Multi-Attribute Tradespace Exploration for US Navy Surface Ship Survivability: A Framework for Balancing Capability, Survivability, and Affordability

by

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B.S., Mechanical Engineering, North Carolina State University, 2005

Submitted to the Department Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degrees of

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and

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MULTI-ATTRIBUTE TRADESPACE EXPLORATION FOR US NAVY SURFACE SHIP SURVIVABILITY: A FRAMEWORK FOR BALANCING CAPABILITY, SURVIVABILITY, AND AFFORDABILITY

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ABSTRACT

In a political environment of austerity, the importance of understanding the design tradeoffs for new naval ship concept designs cannot be understated. A combination of a tightened shipbuilding budget, large high-priority procurement programs, and an emphasis on affordability will require high level tradeoffs to be made in future ship programs. Understanding tradeoffs in naval ship capability and survivability for the sake of affordability early in concept ship design gives Navy leadership real options for affordable ships and reduces the likelihood of detailed design changes late in the acquisition process. In the naval ship design process capability and affordability are typical "ility" tradeoffs made in traditional tradespace exploration. Ship designers must consider survivability as a third dimension independent of capability and cost. A specific ship system can be costly and improve survivability in a design but not deliver a level of desired capability. This thesis proposes a framework based on existing methodologies to perform tradespace exploration by iteratively determining a concept naval ship design's capability, survivability, and cost across large tradespaces of thousands of concepts. The process determines an optimal set of designs using multi-dimensional Pareto-optimization methods. This thesis also demonstrates methods to navigate the space bound by the optimized set of designs so tradeoffs can be made while preserving the optimal balance of capability, survivability, and cost. Survivability-cost relationships are developed with specific design requirements to provide insight into the amount of investment required to improve naval ship survivability. Understanding capability-survivability-cost tradeoffs ultimately informs a ship designer the premium that must be paid for increased survivability for a desired level of capability.

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BIOGRAPHICAL NOTE

Lieutenant Commander Johnathan Walker is from Killeen, Texas and graduated from North Carolina State University in 2005 with a Bachelor of Science in Mechanical Engineering. After graduation he was commissioned as a Surface Warfare Officer in the United States Navy and served sea tours on the guided-missile cruiser USS Antietam and, after nuclear power training, the aircraft carrier USS Harry S Truman.

In 2012, LCDR Walker transferred in the Engineering Duty Officer (Nuclear) community and reported to the Massachusetts Institute of Technology in May of 2013 to earn a Naval Engineer's degree and a Master of Science in Mechanical Engineering. After graduation from MIT, LCDR Walker will report to the Supervisor of Shipbuilding Newport News in Newport News, Virginia to work in the aircraft carrier refueling complex overhaul project office.

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LIST OF ACRONYMS AND ABBREVIATIONS

ABS – American Bureau of Shipping

AHP – Analytic Hierarchy Process

AIREX – Air Explosion

AoA – Analysis of Alternatives

AMW – Amphibious Warfare

ASAP – Advanced Survivability Assessment Program

ASSET – Advanced Surface Ship Evaluation Tool

ASW – Anti-Submarine Warfare

AW – Air Warfare

BCA – Budget Control Act

CBO – Congressional Budget Office

CCC – Command, Control, and Communications

CDD – Capabilities Development Document

CEH – Cost Estimating Handbook

CER – Cost Estimating Relationship

CG – Guided Missile Cruiser

CIC – Combat Information Center

CNO – Chief of Naval Operations

CONOPS – Concept of Operations

CSER – Combat Systems Equipment Room

DC – Damage Control

DDG – Guided Missile Destroyer

DOD – Department of Defense

DON – Department of the Navy

EA – Electronic Attack

EP – Electronic Protection

ES – Electronic Support

ESSM – Evolved Sea-Sparrow Missile

ESWBS – Expanded Ships Work Breakdown Structure

EW – Electronic Warfare

EXW – Expeditionary Warfare

FFG – Guided Missile Frigate

FHP – Force Health Protection

FSO – Fleet Support Operations

FY – Fiscal Year

GD – General Dynamics

GFM – Government Furnished Material

HM&E – Hull, Machinery, and Electrical

HSNCR – High Speed Naval Craft Rules

ICD – Initial Capabilities Document

INT – Intelligence Operations

IO – Information Operations

LOG - Logistics

LCS – Littoral Combat Ship

LFT&E – Live Fire Test and Evaluation

LM – Lockheed Martin

MATE – Multi-Attribute Tradespace Exploration

MAUT – Multi-Attribute Utility Theory

MIW – Mine Warfare

MOB – Mobility

MOS – Missions of State

NCO – Noncombat Operations

NSRP – Naval Shipbuilding Research Project

NSW – Naval Special Warfare

NSWCCD – Naval Surface Warfare Center Carderock Division

NSWCDD – Naval Surface Warfare Center Dahlgren Division

NVR – Naval Vessel Rules

ONI – Office of Naval Intelligence

OPNAVINST – Office of the Chief of Naval Operations Instruction

ORP – Ohio Submarine Replacement Program

POE – Projected Operational Environment

PRA – Probability of Raid Annihilation

RFP – Request for Proposal

ROC – Required Operational Capabilities

SECNAV – Secretary of the Navy

SEWIP – Surface Electronic Warfare Improvement Program

SM – Standard Missile

SSC – Small Surface Combatant

STS – Strategic Sealift

STW – Strike Warfare

SUW – Surface Warfare

SVR – Steel Vessel Rules

SVTT – Surface Vessel Torpedo Tubes

SWaP-C – Size, Weight, Power, and Cost

T-AKE – Naval Replenishment Ship

UNDEX – Underwater Explosion

VLS – Vertical Launching System

1 INTRODUCTION

The U.S. Navy faces a challenging environment of a tightened defense budget and large high-priority procurement programs that will pressure the shipbuilding budget for the next 20 years. During this time the Navy will make critical decisions that affect the total number of ships in the battle force, and critical design decisions that impact the effectiveness or survivability of newly procured ships. If the Navy stands by its battle force plans, with the intention of building up to and maintaining 308 ships, difficult tradeoffs in ship design will be required to balance affordability. In ship concept design, sacrificing capability or survivability for the sake of affordability is common. A recent ship program, the Littoral Combat Ship, saw similar tradeoffs in capability and survivability to achieve affordability goals. The program, responding to design criticism, made major design changes during lead ship construction resulting in cost overruns. The field of concept naval ship design needs a framework to explore ship concepts, finding the optimal balance of capability, survivability, and affordability.

1.1 Cost Growth in U.S. Naval Shipbuilding

Over the last 50 years, U.S. Navy shipbuilding costs have grown at a rate of 7%-11% per year far outpacing the rate of inflation. (Arena, et al. 2006) Two contributing factors for ship building cost growth are economy-driven and customer-driven. A 2006 RAND Corporation study on the escalation in U.S. Navy shipbuilding costs found that economy-driven factors were comparable to the rate of inflation. Customer-driven factors are design requirements and standards desired by the government, which leads to increases in design and construction complexity and ultimately leads to increased costs. (Arena, et al. 2006) More recently, requirements for improvements in ship survivability have led to sharp increases in ship procurement cost. The Littoral Combat Ship (LCS) program, which is comprised of two different classes, the LCS-1 Freedom Class and the LCS-2 Independence Class, saw lead ship cost growth of 149% and 144% respectively (CBO 2015) which were largely due to changes in survivability requirements.

Looking to future shipbuilding, the Navy's 2016 shipbuilding plan calls for a battle force of 308 ships while maintaining above 300 ships by fiscal year (FY) 2020 and intends to achieve the 308 ship goal between FY2022 and FY2034. The U.S. Navy currently has 282 ships. Additionally, the Navy intends to grow the force of Small Surface Combatants from 22 to 52 ships by FY2028.

The Ohio Class Submarine Replacement Program (ORP), which the Navy has designated it's top shipbuilding priority, will pressure the shipbuilding plan for a decade from FY2024 until FY2034 where the Navy plans to procure one Ohio Replacement per year. The Navy projects that ORP will consume about half of the shipbuilding funding available in any given year through the decade of the program. (DON 2015) The strain of ORP on the shipbuilding budget will affect other ship programs by either reducing the procurement of ships in new or current programs or over emphasis on affordability through "ility" tradeoffs in new procurement programs.

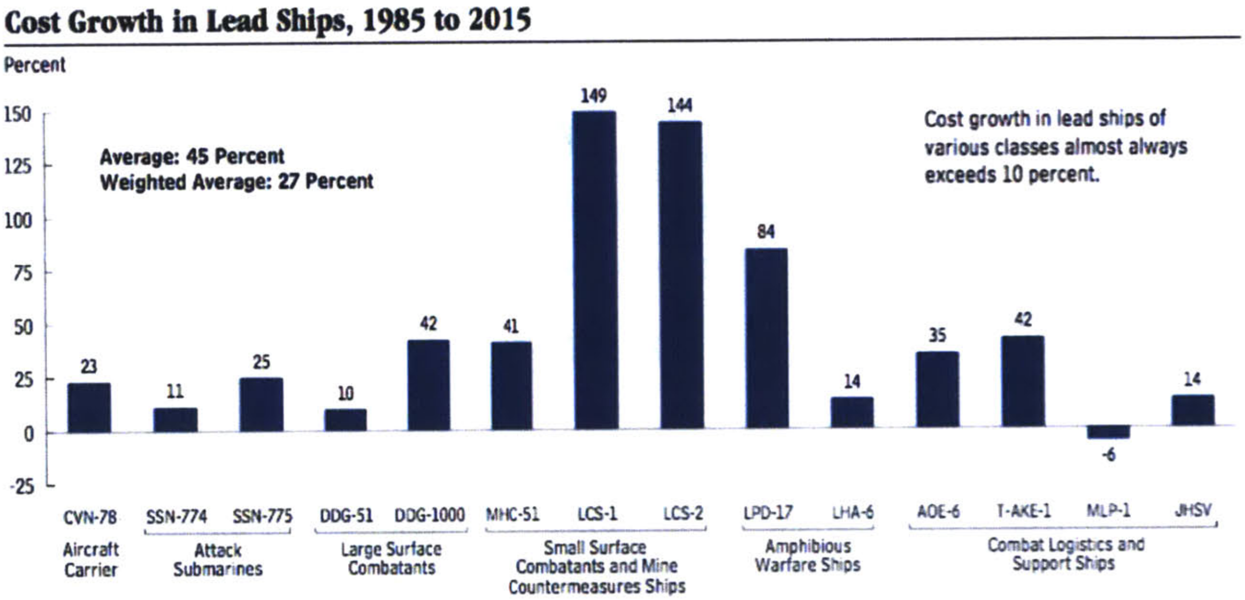


Figure 1-1: US Navy Lead Ship Cost Growth by Ship Class
(CBO 2015)

The Congressional Budget Office (CBO) analysis of the Navy's 2016 shipbuilding plan estimates the total cost of the plan to be about $20 billion annually over 30 years. This annual shipbuilding cost figure is approx. 33% more than the average shipbuilding budget over the last 30 years. Both the Navy and the CBO acknowledge that The Budget Control Act (BCA) of 2011, which placed caps on discretionary spending through 2021, will make implementing the 2016 shipbuilding plan difficult. The shipbuilding funding proposed in the 2016 Future Years Defense Program exceeds the funding available to the Department of Defense (DOD) under the BCA. Navy leadership must decide whether to implement the shipbuilding plan while cutting costs elsewhere or scale back the shipbuilding plan. (CBO 2015)

1.2 Dept. of Defense and Navy Acquisitions and Design Processes

1.2.1 Department of Defense Acquisition Policy

Department of Defense acquisitions policy is defined in DOD Instruction 5000.02, "Operation of the Defense Acquisition System." **Figure 1-2** illustrates the DOD acquisition process and highlights the interaction with capability requirements process. The acquisition process involves 2 decision points, 3 major milestone decisions, and 5 phases. Requirements from a warfare community that define a need for a program to address a specific threat are established in an Initial Capabilities Document (ICD). The Materiel Development Decision, based on the ICD, directs execution of an Analysis of Alternatives (AoA) and to conduct the Materiel Solution Analysis Phase. In the Materiel Solution and Analysis Phase a concept to be acquired is chosen through an AoA process and a Capabilities Development Document (CDD) is drafted that addresses capabilities gaps identified in the ICD as system specific requirements. It is in the Materiel Solution and Analysis Phase and AoA process that key tradeoffs are made in the areas of cost, schedule, and performance. (DOD 2015)

