ND frontier are longer with less beam and draft than DDG-51. This provides a significant resistance advantage for an equivalent displacement.
It is believed that the DDG-51 length was constrained for program reasons to distinguish it from CG-47 class ships.

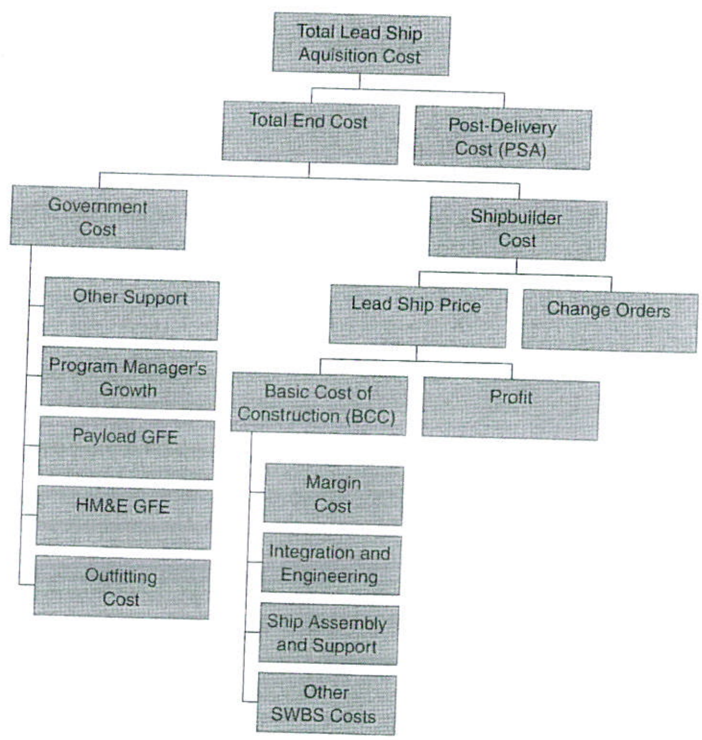


Figure 8: *Naval Ship Acquisition Cost Components*

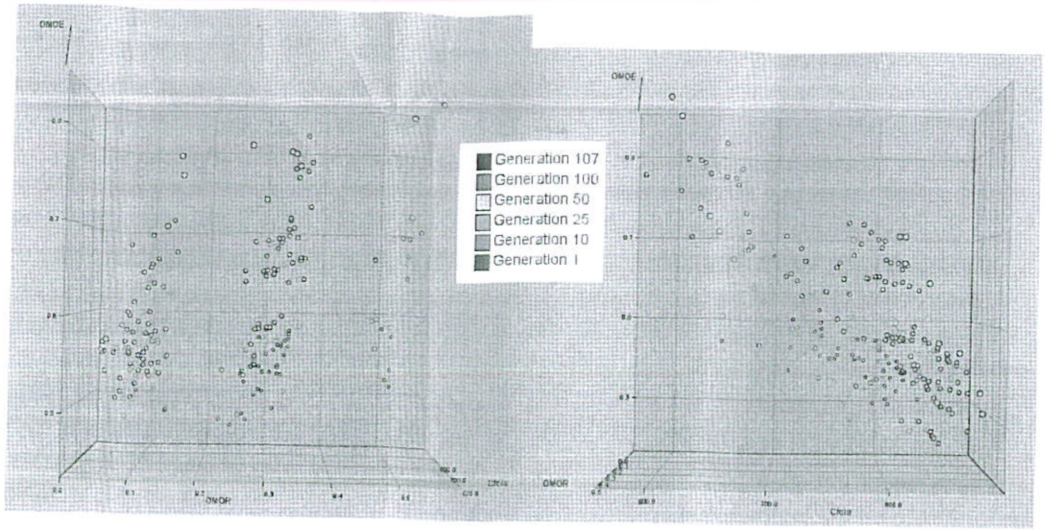


Figure 9: *DDGVT 3D Non-Dominated Frontier*

The actual DDG-51 is a low-risk, high-effectiveness, high-cost alternative very close to the ND frontier. Because the DDGVT process and specific OMOE function were not used for the DDG-51 design, it is remarkable how close to the ND frontier it is. It is an excellent ship, especially considering that RACER was planned for the original design and was never implemented. RACER would have substantially increased endurance range and sustained speed.

Design 17 has a slightly greater effectiveness than DDG-51 with similar low risk, but with $41 million less acquisition cost. This lower cost is the result of better fuel efficiency (CODAG), less resistance, and a smaller sonar (SQS-56 w/o TACTAS), all of which result in a smaller ship. Effectiveness is improved by the embarked LAMPS. This design also has an excellent endurance range (6157 nm), but with a lower sustained speed (29.4 knots), and 76 mm vice 5″-54 gun. It is the authors' preferred design.

Design 54 has slightly less effectiveness than DDG-51 with similar low risk and $79 million less acquisition cost. This is a very significant cost reduction. It is also a CODAG design with embarked LAMPS. The trade-offs for this cost reduction include a sustained speed of 29.7 knots, SQS-56 sonar, 76-mm gun, VLS with only 64 cells vice 96 cells, and marginal endurance range (3,500 nm).

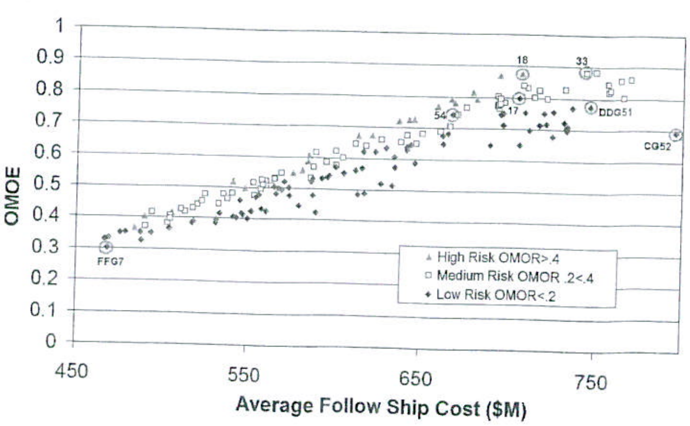


Figure 10: *DDGVT Non-Dominated Frontier*

Design 33 has a similar cost to DDG-51, but with higher risk and substantially higher effectiveness. It has only a single shaft RACER system, but with a 96-cell VLS, embarked LAMPS, SQS-53C sonar, and a 5″-54 gun.

Design 18 has a $39 million less acquisition cost, but higher risk and much higher effectiveness. It is also a single shaft RACER design, but with diesel generators vice gas turbines, and increased automation. This smaller ship has all other DDG-51 systems plus excellent endurance range, embarked LAMPS, SLQ-32V3, and CG-47 CCC.

TABLE 8: Selected ND Designs and Actual Ship Characteristics

Description	DDG-51	Design #54	Design #17	Design #33	Design #18	Design Space
Follow-ship acquisition cost	$746M	$667M	$705M	$743M	$707M	
Technology Risk (OMOR)	0.122	0.103	0.111	0.383	0.408	0–1
Effectiveness (OMOE)	0.773	0.743	0.797	0.883	0.876	0–1
Displacement (MT)	8128	6758	7487	6836	6694	
LWL - Waterline length (m)	141.8	145.5	148.6	146.1	143.9	120–180 m
B–Beam (m)	17.9	16.3	16.2	16.1	16.7	15–18 m
T–Draft (m)	6.1	5.4	5.3	5.2	5.1	5–7 m
D10 - Depth (m)	12.8	11.8	11.8	11.0	10.5	10–13 m
Cp - Prismatic coefficient	0.607	0.61	0.640	0.610	0.61	.55–.65
Cx–Max section coefficient	0.818	0.83	0.880	0.860	0.84	.7–.88
Deckhouse volume (m^3)	5,437	4,700	4,500	5,100	5,200	4,000–6,000 m^3
Deckhouse material	steel	steel	steel	steel	aluminum	steel, aluminum
Ballast/fuel system type	compensated	compensated	compensated	compensated	compensated	clean ballast, compensated
Endurance range (nm)	3,746	3,500	6,157	3,603	5,391	G: 6,500; T: 3,500
Sustained speed (knots)	31.4	29.7	29.4	28.2	28.1	G: 32; T: 28
Seakeeping (McC index)	14.7	10.8	12.0	10.4	10.1	G: 16; T: 6
Propulsion system alternative	Option 3) MD, CPP, 2 Shaft, 4xLM2500	Option 5) MD, CPP, 2 Shaft, 2xLM2500, 2xPC2/16-DD/ CODAG	Option 5) MD, CPP, 2 Shaft, 2xLM2500, 2xPC2/16-DD/ CODAG	Option 1) MD, CPP, 1 Shaft, 2xLM2500/COGAS (RACER)	Option 1) MD, CPP, 1 Shaft, 2xLM2500/COGAS (RACER)	Options 1–17
Ship service generator system alternative	Option 1) 3x3000 kw Allison 501-K17, SSTG	Option 2) 4x3000 kw Allison 501-K17, SSTG	Option 1) 3x3000 kw Allison 501-K17, SSTG	Option 2) 4x3000 kw Allison 501-K17, SSTG	Option 7) 4x1566 kw FM 12V, SSDG	Options 1–8
Collective Protection System	partial	partial	partial	partial	partial	0 = none, 1 = partial, 2 = full
Degaussing system	degaussing	degaussing	degaussing	degaussing	degaussing	0 = none, 1 = degaussing
Manning reduction factor	1.0	0.97	0.96	0.98	0.95	0.95–1.0
Crew	345	302	305	322	305	
AAW system alternative	Option 3 (DDG-51): 1xSPY-1D, 3xSPG-62, AEGIS Combat System, MK99 FCS	Option 3 (DDG-51): 1xSPY-1D, 3xSPG-62, AEGIS Combat System, MK99 FCS	Option 3 (DDG-51): 1xSPY-1D, 3xSPG-62, AEGIS Combat System, MK99 FCS	Option 3 (DDG-51): 1xSPY-1D, 3xSPG-62, AEGIS Combat System, MK99 FCS	Option 3 (DDG-51): 1xSPY-1D, 3xSPG-62, AEGIS Combat System, MK99 FCS	Options 1–10

Table 8. (Continued).