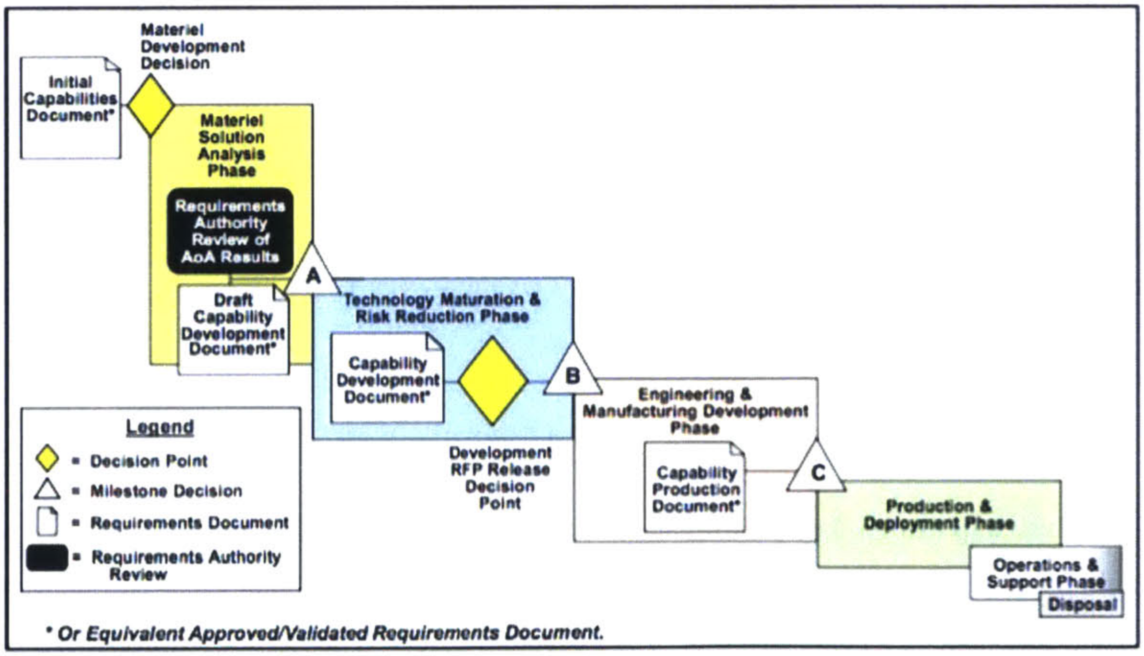


Figure 1-2: Interaction Between the Capability Requirements Process and the Acquisition Process
(DOD 2015)

1.2.2 Navy Acquisition Process

The Navy shipbuilding process in acquisitions is commonly referred to as a 2-Pass, 6-Gate Process, shown in **Figure 1-3**. Pass 1 includes the first 3 gates, which are "Requirements" gates and Pass 2 includes the last three gates, which are "Acquisition" gates. The goal of the Pass 1 Requirements Gates is to approve the ICD, approval of the preferred alternative design, and to approve the CDD and the Concept of Operations (CONOPS). Pass 1 ends leading up to program approval at Milestone A. The goal of the Pass 2 Acquisition gates is to approve the System Design Specification Development plan, approve release of a Request for Proposals, assesses the readiness of the program for production, conducts an Integrated Business Review and awards contracts. (SECNAV 2011)

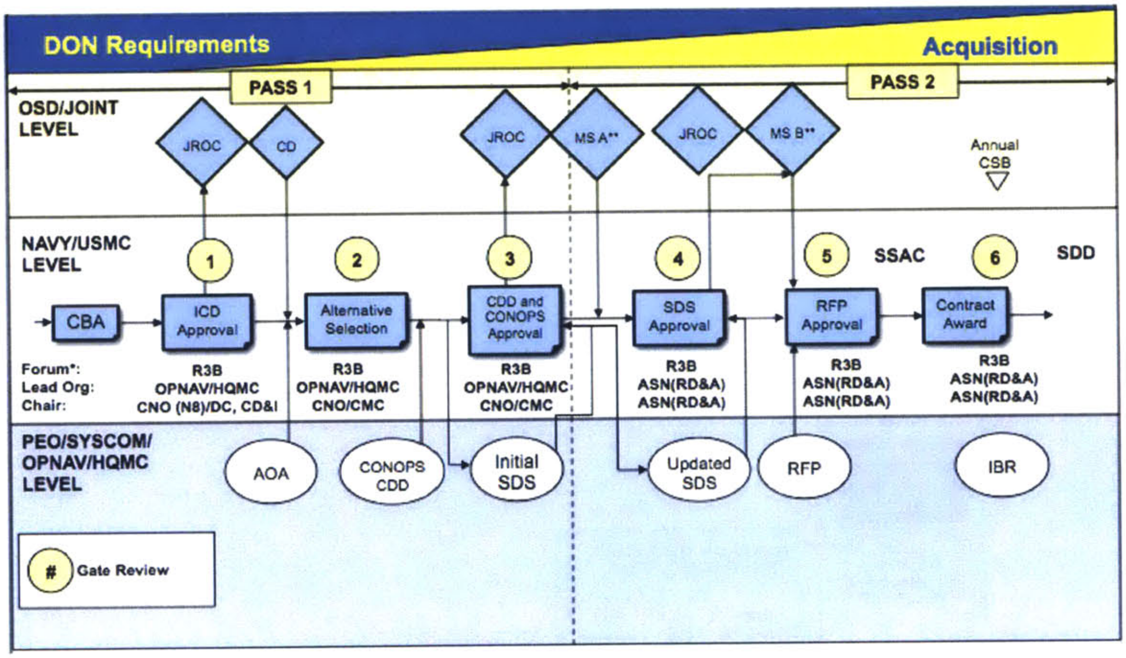


Figure 1-3: Department of the Navy 2-Pass, 6-Gate Acquisition Process
(DAU 2009)

In U.S. Naval ship design, key performance, or "ility", tradeoffs occur during the AoA process. During this phase of the process, specifically between Gates 1 and 2, it is important to understand the tradeoffs being made between capability, survivability, and affordability in ship design.

1.3 Defining Survivability

Survivability can have a number of definitions depending on its application. Survivability simply defined is the ability of a system to continue performing a desired function following a disturbance. Definition of the system, the desired function, and the disturbance depend on the application, the multiple stakeholders involved in the design process, and ultimately, the customer. The system involved could be a mechanical system, a physical process, or a procedure. The function is a requirement established by the customer based on their desired minimum required functionality post disturbance. Finally, the disturbance can be naturally occurring, like an earthquake, or man-made, like an accident, attack, or explosion. When defining survivability for a system it's important to define the stakeholders and the customer, what disturbances the system could possibly encounter, and what the customer's desired functionality post disturbance is.

In U.S. Naval ship design survivability is defined by Office of the Chief of Naval Operations Instruction (OPNAVINST) 9070.1A "Survivability Policy and Standards for Surface Ships and Craft of the U.S. Navy." The instruction states survivability is:

> *"A measure of both the capability of the ship, mission critical systems, and crew to perform assigned warfare missions, and of the protection provided to the crew to prevent serious injury or death. Both of these capabilities are applicable whether in combat or in either combat or non-combat related accidents (e.g., groundings, collisions, fires). The three principal disciplines of survivability are susceptibility, vulnerability, and recoverability"* (DON 2012)

In other words, a ship is a system of systems that must perform certain warfare mission functions and protect its crew after a combat or non-combat related disturbance.

OPNAVINST 9070.1A also further defines the three principle disciplines of naval survivability: Susceptibility as the "*measure of the capability of the ship... and crew to avoid and or defeat an attack*"; Vulnerability as the "*measure of the capability of the ship... and crew to withstand the initial damage effects... and to continue to perform assigned primary warfare missions...*"; and Recoverability as the "*measure of the capability of the ship and crew, after initial damage* *effects… to take emergency action to contain and control damage, prevent loss of a damaged ship, minimize personnel casualties, and restore and sustain primary mission capabilities*." The instruction also defines threats in four categories: Conventional, CBRN (Chemical, Biological, Radiological, or Nuclear), Terrorist/Asymmetric, or Network-Based Information System threats.

The previous version of the OPNAVINST 9070.1 defined discrete survivability levels. Level I, the lowest level of survivability, applied to auxiliary ships, patrol craft, and mine warfare ships. Level II, or moderate survivability, applied to small surface combatants and amphibious ships. Level III, or high survivability, applied to capitol warships such as cruisers, destroyers, or aircraft carriers. (Said 1995) Although these levels were not included in the most recent version of OPNAVINST 9070.1 the new instruction states that those levels remain valid for prior ships and systems requirements. It is evident, though, that the U.S. Navy wished to move away from rigid survivability measures and towards survivability standards tailored to the ship's mission and based on its required capabilities and concept of operations.

Surface Ship Survivability Levels

Level	Survivability Hardening	Ship Type
I	Low	Mine Warfare Ship, Patrol Combatant or Auxiliary Ship
II	Moderate	Minor Combatant or Amphibious Warfare Ship
III	High	Capitol Ship or Major Combatant

Table 1-1: Legacy U.S. Navy Survivability Levels
(Said 1995)

1.4 The Littoral Combat Ship – A Case Study

Since it's inception, the Littoral Combat Ship (LCS) program has been controversial. In the 1990's the U.S. Navy envisioned the need for a small, affordable combatant that was capable of traversing littoral waters where the larger combatants could not operate. On November 1, 2001, the Navy announced it would build the LCS with the "…objective being a survivable, capable, near-land platform to deal with threats of the 21st century." (DOD 2001) In the development of the program requirements Robert O. Work, a former Under Secretary of the Navy and current Deputy Secretary of Defense, identified six key elements of the early stages of the LCS concept. Of these key elements, most notable are the overriding emphasis on affordability, relying on force architecture for survivability and capability, and a high priority on getting the LCS into service as fast as possible. (Work 2012)

With maintaining surface combatant force numbers in mind, the Navy sought to buy three missionized LCSs for the price of one DDG-51 Arleigh Burke class destroyer, which equated to a minimum cost of approx. $400M per ship. In February 2003, the Chief of Naval Operations (CNO), Admiral Vern Clark, desired the cost threshold per ship to be a maximum of $250M per missionized LCS so the Navy could buy 5 LCSs for the price of one DDG-51. Both costs are in 2005 dollars. (Work 2012) The average cost of an FFG-7 Oliver Hazard Perry class frigate, which is similar in size and mission, was $581M in 2005 dollars. (GAO 1979) It would be difficult for the navy to achieve either of those two cost targets without making some difficult tradeoffs in capability and survivability by considering designing the LCS to commercial standards or reducing mission requirements.

Figure 1-4: LCS-1 USS Freedom
(Wikipedia 2016)

Navy leadership decided that the LCS would be built to survivability Level I standards of the legacy survivability levels in OPNAVINST 9070.1 to meet affordability goals. The Oliver Hazard Perry class frigate was designed to Level II. Consistent with a Level I survivability design the Navy asked the two prototype shipbuilders, Lockheed Martin (LM) and General Dynamics (GD), for designs using American Bureau of Shipping (ABS) High Speed Naval Craft Rules (HSNCR) which are "essentially commercial standards." (Work 2012) HSNCRs have hull requirements set with maximum attainable speed in mind and have hull structural material requirements that are the same as commercial craft unless specified differently by the Navy. (Curry, et al. 2002) The Navy responded to survivability criticisms of using commercially derived design standards by focusing the design on reduced susceptibility measures with high design speeds, signature reduction, and self-defense systems, to compensate for the reduced vulnerability and recoverability performance as a result of using commercial standards. (Work 2012)

In 2005, after continued criticism of the LCS's vulnerability, from the Surface Ware community, the Navy directed the ship builders to change design specifications from ABS HSNCRs to ABS Naval Vessel Rules (NVR) during lead ship construction. ABS NVRs are combatant standards for design of a ships hull, machinery, and electrical systems (HM&E). As a result of the change in design rules, additional requirements for structural strength, redundancy and separation, shock hardening, and watertight compartmentalization were added to the design. Many of the additional requirements are synonymous with survivability levels II or III. With ABS NVRs only being applicable to HM&E no changes were made to the ship's combat systems. (Work 2012)

As expected, the design standards change during lead ship construction caused a significant disruption for the LCS program. In FY2004 the objective and threshold cost requirements for the LCS were updated to $225M and $370M per ship respectively. In 2007, the Navy cancelled funding for additional ships beyond the first two prototypes as each lead ship prototype was now exceeding $750M. (Work 2012) The LCS program eventually continued and contracts were renewed for additional ships in 2009. The Navy's FY2016 shipbuilding plan requests $1,357M dollars in funding for 3 LCSs, which is approximately $452M per ship. The LCS funding requested for FY2016 does not include funding for the mission modules that make the LCS "missionized." (DON 2015)

1.5 Problem Statement

In a political environment of austerity brought about by the BCA of 2011, the importance of understanding the "ility" tradeoffs being made in new ship concept design is crucial. Understanding these tradeoffs early in the concept ship design phase gives Navy leadership real options for affordable ships that still provide the desired capability with an acceptable level of survivability. A combination of a tightened shipbuilding budget, large high priority procurement programs, and an emphasis on affordability will require high level tradeoffs to be made in future ship programs.

Capability and affordability are common "ility" tradeoffs in ship design. Survivability is an important third dimension that must be considered independently of capability and cost. A specific ship system may be costly and bring survivability to a design and not deliver a level of desired capability. An example of this type of system is the Aegis Combat System. The Aegis Combat System is a costly air warfare system that contributes greatly to a ship's survivability, because it reduces susceptibility to numerous air threats. Inclusion of an Aegis system on a small surface combatant, whose primary ship mission is anti-submarine warfare (ASW), would not contribute significant value to the ship's mission capability and would add considerable cost. Thorough analysis of the optimal selection of capability, survivability, and affordability in a small surface combatant may very well produce designs that include an Aegis combat system but will do so by making tradeoffs with other systems or design specifications to balance the ship's optimal capability and cost.

This thesis proposes a framework to independently assess a concept naval ship design's capability, survivability, and cost to determine an optimal set of designs using multi-dimensional Pareto optimization methods. This thesis will also demonstrate methods to navigate the space bound by the optimized set of designs so tradeoffs can be made while preserving optimal design capability, survivability, and affordability. Ultimately, the proposed framework seeks to answer the research question of how much additional investment is required to improve naval ship survivability. Understanding the optimal survivability-cost tradeoffs informs the designer the premium that has to be paid for increased survivability for a constant level of capability. Not understanding the tradeoffs being made in the AoA process between acquisition Gates 1 and 2 of concept design can have harmful effects that reverberate throughout the ship program. Although it is argued by Secretary Work that the capability, affordability, and survivability tradeoffs performed early in concept design were clearly understood and agreed on for the LCS, the case study of the LCS program shows how damaging not understanding those tradeoffs can be for a ship program.

2 LITERATURE REVIEW

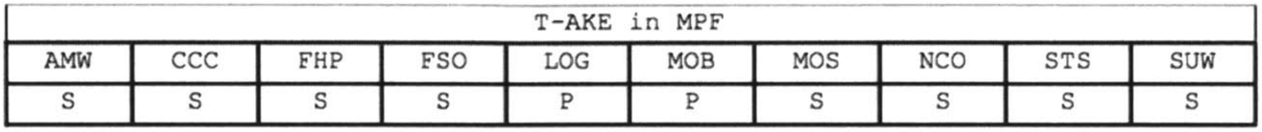
The literature review provides the background information necessary for the process of evaluating a concept ship design's capability, survivability, and cost within a tradespace exploration framework. Ship mission area definitions, US Navy survivability policy, damage mechanisms of naval vessels, assessing survivability probabilistically, and US Navy survivability assessment methods are reviewed. US Navy cost estimation methods and practices are examined including an introduction to the US Navy's expanded ship work breakdown structure as well as a discussion of the effect of survivability requirements on ship cost. A process foundation will be established to perform the tradespace analysis including how to integrate the "ilities" into a tradespace framework.

2.1 Navy Missions and Operational Environments

2.1.1 Navy Mission Areas

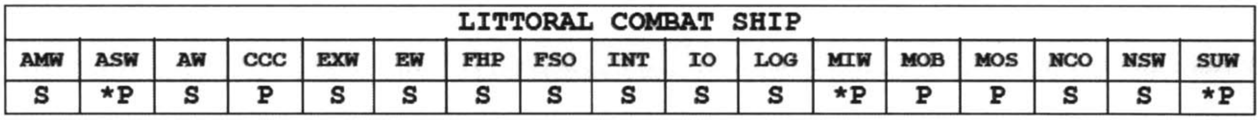
The US Navy classifies 21 mission areas each of which has multiple specific sub-mission areas. A complete list of mission areas and their descriptions is provided in Appendix A. Some examples of common mission areas specific to surface combatants are Mobility (MOB), Anti-Air Warfare (AW), Anti-Submarine Warfare (ASW), Surface Warfare (SUW), and Mine Warfare (MIW). (DON 2011) The LCS operational mission areas are shown in Table 2-2 as an example. 17 of the 21 applicable mission areas are shown and are designated as primary or secondary.

A naval ship's mission requirements are delineated in the Required Operational Capabilities (ROC) document. The ROC is specific to a class of ships and specifies which applicable missions areas are primary or secondary. The ROC continues to describe the sub-mission areas as "Full" or "Limited" capability by several defined operating conditions that vary between wartime readiness, peacetime readiness, and inport readiness. The following figures demonstrate the differences in the operational mission areas between different ship classes; an auxiliary, a small surface combatant, and a major combatant respectively. The examples demonstrate which mission areas are applicable by ship class as well as which are designated primary or secondary. The LCS and CG-47 mission areas are typical of combatants and show the difference between the number of required primary missions areas between a small surface combatant and a major combatant. The T-AKE, an auxiliary, has fewer required mission areas and only 2 primary missions.



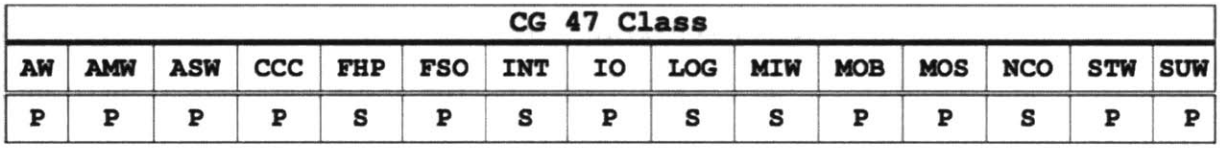
T-AKE in MPF									
AMW	CCC	FHP	FSO	LOG	MOB	MOS	NCO	STS	SUW
S	S	S	S	P	P	S	S	S	S

Table 2-1: Mission Areas for T-AKE (Auxiliary)
(DON 2011)



LITTORAL COMBAT SHIP																
AMW	ASW	AW	CCC	EXW	EW	FHP	FSO	INT	IO	LOG	MIW	MOB	MOS	NCO	NSW	SUW
S	*P	S	P	S	S	S	S	S	S	S	*P	P	P	S	S	*P

Table 2-2: Mission Areas for LCS (Small Surface Combatant)[1]
(DON 2014)



CG 47 Class														
AW	AMW	ASW	CCC	FHP	FSO	INT	IO	LOG	MIW	MOB	MOS	NCO	STW	SUW
P	P	P	P	S	P	S	P	S	S	P	P	S	P	P

Table 2-3: Mission Areas for CG 47 (Major Combatant)
(DON 2014)

2.1.2 Navy Operational Environments

The operational environment for a ship program is detailed in the Projected Operational Environment (POE) document. The POE provides a narrative describing the ship's intended operations and response to various threats. The operational description also provides additional details concerning the primary and secondary missions assigned in the ROC. For the LCS, AW is a secondary mission designated in the program's ROC but the POE expands on the LCS AW mission describing more of a self-defense posture stating:

> *"The core systems provide the ship with the capability to detect, identify, track, and defend itself against anti-ship cruise missiles and threat aircraft but the ship is not designed or intended to operate in a high-intensity air defense environment unless these operations are being conducted under the air defense coverage of a CSG, ESG, or an air defense asset such as an Aegis cruiser or destroyer."* (DON 2014)

The POE describes potential demanding environments for a ship and potential attack mechanisms like torpedoes, coastal missiles, mines, cruise missile, or asymmetric threats.

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[1] *P Denotes a primary mission area when mission package is installed. This feature is unique to LCS.

2.2 Naval Survivability Policy and Practice

2.2.1 U.S. Navy Survivability Policy

Department of Defense policy has few guidelines for responsibility and implementation of the design process for survivability. DOD Directive 5000.01 "The Defense Acquisition System" mentions survivability to say that the Program Manager (PM) "*shall... optimize total system performance, operational effectiveness, and suitability, survivability, and affordability.*" (DOD 2007) DODINST 5000.02 Enclosure 5 contains guidelines for Operational & Live Fire Test and Evaluation to characterize effectiveness, suitability, and survivability. (DOD 2015) Neither DOD documents contain instructions nor guidelines for survivability in concept design.

Survivability policy for ship design in OPNAVINST 9070.1A was briefly introduced in Section 1.3. The overall purpose of OPNAVINST 9070.1A is to "*determine a balance of survivability performance and risk and cost in surface ship... design.*" The instruction refers to survivability in terms of capabilities instead of strict or required characteristics. The previous version of this instruction was prescriptive while the current version recognizes survivability to be dynamic and dependent on a ship's projected operation environment and expected threats. The instruction establishes a new requirement to develop a minimum survivability baseline that is based on the ship programs' ICD where the ICD provides a general discussion of the ship's CONOPS and expected threats. The Office of the Chief of Naval Operations N8 Assessment office, OPNAV N81, as well as the Office of Naval Intelligence (ONI) assist in determining what possible threats a ship could face.

The objective of the instruction is process oriented for the development of platform specific survivability requirements. The recommended process included in the OPNAVINST is shown in Figure 2-1. The results of this process are specific survivability requirements defined in terms of specific threats and a remaining post hit capability, which are then codified in the CDD. An example of a resulting survivability requirement would be, "*The ship sustaining a hit from threat X will have Y remaining capability in Z mission areas.*"

The policies outlined in the OPNAVINST are clear that a systems engineering approach shall be taken to assess survivability performance, risk, and cost. The instruction also discusses tradeoff and effectiveness assessments to address degradation of mission systems due to damage or accidents with the goal of addressing overall system survivability while minimizing cost. (DON 2012) The OPNAVINST is broadly based and defines policy at a high level providing latitude to those responsible for executing policy. Missing, however, are the details or guidance associated with the systems engineering processes mentioned or requirements and limitations to methods to perform tradeoffs. Another perceived limitation is treatment of survivability as an inherent capability similar to other ship characteristics. This limitation will be discussed in Section 2.4.3.

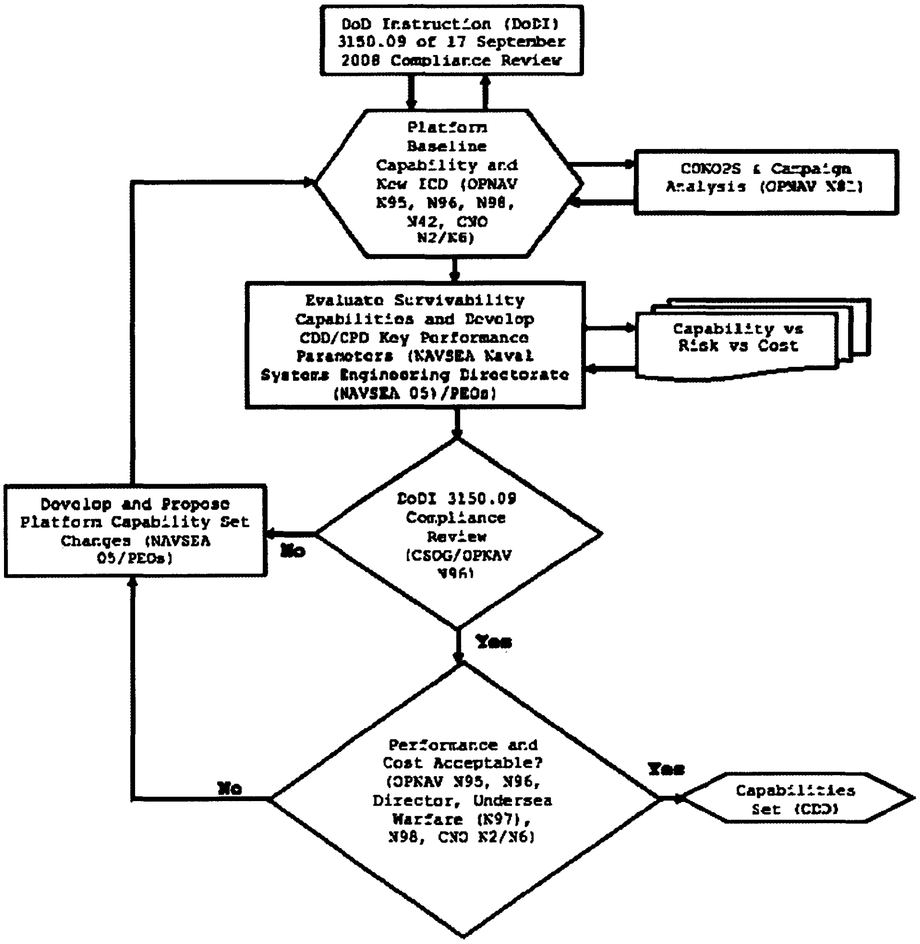

Figure 2-1: U.S. Navy Process for Development of Survivability Requirements[2] (DON 2012)

Enclosure 2 of the OPNAVINST 9070.1A defines survivability components of surface ships in categories of susceptibility reduction, vulnerability reduction, and recoverability enhancement. For each of the three principle survivability disciplines a type of reduction or enhancement effort is identified and matched with a shipboard capability or component. The capabilities and

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[2] DoDI 3150.09 addresses Chemical, Biological, Radiological, and Nuclear (CBRN) Survivability Policy.

components listed in the enclosure are recommendations for establishing a ships baseline and are not intended to require use of the listed capacities and components or be prescriptive in any way. Enclosure 2 of OPNAVINST 9070.1A is provided in Appendix B.