Description	DDG-51	Design #54	Design #17	Design #33	Design #18	Design Space
ASUW system alternative	Option 1 (DDG-51): SPS-67, SPS-64, MK 160/34 GFCS, Harpoon WCS SWG-1, Small Arms	Option 1 (DDG-51): SPS-67, SPS-64, MK 160/34 GFCS, Harpoon WCS SWG-1, Small Arms	Option 1 (DDG-51): SPS-67, SPS-64, MK 160/34 GFCS, Harpoon WCS SWG-1, Small Arms	Option 1 (DDG-51): SPS-67, SPS-64, MK 160/34 GFCS, Harpoon WCS SWG-1, Small Arms	Option 1 (DDG-51): SPS-67, SPS-64, MK 160/34 GFCS, Harpoon WCS SWG-1, Small Arms	Options 1–4
ASW system alternative	Option 2 (DDG-51/DDX3&4): SQS-53C, SQR-19 TACTAS, Nixie, 2xMK 32 Triple Tubes, SQQ 89	Option 8 (DDX-7): SQS-56, Nixie, 2xMK 32 Triple Tubes, SQQ 89	Option 8 (DDX-7): SQS-56, Nixie, 2xMK 32 Triple Tubes, SQQ 89 FCS	Option 3 (DDX-2): SQS-53C, Nixie, 2xMK 32 Triple Tubes, SQQ 89 FCS	Option 3 (DDX-2): SQS-53C, Nixie, 2xMK 32 Triple Tubes, SQQ 89 FCS	Options 1–9
NSFS system alternative	Option 1: 5″ 54 gun	Option 2: 76 mm gun	Option 2: 76 mm gun	Option 1: 5″ 54 gun	Option 1: 5″ 54 gun	Options 1–2
CCC system alternative	Option 2: DDG 51	Option 2: DDG 51	Option 1: CG 47	Option 1: CG 47	Option 1: CG 47	Options 1–5
Signal and electronic warfare system alternative	Option 2: SLQ-32-V2, MK 36 SRBOC	Option 1: SLQ-32-V3, MK 36 SRBOC	Option 1: SLQ-32-V3, MK 36 SRBOC	Option 2: SLQ-32-V2, MK 36 SRBOC	Option 1: SLQ-32-V3, MK 36 SRBOC	Options 1–2
LAMPS/helo system alternative	Option 2: LAMPS haven (flight deck)	Option 1: Embarked LAMPS w/Hangar	Option 1: Embarked LAMPS w/Hangar	Option 1: Embarked LAMPS w/Hangar	Option 1: Embarked LAMPS w/Hangar	Options 1–3
Self-Defense Systems	Option 2: 2xCIWS	Option 2: 2xCIWS	Option 3: 1xCIWS	Option 2: 2xCIWS	Option 3: 1xCIWS	Options 1–3
Guided Missile Launching System alternative	Option 2 (DDX5-7/DDG-51) MK 41 VLS 96 cell, AN/SWG-3A Tomahawk WCS, MK 141 Harpoon Box Launcher	Option 4 (DDX 4) MK 41 VLS 64 cell, AN/SWG-3A Tomahawk WCS, MK 141 Harpoon Box Launcher	Option 2 (DDX5-7/DDG-51) MK 41 VLS 96 cell, AN/SWG-3A Tomahawk WCS, MK 141 Harpoon Box Launcher	Option 2 (DDX5-7/DDG-51) MK 41 VLS 96 cell, AN/SWG-3A Tomahawk WCS, MK 141 Harpoon Box Launcher	Option 4 (DDX 4) MK 41 VLS 64 cell, AN/SWG-3A Tomahawk WCS, MK 141 Harpoon Box Launcher	Options 1–7

For abbreviations please see nomenclature.

Conclusions

DDG-51 is an excellent design. The DDG-51 concept design lasted more than 3 years (or 10 years with DG-AEGIS) with multiple panels and executive boards periodically reviewing the proposed alternatives, and yet at no time could there be rational confidence that a particular design was non-dominated. It was a painful and costly birth. Without quantified estimates of cost, risk, and effectiveness, it is difficult to defend rational selections against political and other considerations. The process used in this case study provides 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. This process also provides an efficient and robust method to search the design space for optimal concepts.

DDG-51 and theoretically superior designs were identified by this study with a modest effort and rational process. Cases for options such as an embarked LAMPS and helo hangar, lower risk energy-saving propulsion alternatives like CODAG, smaller sonar, 64 vice 96 cells VLS, and greater hull length could be achieved much more effectively given this framework. We have the systems engineering tools today to make this a rational vice political process. These are already being used in other fields throughout industry. It is time for us to change.

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