2.2.2 Damage Mechanisms of Naval Vessels

The primary combat damage mechanisms for naval ships are from various explosions, specifically, underwater explosions (UNDEX), internal explosions, contact external explosions, and air explosions (AIREX) in close proximity to the ship. The initial shock loading and the propagating pressure wave damage the ship's structure and internal components resulting in lost capability.

An UNDEX from a high explosive forms a superheated and compressed gas bubble and generates a shock wave that permeates through the surrounding water. Additional pressure pulses are emitted as the gas bubble expands and contracts several times while the bubble migrates to the surface due to gravitational forces. The gas bubble pulsations in phase with hull girder vibrations may produce a whipping response that could result in failure of the hull structure. A contact UNDEX from a torpedo or mine tears a large (9 m to 15 m) hole in the hull of a ship and ruptures the bulkheads in the vicinity of the explosion resulting in catastrophic damage and flooding. Damage from a proximity UNDEX depends on the charge size and standoff distance but the extent and severity of damage depends largely on the UNDEX occurring under or off the side of the ship. An UNDEX under a ship is more severe even though the bottom structure is stronger due to the ship being in the way of the compressed gas bubble's upward migration in addition to the initial shock load. Very large localized hull loading develops when a gas bubble pulse occurs near the hull bottom. The ship internals are subjected to high velocities from the incident shock wave, gas bubble pulsations, and the ship's whipping response. These motions can shock damage equipment and machinery resulting in lost capability. (Keil 1961)

A ship internal explosion produces a large incident shock load and a shock wave. The explosion propagates through the ship causing structural damage. The fragmentation from the explosion and an over-pressure field can damage equipment and machinery in the blast propagation path. Although the damage from the missile explosion may not be enough to sink a ship, the fire resulting from the explosion, fed by the missile's remaining fuel, can cause cascading damage and extremely high temperature fires that will. During the Falkland Wars the Royal Navy Guided

Missile Destroyer HMS Sheffield was hit by an air launched Exocet anti-ship missile leaving a 4.5 m x 1.2 m hole in her side. The ship was abandoned but did not sink until fires burned on board for days after the incident. (Royal Navy 1982) Damage from a ships internal explosion occurs due to the initial shock load, propagating over pressure field, and cascading damage due to fires.

A ship external explosion's damage mechanisms occur similarly to internal explosions but are less severe. Damage occurs due to the initial shock load that may penetrate the hull of the ship causing internal damage and fire. Severe damage to external systems, such as sensors, communications, and weapon systems, cause a loss of ship capability. Air explosions in close proximity to the ship cause damage by the initial shock load and fragmentation damage to external ship components.

2.2.3 Defining Naval Ship Probabilistic Survivability

When determining overall naval ship survivability in a probabilistic manner it is important to decompose survivability into its three principle disciplines: Susceptibility, Vulnerability, and Recoverability. Recall that susceptibility is the capability of a ship to avoid attack, vulnerability is the capability of a ship to withstand initial damage and continue to perform mission functions, and recoverability is the capability of a ship to prevent ship loss and to restore primary mission functions. These three principle disciplines of survivability are represented in terms of the probability of an outcome. Probabilistic assessment of survivability has its origins in combat aircraft survivability as demonstrated by Robert Ball, 1985, in his book "The Fundamentals of Aircraft Combat Survivability Analysis and Design" (Ball 2003) and was then applied to surface ship survivability in (Ball and Calvano 1994). The applied principles to ship survivability only consider naval ship susceptibility and vulnerability.

Ship susceptibility is defined by Ball & Calvano as the probability of hit, P(Hit), and is further decomposed into three successive phases: the probability of threat activity (P_A), the probability that the enemy can detect, classify, and target the ship (P_{DCT}), and the probability that the enemy weapon will launch, fly out, and impact the ship (P_{LFI}). P_A is a function of the ship's CONOPS as where or how the ship operates exposes it to various threats. P_{DCT} takes the ship's signatures into account as a ship's thermal, acoustic, and magnetic signature as well as its radar cross section contribute to a ship's overall detectability. P_{LFI} considers the threat's ability to launch an attack, the threat reaching the target ship, and includes the probability of impact and detonation of the target ship. The overall probability of hit is: (Ball and Calvano 1994)

$$P(Hit) = P_A \cdot P_{DCT} \cdot P_{LFI}$$

Ball & Calvano define vulnerability as the conditional probability of a ship kill given a hit, P(Kill/Hit), and defines varying distinctions of ship "kill". Ship kills are defined by severity; total kill or ship loss, mobility kill, mission kill, or system kill. Survivability is determined by taking the compliment of the probability of kill, which is the product of the probability of a hit and the probability of a kill given a hit. The final equation being: (Ball and Calvano 1994)

$$P(Survival) = 1 - P(Kill) = 1 - [P(Hit) \cdot P(Kill\ /\ Hit)]$$

Ball & Calvano's ship survivability assessment, illustrated in Figure 2-2, equates a method for combat aircraft to a naval surface ship when a naval ship is far more complex and faces more diverse threats. The phases of susceptibility requires expansion to define the probability of impact as a component of the previously described P_{LFI} to account for the survivability performance of systems under consideration for tradeoffs. P(Impact) accounts for the own ship's capability to detect and target an incoming threat and to destroy or evade the threat. Combat aircraft design relies on signature reduction and decoys for improved susceptibility performance but naval surface ships rely on those features plus several multi-mission self-defense weapons systems to detect, target, and destroy the threat. In conceptual design, when attempting to make high-level system survivability trade-offs, it is important to capture susceptibility performance from all those major systems variables. The vulnerability determination does take into account different levels of "kill" which are easily equated to a naval surface ship. The vulnerability process also allows incorporating various levels of ship post-hit capability required.

The method outlined by Ball and Calvano has been amended to include recoverability simply as the probability of recovery, P(Recovery), which demonstrates the ability of a ship and crew to restore capability to a desired level after initial damage. Probability of kill includes the compliment of probability of recovery or the probability of not recovering the ship. The final probability of surface ship survival with recoverability is: (TSSE 2003)

$$P(Survival) = 1 - [P(Hit) \cdot P(Kill\ /\ Hit) \cdot (1 - P(Recovery))]$$

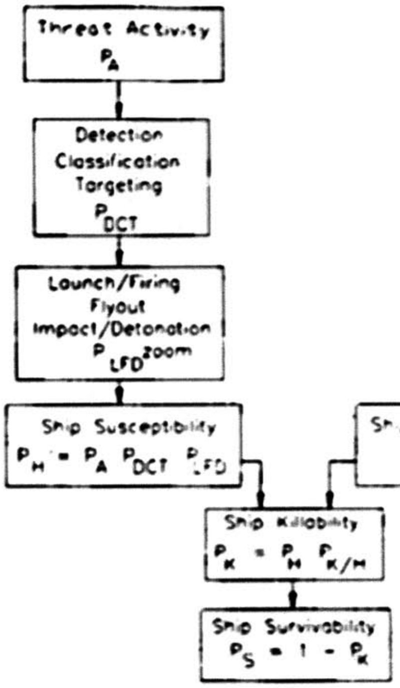

Figure 2-2: Surface Ship Probabilistic Survivability Assessment
(Ball and Calvano 1994)

Kim, et al, (2004) defines naval ship susceptibility assessment similarly to Ball and Calvano's probabilistic method but only considers probability of detection by the threat and the probability of target hit by a threat. Kim, et al gives additional details on their probabilistic methodology in determining the probability of a threat impact on a target ship by simulation. The steps they outline to calculate hit probability are 1.) Determine target area for analysis, 2.) Determine probability distribution of hit locations, and 3.) Determine hit distribution based on target area and distribution of hit locations. The difficult step in this process is determining the hit location distribution. The authors note that a distribution can be obtained from actual Live Fire Test & Evaluation (LFT&E) data or assumed to be normally distributed or in a Weibull distribution. A naval ship survivability analysis program called Measure of Total Integrated System Survivability (MOTISS) uses a normally distributed hit location longitudinally and a Weibull distribution hit location vertically. For the purposes of survivability assessment of a concept ship design, normally distributed hit locations are appropriate. Normal distribution of hit location certainly provides a higher level of accuracy than a random scatter of hit locations. (Kim, Hwang and Lee 2014)

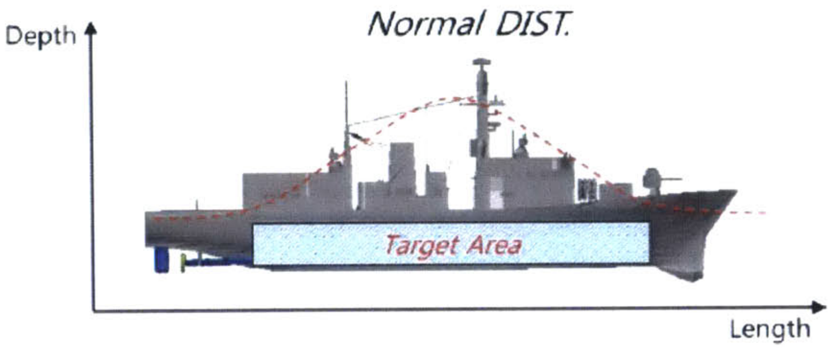

Figure 2-3: Example Probability Distribution for Target Hit Location
(Kim, Hwang and Lee 2014)

2.2.4 U.S. Navy Survivability Assessment Methods

U.S. Navy survivability assessments are primarily performed at the Vulnerability Assessment Branch at the Naval Surface Warfare Center Carderock Division (NSWCCD). While the assessment branch's main resources support vulnerability and recoverability assessments, susceptibility assessments are subcontracted to other organizations. (Beechener 2016)

Susceptibility assessments are performed at various warfare centers and research labs and support simulation based assessments for cruise missile, torpedo, and mine threats. The Naval Research Lab uses a physics-based computer simulation model of ship missile defense systems called CRUISE_Missiles. The model simulates the interaction between an incoming missile, one or more targets, and marine environment effects in a closed loop process. The model loop cycle time is clocked to correspond to the incoming missile's radar pulses and the ships reflected response is computed every cycle. The model simulations give the Navy an assessment into ship signatures and defensive countermeasure performance against anti-ship missiles. (Scannell, et al. 2011) The Pennsylvania State University Applied Research Laboratory Systems Analysis and Simulation division performs torpedo susceptibility assessments using a physics-based simulation package called Technology Requirements Model. (PSU 2013) The Naval Surface Warfare Center in Panama City performs susceptibility assessments for mines using a tool called the Rapid Mine Simulation System Enterprise Architecture. The simulation tool develops an encounter space between a ship and various threat mines where different ship configurations are considered to determine if a mine will detect a ship and detonate. (Jain, et al. 2011) While these tools consider many architectural design variables these susceptibility assessments largely determine ship signatures performance. NSWC Dahlgren Division primarily performs susceptibility assessments that include self-defense systems. A probability of raid annihilation (PRA) is determined for a ships self-defense system and assists in determining if those applicable design requirements are met. There is no overall susceptibility "score" that incorporates all the individual susceptibility assessments conducted by the various organizations. (Beechener 2016)

Vulnerability and recoverability assessments are performed by NSWCCD vulnerability assessment branch using a high fidelity physics-based modeling and simulation program called the Advanced Survivability Assessment Program (ASAP). (Hurwitz 2011) ASAP is a detailed ship design tool that simulates internal and underwater explosions and takes a probabilistic approach to predicting a ship's survivability and response by conducting a large number of threat simulations. A surface ship's mechanical and electronic systems (i.e. equipment, pipes, computers, cableways, etc.) are modeled so detailed arrangements must be known or assumed when an analysis is conducted. The program determines the effects from these explosions by predicting blast propagation internal to the ship and accounts for the damage effects of fragmentation and the over-pressure field on modeled systems. (Frietas 2012) In effect a type of "kill" is determined with each hit scenario and an overall probability of a kill given the type of threat hit is determined through numerous simulations. ASAP is also used to predict a ship's recoverability response in similar fashion by modeling ship's personnel into the simulation.

Given ASAP's high fidelity of modeling, a survivability assessment for detailed design of ships takes time. The details required for an analysis precludes the use of ASAP for concept design exploration without making many general assumptions. Since the release of the current version of the U.S. Navy's survivability policy, OPNAVINST 9070.1A, there has only been one new surface ship program, the LX(R) amphibious ship replacement, to use the new non-prescriptive approach of determining a ship's minimum survivability baseline based on expected threats and the ships CONOPS. In the LX(R) AoA process, 11 final designs were chosen for survivability assessment. A full analysis of one design took approximately 4 months to complete but several design assessments were performed in tandem. The assessments considered all threats identified by ONI. The program ICD and OPNAV N81 war-fighting analyses were used to characterize threats in context of each CONOPS. All 11 of the proposed designs in the LX(R) AoA took about a year to complete. Systems level details of the LX(R) concept designs were not defined so current models for LPD-17 and LSD-49, similarly classed ships to the LX(R), were reduced down to concept level detail and used for survivability assessments. (Wynn 2016)

The survivability assessment tools used by the U.S. Navy highlight the need for a concept design survivability assessment process that gives ship designers an overall holistic view of a ship concept's survivability. A survivability assessment process must capture all design variables being considered to enable tradeoffs of major systems in the early stages of a shipbuilding program. A more holistic approach to concept survivability assessment allows these major systems tradeoffs and their effects on overall survivability performance and ship cost to be better understood.

2.3 Naval Cost Engineering

2.3.1 The Cost of Survivability in Naval Shipbuilding

A frequent question in naval surface ship survivability design is "*Why does survivability cost so much?*" Considering the cost per long ton of different ship classes in the U.S. Navy, shown in Figure 2-4, clearly shows the cost of a U.S. Navy ship increases with mission capability and survivability level (using legacy survivability levels). Achieving a greater level of survivability in a ship design requires expensive and exotic materials, increased labor costs, as well as more non-recurring engineering work.

Generally, survivability enhancement features drive system level complexity. To explain the differences in cost between a commercial and military ship consider a shipboard fluid system. A shipboard fluid system, for example, could be a freshwater cooling system, firemain system, lube oil, or fuel oil system. The hypothetical fluid system designed to commercial standards would include a single pump, piping, and components whose materials are cheaper, more commonly used, and is easier to design and procure. A military design of the same fluid system must adhere to additional design requirements. A military system would require redundancy of vital equipment increasing the number of pumps from a single pump to 2 to 4 pumps. The pumps are vital components and would be required to be separated and located in different watertight compartments so damage in one area would not eliminate use of the entire system. System component separation would increase the length of piping and the number of other components, such as valves and joints, needed to form the system. The welding of the system together would require additional quality control checks, as would the piping penetrations through watertight bulkheads. The pumps in the system would be required to be shock hardened by design or placed on a shock-isolating mount, which would also require shock testing. All of these additional design factors increase the system's complexity, which results in increased cost of materials and labor as well as increased time to design the system and, ultimately, increasing system procurement cost. A Naval Shipbuilding Research Program (NSRP) study found a seawater service system with the same functional requirements designed to commercial ABS Steel Vessel Rules versus ABS Naval Vessel Rules resulted in the naval system being 3.3x the cost of the commercial system. (NSRP 2012)

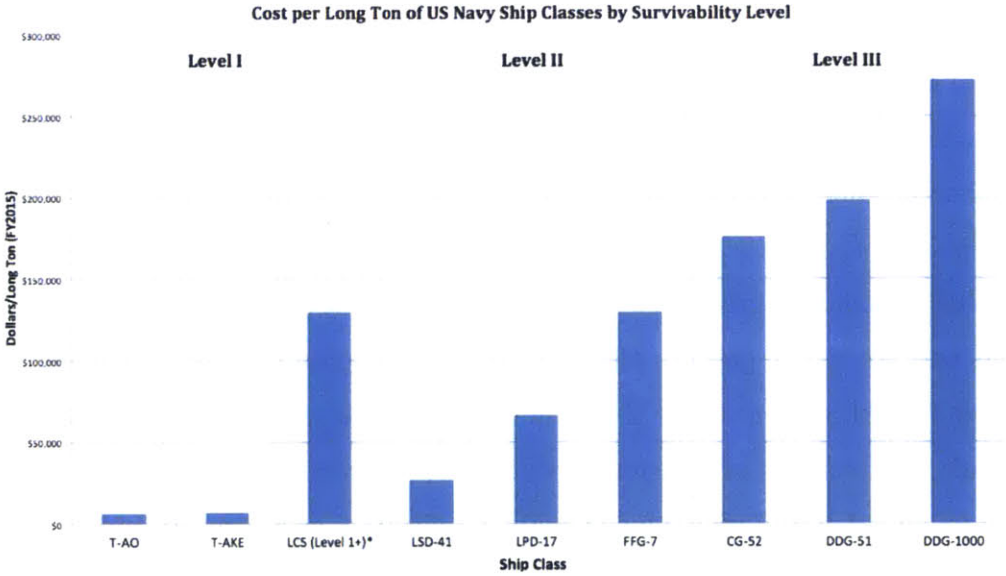

Figure 2-4: Cost per Long Ton of US Navy Ship Classes[3]

Relative to commercial shipbuilding practices; military shipbuilding has more requirements and unique features that drive cost and complexity in design. A RAND Corporation study on the differences between commercial and military shipbuilding found that while commercial ships, on average, are 3 times larger than the average military ship, military ships are much more complex and far more expensive to build. (Birkler, et al. 2005) The outfitting of multi-mission systems and additional survivability enhancement features drives design density and complexity in military ships where commercial ships are mostly empty steel structures with simple internal

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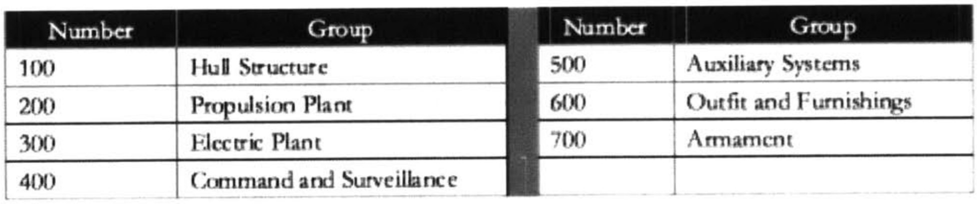
[3] T-AO and T-AKE are auxiliaries, LSD-41 and LPD-17 are amphibious ships, others ships are combatants. Unit costs were corrected to 2015 dollars.

* LCS is designated as Level 1+ and is similar in design and mission to an FFG-7

systems. The design effort of a military ship also drastically differs from a commercial ship. It is noted in the RAND study that a military ship design can take two years or more when a commercial ship design can take six months which results is higher non-recurring engineering costs. (Birkler, et al. 2005) One other important distinction between commercial and military shipbuilding is quality control. Military standards have much more demanding quality control standards to guarantee crew safety and ship survivability. Higher quality control standards requires more equipment and materials to be certified to meet the higher design specification, again driving up cost. The RAND Corporation study found that a military ship is roughly 100 times the cost of a commercial ship by volume. (Birkler, et al. 2005)

2.3.2 Expanded Ship Work Breakdown Structure

The principal means of communication between ship designers, cost estimators, and shipbuilders is the Expanded Ship Work Breakdown Structure (ESWBS). (NAVSEA 05C 2005) ESWBS is coded to relate physical ship systems of varying degrees of accuracy to weight. ESWBS relates physical ship weight to cost via an estimating relationship accessed to the ESWBS code level of detail. ESWBS is coded by group in one, two, or three-digit levels of detail. ESWBS descriptions are divided into ten major groups. There are seven core groups of functional technical areas, ESWBS 100-700, shown in Table 2-4. These seven groups represent the whole ship minus variable loads, such as fuel or mission expendables, excluded design margins, and represent a single-digit level of detail. Variable load weight is referred to as F00 weight.



Number	Group	Number	Group
100	Hull Structure	500	Auxiliary Systems
200	Propulsion Plant	600	Outfit and Furnishings
300	Electric Plant	700	Armament
400	Command and Surveillance		

Table 2-4: Seven Functional Technical ESWBS Groups
(NAVSEA 05C 2005)

Additional levels of physical ship details are coded using additional ESWBS digits. For example, ESWBS 100 represents the entire ship's hull structure, ESWBS 130 represents all the hull decks, and a specific deck, like the main deck, is ESWBS 131. The remaining three ESWBS groups not considered core are administrative. ESWBS 000 is an administrative group dealing with operational, logistics, management and planning functions. ESWBS 800 represents recurring and non-recurring engineering and integration. Last, ESBWS 900 captures ship assembly and support services. Additional information about ESWBS structure is included in Appendix C. (NAVSEA 05C 2005)

2.3.3 U.S. Navy Cost Estimation

Accurate cost estimations are important to a navy program's management, planning, and decision-making and are critical in the early stages of a new ship program. New ship cost estimations are the primary responsibility of the NAVSEA Cost Estimation and Industrial Analysis Division, NAVSEA 05C. NAVSEA 05C supports cost estimations throughout the acquisition process. The division performs budget estimates, conducts milestone reviews, and participates in AoAs and special studies. (NAVSEA 05C 2005)

NAVSEA 05C designates 5 cost estimation classification codes; C, D, F, R, and X. NAVSEA's governing guidance for estimation classification is NAVSEA Instruction 7300.14. Class C and D cost estimations are "budget quality" estimations for new ship construction and ship conversion programs respectively. Budget quality class estimations are an assurance to Congress from the Navy that no additional funds will be required for the program and represents a high level of accuracy. Class C cost estimations for new ship construction requires a Design Weight Estimate to the three-digit ESWBS level. Class D cost estimations for ship conversion relies more on the scope of work and alterations but also takes into account ESWBS weights for additions and removals. A Class F cost estimation is a feasibility estimate and uses single-digit ESWBS weights resulting from a ship feasibility study. The feasibility estimate designation also applies to an estimate that inflates to current year dollars a previous estimate of a similar ship and then makes rough estimates for design or requirements changes. Class R cost estimates are a rough order of magnitude and are used when design information is not detailed enough to the level of a feasibility study. Any cost estimate not developed through the normal NAVSEA 05C process or is performed by an organization outside of NAVSEA is designated a Class X estimate. (NAVSEA 05C 2005)

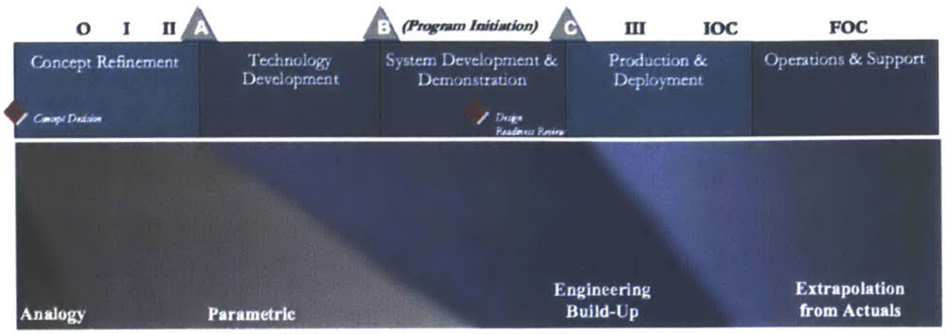


Figure 2-5: Cost Estimating Methods by Life Cycle
(NAVSEA 05C 2005)

Cost estimation methods included in the NAVSEA Cost Estimation Handbook include analogy cost estimation, parametric cost estimation, and engineering build up cost estimation. Analogy cost estimations use historical cost data from similar ship programs. The historical costs are adjusted for inflation and for differences in design. These subjective adjustments of historical costs reduce the credibility of the estimate. The parametric cost estimation is typically used in the concept design phase. A numerical relationship is established between cost and an independent variable that is a physical property related to ship design. In ship cost estimation the parametric used is called a Cost Estimating Relationship (CER) and is typically a relationship between cost and ESWBS weight. The NAVSEA CEH points out that weight is the most consistent physical property that a ship designer can provide to a cost estimator. Engineering build up estimation uses system materials and labor estimates and are priced in the marketplace for materials and uses estimated shipyard labor rates. (NAVSEA 05C 2005)

A total ship end cost calculation uses ESWBS weights and CERs to figure basic construction cost, and includes government furnished material costs, and support costs. A complete description of the total ship cost calculation is provided in Appendix C.

2.4 Tradespace Exploration

2.4.1 Multi-Attribute Tradespace Exploration

Multi-Attribute Tradespace Exploration (MATE), a concept design process that uses decision theory in model and simulation based design, was first outlined by (Ross 2003). There are five phases in MATE: Need Identification, Architecture Solution Exploration, Architecture Evaluation, Design Solution Exploration, and Design Evaluation. Need identification is at the center of the process and informs both architecture phases and design phases. (Ross 2003)

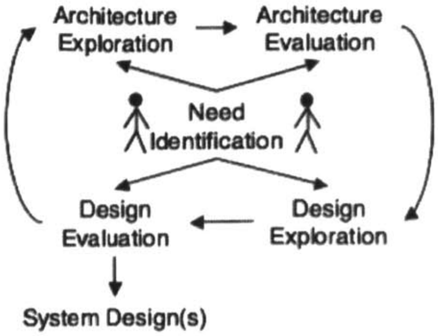


Figure 2-6: Multi-Attribute Tradespace Exploration Process
(Ross 2003)

The Need Identification phase determines decision maker requirements and "translates" those requirements and preferences into a common value-centric metric. A common process for accomplishing this is called Multi-Attribute Utility Theory (MAUT). In MAUT individual attribute utilities are combined into a utility function whose result gives a single metric to represent the requirements and preferences of the decision maker. This single metric is called utility, $U(X)$. Once a set of design attributes has been determined and their ranges are understood each attribute is weighted, k_i, and a utility curve, $U(X_i)$, for each is determined. The overall design utility is the weighted sum of each attributes utility value where N is the total number of attributes. (Ross 2003)

$$U(X) = \sum_{i=1}^{N} k_i U(X_i) \ where \ \sum_{i=1}^{N} k_i = 1$$

In the architecture solution exploration and evaluation phases design variables are chosen that can best achieve the requirements and preferences of the decision makers. All possible combinations of design variables form a design vector tradespace. Each design variable is modeled to an attribute and contributes a defined amount of utility. A design's utility is then the weighted sum of each attributes utility. Utility is a dimensionless metric from 0 to 1 representing acceptability of a design relative to the decision maker's requirements and preferences. Each design's cost is determined in conjunction with it's utility and each design is plotted on a utility-cost space. From the plot, the best designs that give the most utility for a specific cost can be determined. These designs are the Pareto-optimal designs. The design solution and evaluation phases examine the Pareto optimal designs with greater detail and make tradeoffs along the Pareto frontier. (Ross 2003)

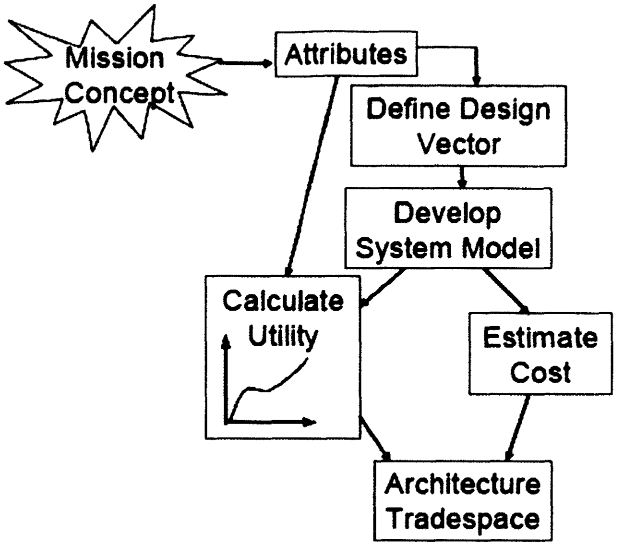


Figure 2-7: Functional MATE Process
(McManus, et al. 2007)

The MATE process is ideal for concept ship design as it includes a decision maker's desired mission requirements, weighted mission attributes, ship architectural design variables, and develops a design vector of proposed ship designs. The tradespace of concept ship designs allows an optimal set of designs to be isolated and further analyzed. The mission attributes that contribute to the utility function can be weighted to represent the decision maker's preference for primary, secondary, or tertiary mission sets. The MATE process provides the baseline concept design performance of mission capability and cost. The third dimension of survivability must be introduced into the process to perform optimal tradeoffs.

2.4.2 Multi-Attribute Tradespace Exploration to Survivability

The existing MATE process was expanded by Richards (2009) to define additional steps to characterize disturbances, apply survivability principles, model the effects of disturbances on design performance, and apply survivability metrics. Richards' MATE for Survivability process also demonstrates methods to explore the utility, survivability, and cost tradespace. MATE for Survivability is value-centric and gives designers an approach to determining how a system delivers value to a customer across varying disturbance environments. The process has evolved from MATE to not only account for decision maker requirements and preferences in a normal state but to also account for decision maker requirements and preferences for a system in a disturbed state. **Figure 2-8** illustrates Richard's process and indicates the relationship between the existing MATE process and the additional steps in MATE for Survivability.

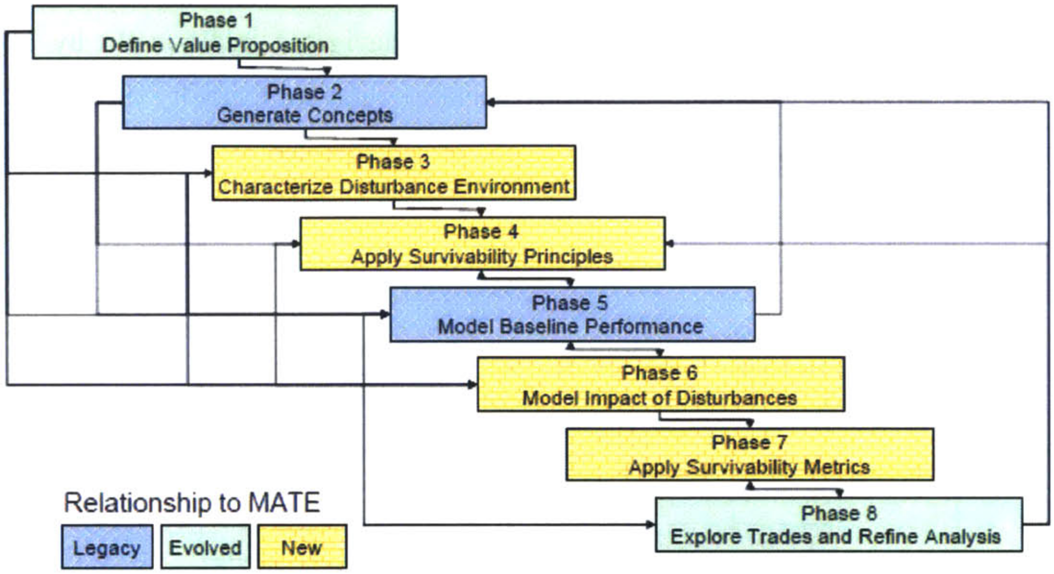


Figure 2-8: Multi-Attribute Tradespace Exploration for Survivability
(Richards 2009)

Phase 1 of the MATE for Survivability process is similar to the existing MATE process but includes steps to quantify a decision maker's requirements in a disturbed state in addition to the normal operating state. Specifically, the decision maker must designate a threshold of minimum desired value in a disturbed state. This allows the process to determine success of a survivable design if it meets the minimum threshold in a disturbed state. Phase 3 of the process is a new step to characterize the disturbance environment. A system designer must consider all the disturbances or threats that a system will face in its lifecycle and develop a model of these disturbances. Phase 4 of the process is an additional step that builds on the concept generation phase of the existing MATE process. By applying survivability principles the process essentially repeats the step to develop design variables that address the decision makers system requirements in a normal state and adds design variables that address the decision makers system requirements in a disturbed state with full consideration to the disturbance environment. Phase 4 finalizes the design vector and the baseline performance of cost and utility are determined for each design in Phase 5. Phase 6 determines the system performance in a disturbance environment. The survivability assessment described in the process is probabilistic and uses modeling and simulation to determine disturbed system performance. In Phase 7, Richards uses two survivability metrics, time-weighted average utility loss, and threshold availability. These metrics give an evaluation of a systems performance to disturbance environments over its lifecycle. Finally, Phase 8 explores the 2-dimensional tradespace of utility versus cost of the 3-dimensional Pareto-surface designs. The tradespace is navigated traditionally by examining designs that are low cost, high utility, but then examines the survivability metrics. Richards' (2009) complete methodology including the 8 phases and the sub tasks within each phase is provided in Appendix D.

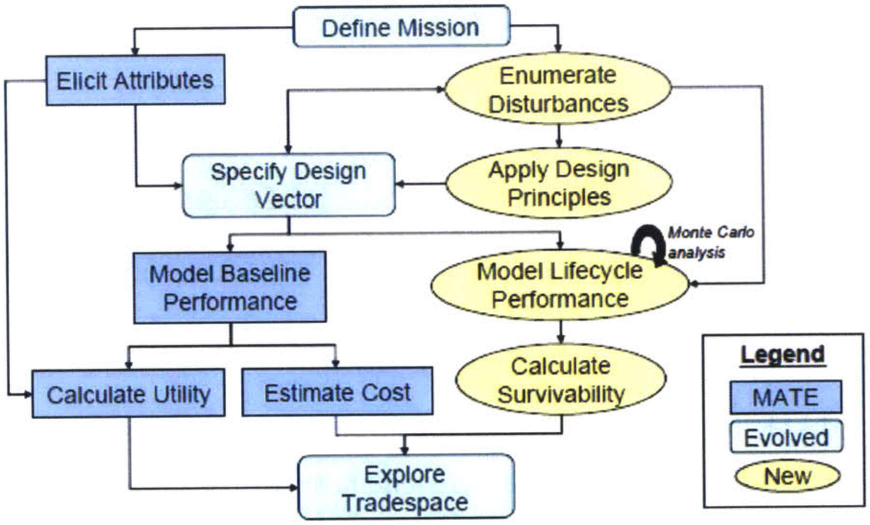


Figure 2-9: Functional MATE for Survivability Process
(Richards 2009)

Richards points out most notably that by including survivability before a baseline concept is established, the process allows survivability to be incorporated earlier into concept development. This diverges from the process of determining cost effective survivability measures after a concept has been determined. The MATE for Survivability process is well-suited to concept naval ship design tradespace exploration of capability, survivability, and cost. The process captures decision maker preference for required disturbance value, or in the case of naval ships, required post hit capability. The process incorporates including design variables that address decision maker requirements in a normal state and disturbed state. The Phase 7 survivability metrics are the exception to suitability for ship concept design. The survivability metrics of time-weighted average utility loss and threshold availability considers a systems performance in multiple disturbance environments over its life. The application used by Richards was in aerospace systems and the example to demonstrate the process was the tradespace exploration of a satellite design. While a satellite must be survivable to multiple disturbance environments over its life, ship design considers independent disturbance events that may include one or multiple hits. A naval ship is expected to survive a disturbance event but has the opportunity to be repaired and to reenter service. The survivability metrics in Phase 7 not being compatible with navy ships a different method to explore the utility-cost-survivability tradespace must be considered.

2.4.3 Incorporating the "ilities" in Tradespace Exploration

Incorporation of the "ilities" into tradespace studies can produce useful information for designers and decision makers. The "ilities" can potentially describe critical system performance parameters of a successful design such as flexibility, modularity, or survivability. The "ilities" can be ambiguous and are neither explicit nor easily assessed. A comprehensive framework for analyzing systems with these "ilities" properties and including them in tradespace studies is described by (McManus, et al. 2007).

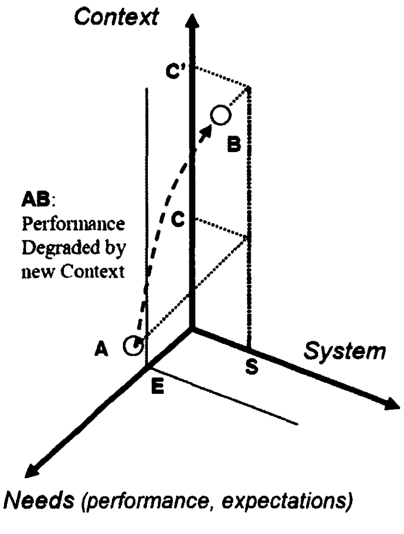


Figure 2-10: 3D Illustration of an "ilities" Space (McManus, et al. 2007)

The "ilities" are described in terms of three dimensions; changes in context, changes in needs, and changes in the system. (McManus, et al. 2007) The context is a function of time and can represent several distinct periods where the system must perform successfully. Changes in needs are value driven or represent varying expectations across different contexts. So the "ilities" are measures of performance where the system must perform successfully across different contexts with varying needs. **Figure 2-10** shows the 3 dimensional context-needs-system space. In the case of survivability an example of the initial context is normal operation of a system, the following context is initial hit damaged operation, and the final context is post recovery operation. Each survivability context has a defined need or expectation. In effect, in this three-context system, survivability is the measure of a design's sensitivity to changes, thus a survivable system is insensitive to changes in context. (Richards 2009) The system can change but it is useful for a system designer to maintain the system constant and consider responses to changes in context and needs. The three-context model applicable to survivability is illustrated in **Figure 2-11**.

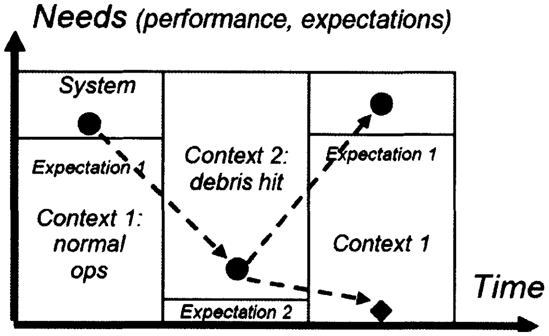


Figure 2-11: Three-Context Model of Survivability
(McManus, et al. 2007)

An important concept discussed by (McManus, et al. 2007) is the innate dependencies of the "ilities." The "ilities" are not independent system attributes and should not be counted as such in a value function. System attributes are performance parameters that contribute to an overall utility metric where "ilities" demonstrate the ability of those attributes to continue to deliver value across different contexts. So if "ilities" parameters are included into the multi-attribute utility function those attributes represented by the "ility" metric will be over represented in the value function. The "ilities" must be assessed independently from the utility function within the tradespace framework and must not be combined into the overall utility function. In the case of survivability, survivability performance could be interpreted as an inherent capability. By definition, survivability is the ability of a ship to continue to provide capability through changing conditions. The navy's survivability instruction refers to survivability as a capability, which misrepresents the design attributes described by the capability and survivability metrics.

Conducting tradespace exploration can be difficult with the addition of an independently assessed "ility." McManus, et al, demonstrates a method of representing cost, utility, and a third "ility" in a three dimensional tradespace. Navigating a cloud of point designs can be problematic as seen in **Figure 2-12**. With the tradespace in three dimensions a surface of Pareto optimal designs can be determined and then projected onto a two dimensional plane. With the Pareto surface designs projected onto the utility-cost plane the space can be navigated by considering iso-cost bands and analyzing utility-survivability design trades. The same method can be applied to considering iso-utility bands and analyzing survivability-cost design trades. Both tradespace navigation methods offer promising results for a concept naval ship design tradeoff strategy.

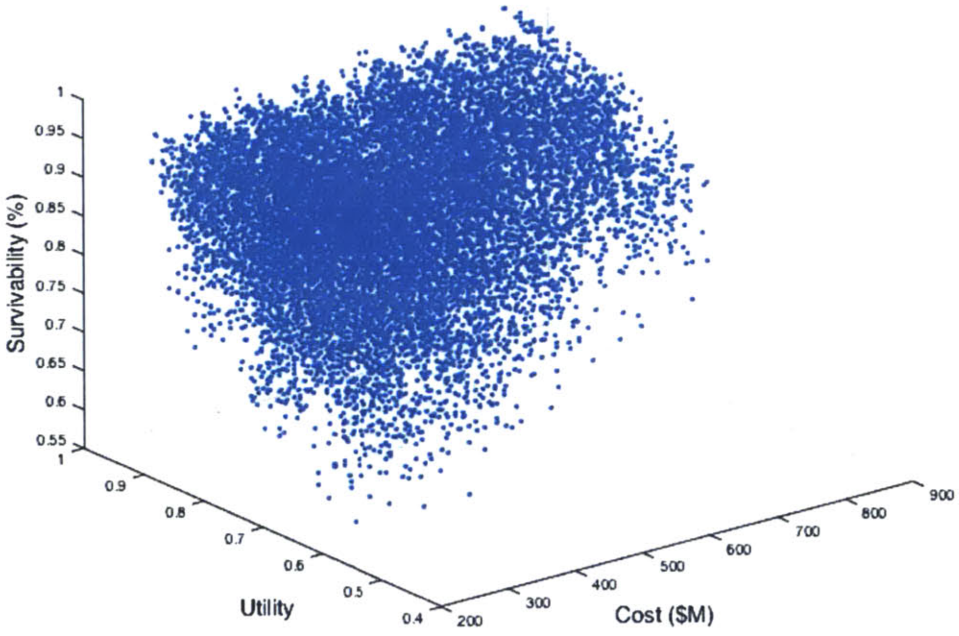


Figure 2-12: Cost-Utility-Survivability Tradespace

3 NAVAL SURVIVABILITY TRADESPACE METHODOLOGY

This section introduces the methodology to assess a concept naval surface ship design's capability, survivability, and cost to explore potential high-level tradeoffs and to understand survivability-cost relationships. The methodology adapts Richards' MATE for Survivability 8 phase process described in the previous section and applies it to the design of navy surface ships. This process differs from the MATE for Survivability process in that it does not incorporate the operational survivability metrics of time-weighted average utility loss and threshold availability but instead develops a probabilistic survivability assessment process that is more applicable to naval ship design. The process determines probability of ship survival, P(Survival), incorporating the three principle disciplines of naval survivability; susceptibility, vulnerability, and recoverability. This process also adds an intermediate step to determine desired mission areas from decision maker requirements and preferences. Design attributes are then determined from the required mission area requirements. The major steps in the process are described below. The sub-steps included in Richards' MATE for Survivability process were used, modified, or combined as necessary when applied to naval ship design.

1. **Generate Ship Requirements** – Identify missions that the ship is expected to perform and requirements for mission capability in normal, damaged, and recovered states. Design attributes are selected to meet mission requirements.
2. **Generate Ship Concept Designs** – Design variables are chosen to address design attributes in a normal state. The design vector is the full-factorial combination of all design variables.
3. **Characterize Ship Threat Environment** – Develop models that consider the potential operating environment of the ship and all the threats the ship is expected to face.
4. **Apply Survivability Variables and Finalize Design Vector** – Apply navy susceptibility reduction, vulnerability reduction, and recoverability enhancement features as design variables into the design space. This step also finalizes the design vector.
5. **Design Synthesis and Ship Baseline Performance** – Determine design weight distribution by single-digit ESWBS and other ship performance parameters relative to design utility. Determine design utility through the multi-attribute utility function to show if normal state requirements are met. Use single-digit ESWBS weight distribution to predict concept ship end cost using appropriate CERs.

6. **Survivability Assessment Model of Naval Ship Concepts** – Calculate design susceptibility, vulnerability, and recoverability performance using modeling and simulation techniques against modeled threat environments to determine each design's overall survivability performance.
7. **Tradespace Exploration** – Analyze design capability, survivability, and cost tradespace to determine optimal designs for tradeoffs and to gain insights into survivability-cost relationships.

Each step of the process will be discussed in greater detail in the following sections. Sub-steps will be defined for each major step. The methodology will be demonstrated with examples from the following small surface combatant trade study.

3.1 Generate Ship Requirements

The first step of the process is to understand decision maker requirements and preferences as it pertains to a new naval ship program. The ship designer must know the mission capabilities required as well as the ships required capability in a damaged state and the ships required capability in a post-damage recovered state. The majority of this information is collated in the ship's ICD and its ROC and POE. The sub-steps within this major step are to:

1) Determine Mission Area Requirements
2) Establish the Multi-Attribute Utility Function
3) Determine Survivability Requirements

3.1.1 Determine Mission Area Requirements

The applicable primary and secondary mission requirements are identified in the ship program's ROC. The mission areas that the ship program is expected to accomplish influences the design attributes selected. Key in this sub-step is to identify attributes and weight factors that best represent the decision maker's needs and preferences to meet mission area requirements. Identified attributes provide a parameter for how well a mission requirement is met through an attribute range. The identified range of low to high values that represent decision maker satisfaction of requirements being met is also elicited. The attributes can be continuous variables like ship speed or discrete variables corresponding to levels of system architectures. Decision maker preference between attributes must also be identified through weighting factors. Identified program mission areas are weighted to represent decision makers preference for primary or secondary mission areas and can also demonstrate decision maker preference for one primary mission area over another primary mission area. Weighting mission areas improves expression of decision maker requirements and preferences over a binary distinction between primary and secondary.

Weight factors are determined systematically using the analytic hierarchy process (AHP) pairwise comparison method. The use of AHP with MAUT in naval ship design is demonstrated by (Demko 2005). The process polls the decision maker for his preference of importance of each mission area relative to the other mission areas. The mission areas are ranked on a [1, 3, 5, 7, 9] scale where a rank of 1 reflects equal importance and increases in importance from moderate to strong to extreme importance. A comparison matrix is formed of the relative importance scores. From the rankings between mission areas a best-fit set of weights is determined from the real, strictly positive, and normalized eigenvector. The same process is also used to weight discrete design attributes. A simple example is given below for 3 attributes, A, B, & C, where A is twice as important as B and four times as important as C, and B is twice as important as C. The pairwise comparison matrix is: $\begin{array}{cccc} & A & B & C \\ A & 1 & 2 & 4 \\ B & 1/2 & 1 & 2 \\ C & 1/4 & 1/2 & 1 \end{array}$ which results in an eigenvalue and eigenvector of $\lambda = 3\ and\ v = \begin{bmatrix} 0.873 \\ 0.436 \\ 0.218 \end{bmatrix}$. The resulting normalized eigenvector forms the weights for the attributes A, B, & C: $w = \begin{bmatrix} 0.571 \\ 0.286 \\ 0.143 \end{bmatrix}$

The sum of mission area weights and the sum of the individual design attribute weights should equal to one to satisfy the requirements of MAUT. Figure 3-1 illustrates design attributes developed from the mobility mission area.

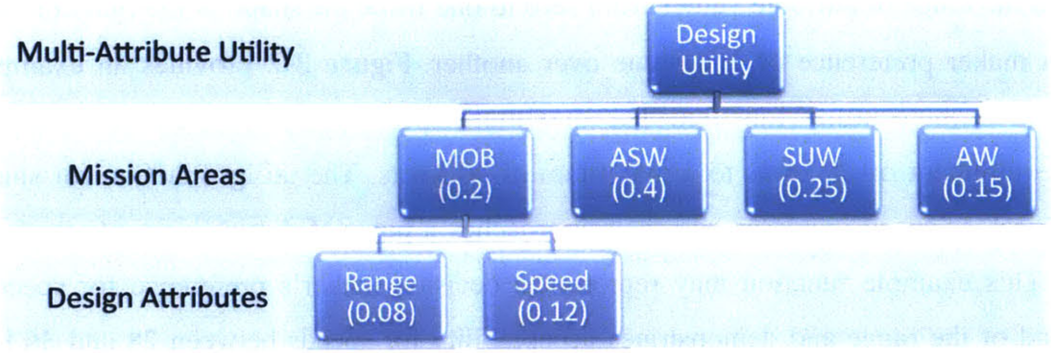


Figure 3-1: MAUT Structure with Mission Areas and Design Attributes

The desired mission areas for a naval ship will result in varying design attributes. Primary naval combatant mission areas include design attributes for detection, tracking, and engagement of hostile threats according to warfare area. The process can easily be tailored to another naval ship, such as an amphibious ship or auxiliary, by considering the mission areas applicable to those platforms. A naval ship with a primary Amphibious Warfare (AMW) mission area, like an LPD-17, would have design attributes related to the ability to load, transport, and deliver equipment, material and personnel for an amphibious operation. AMW design attributes would include examples such as cargo volume, troop capacity, and higher aviation capabilities. An auxiliary ship with a primary Logistics (LOG) or Strategic Sealift (STS) mission area like a T-AKE would have design attributes for loading, transporting, and delivering dry cargo.

3.1.2 Multi-Attribute Utility Function

A decision makers requirements and preferences are translated into quantifiable metrics through attributes and their ranges of acceptability. A ship designer must ensure that the set of attributes and the acceptability ranges for each are defined by the decision maker and are an accurate representation of their requirements and preferences. In effect, the ship designer takes requirements from key documents, the ICD and the ROC and POE, codifies them into design attributes and determines a threshold and goal value range for each. Communication between designers and decision makers is key to having an agreed on set of attributes and threshold and goal range values.

Once design attributes and their ranges are agreed on each individual attribute utility function is determined. Utility values range from zero to one so each individual utility function must represent the range of attribute values from zero to one while the shape of the function represents decision maker preference of one value over another. **Figure 3-2** provides an example of an individual attribute utility function. The maximum speed utility function shows a minimum speed requirement of 25 knots to a maximum of 40 knots. The utility function for ships speed rapidly rises as speed increases and then approaches a point of diminishing returns for greater speeds. This example function may represent a decision maker's preference for speeds at the lower end of the range and demonstrates acceptability for speeds between 28 and 36 knots but shows a lack of additional utility for speeds above 36 knots.

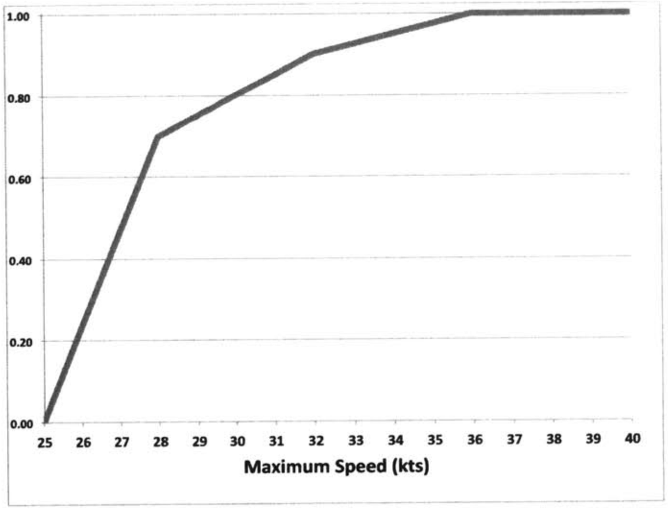


Figure 3-2: Single Attribute Utility Function (Maximum Ship Speed)

Multiple attributes are represented by a weighting factor, k_i, which also reflects decision maker preferences between attributes. The multi-attribute utility function, described in (Ross 2003), is the weighted sum of the individual attributes and describes a concept designs overall ability to meet decision maker requirements and preferences.

$$U(X) = \sum_{i=1}^{N} k_i U(X_i) \text{ where } \sum_{i=1}^{N} k_i = 1$$

The descriptions of design utility and ship capability are synonymous due to the multi-attribute utility function having been derived from decision maker required mission areas. The utility value described in this section and the remaining sections of the methodology is often referred to as capability and are used interchangeably.

3.1.3 Survivability Requirements

In addition to overall design capability and performance a decision maker must also express the desired level of capability in other contexts. When incorporating survivability into naval ship tradespace studies three operational contexts are used, normal operation, post-hit damaged operation, and post-hit damage recovery operation. Normal operation capability is defined by the multi-attribute utility function. Survivability assessment in vulnerability and recoverability relies on defined reduced capability requirements and the multi-attribute utility function to determine if a design operates successfully in each additional context. A contextual representation of survivability requirements is illustrated in **Figure 3-3**.

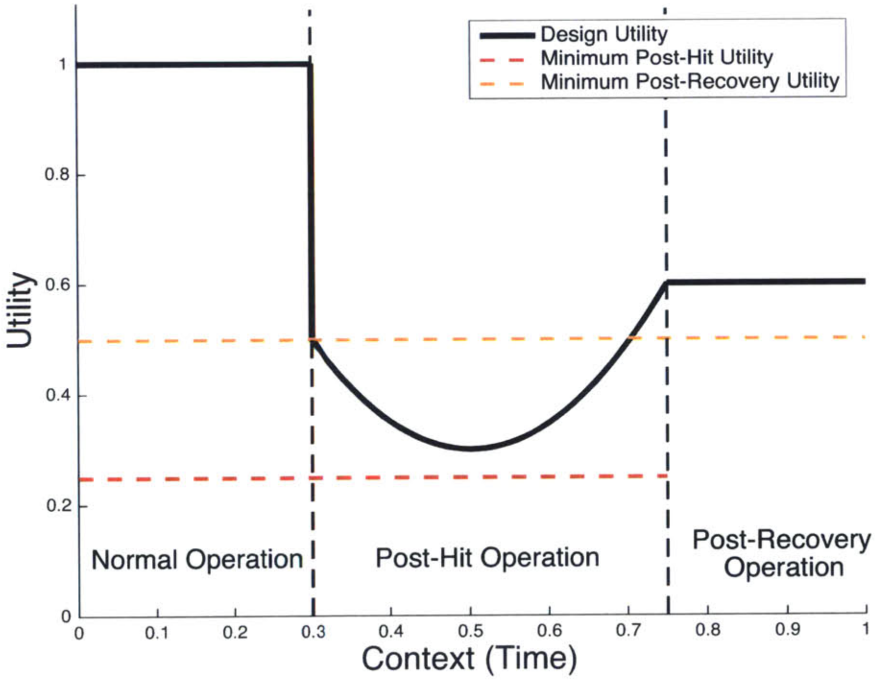


Figure 3-3: Contextual Survivability Requirements

In the post-hit damaged state a different set of acceptability ranges for each attribute or a required percentage of capability is determined. As discussed in Section 2.2.1 a survivability requirement can address a specific threat and the required amount of remaining capability. An example is "*The ship, sustaining a hit from weapon X, must retain Y capability in Z mission areas*." The weapon "*X*" is determined in the step to characterize the ship's threat environment however requirements are written to address all possible threats. Decision makers must determine the amount of desired capability "*Y*" after hit and in which mission areas "*Z*" for a list of all possible threats "*X*." In the vulnerability assessment a kill can be determined in a modeled simulation if the amount of post-hit capability is less than the established requirement.

Requirements in the damage recovery state are similar to that of the post-hit damaged state requiring a specified amount a capability to recover to in specified mission areas after sustaining damage from a threat. The recoverability requirement can include a time dimension that requires capability be restored to a required level within a specified time. For example "*The ship, after sustaining a hit from threat X, must restore Y capability in Z mission areas within T timeframe.*" Similar to vulnerability, recoverability can be determined if the amount of capability recovered to is greater than the post-hit damage recovery requirement in a modeled simulation.

3.2 Generate Ship Concept Designs

Once a ship program's requirements and multi-attribute utility function are known a ship designer can propose design variables to satisfy attributes and meet mission area requirements. The proposed design variables must address the selected design attributes. Richards (2009) uses a practical method to map design variables to attributes called Design Value Mapping. The full-factorial combination of all design variables establishes the baseline design vector. The sub-steps within this major step are to:

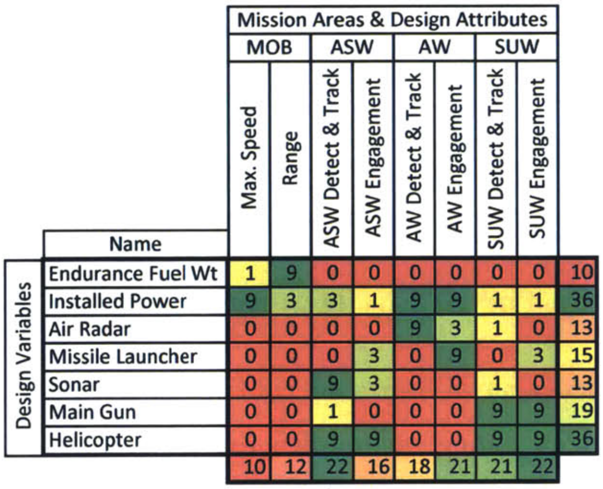
1) Propose Design Variables
2) Map Design Variables to Attributes
3) Establish Baseline Design Vector

3.2.1 Propose Design Variables

Once a ship program's requirements are determined and design attributes and the multi-attribute utility function are generated a ship designer can propose quantifiable design variables that address the design attributes. To address the ship speed attribute, for example, a ship designer would propose the ship's installed power as a design variable with a range of powers that can achieve the speed attribute range specified. Design variables must be chosen with respect to any identified design constraints such as using existing marine systems or systems that are expected to be technologically mature by ship operation. Naval ship design tends to rely on existing systems architectures that are developed in parallel to other ship design efforts and are used across different programs.

3.2.2 Map Design Variables to Attributes

To verify that the proposed design variables adequately address the design attributes a method called Design Value Mapping is used by (Richards 2009). The method used by Richards is derived from the Quality Function Deployment process and is comprised of four steps. First, form a matrix with design attributes as columns and design variables as rows. Second, determine the strength of the relationship between the individual design variables with each design attribute using a non-linear scale: 0 for no relation, 1 for low relation, 3 for medium relation, and 9 for strong relation. Third, sum the rows to indicate the importance of each design variable relative to the design attributes. Last, sum the columns to indicate how well each attribute is addressed by the design variables. The last two steps outlined in this process comprise the verification that design attributes are adequately addressed in the overall methodology. This is important to ensuring that the generated concepts satisfy decision maker's requirements. This process will be repeated to analyze design variable's adequacy in addressing survivability requirements in a later step.



		Mission Areas & Design Attributes								
		MOB		ASW		AW		SUW		
	Name	Max. Speed	Range	ASW Detect & Track	ASW Engagement	AW Detect & Track	AW Engagement	SUW Detect & Track	SUW Engagement	
Design Variables	Endurance Fuel Wt	1	9	0	0	0	0	0	0	10
	Installed Power	9	3	3	1	9	9	1	1	36
	Air Radar	0	0	0	0	9	3	1	0	13
	Missile Launcher	0	0	0	3	0	9	0	3	15
	Sonar	0	0	9	3	0	0	1	0	13
	Main Gun	0	0	1	0	0	0	9	9	19
	Helicopter	0	0	9	9	0	0	9	9	36
		10	12	22	16	18	21	21	22	

Table 3-1: Design Value Map Matrix for a Naval Combatant Concept

Table 3-1 shows a design value map applied to a concept naval combatant design. The design attributes (columns) are derived from chosen mission areas and design variables (rows) were chosen to address the design attributes. The sum of the rows shows the relative impact of each design variable across the chosen design attributes. The sum of the columns illustrates the adequacy of addressing the chosen design attributes. From the example, fuel weight has the lowest relative importance to the design where installed power and the ability to embark a helicopter are shown to be relatively important to the design. Most of the design attributes in the example are addressed relative to each other with the exception of speed and range.

3.2.3 Establish Baseline Design Vector

Once a ship designer is satisfied with the selected design variables and their adequacy to address design attributes a baseline design vector is established. The design vector is the full-factorial combination of all design variables and their value ranges. The design variable ranges can be continuous or discrete but must adequately cover the ranges chosen for the design attributes. Table 3-2 builds on the example in Table 3-1 and shows the resulting design vector. The design variables and their discrete ranges produce a tradespace of 1296 designs.

Baseline Design Variables						
Fuel Wt	**Power**	**Air Radar**	**Missile**	**Sonar**	**Main Gun**	**Helicopter**
200 Mt	30 MW	None	None	Passive System	57 mm	None
500 Mt	50 MW	TRS-3D	Deck Mount	Active&Passive	76 mm	1 Embarked
800 Mt	100 MW	Spy-3	VLS			2 Embarked
1200 Mt						

Table 3-2: Example Baseline Design Vector for a Naval Combatant Concept

The baseline design vector addresses decision maker mission area requirements and resulting design attributes but does not address decision maker survivability requirements. The threat environment that a ship design faces must be known in addition to the decision maker's survivability requirements to propose design variables to adequately address all requirements.

3.3 Characterize Ship Threat Environment

The operational environment a naval combatant could potentially face has an immense impact on its conceivable design. The operating environment exposes a ship to various threats that must be understood to propose design variables that address survivability requirements. A small surface combatant operating in littoral waters faces different threats than a major combatant operating in an open ocean environment. The littoral, or coastal, environment is the most demanding operating environment a naval combatant can anticipate. Littoral waters are characterized by congested seaways occupied by commercial shipping and potential adversaries and exposes a ship to coastal missiles, submarines, mines, and asymmetric surface threats. (DON 2014) The major categories of threats to a surface combatant are anti-ship missiles, underwater explosions from mines and torpedoes, and asymmetric attack from other surface combatants or small attack craft. The various weapons corresponding to these major threat categories must be understood to develop design variables to address them. The sub-steps within this major step are to:

1) Gather Threat Activity Data
2) Develop Model of Threat Activity

3.3.1 Gather Threat Activity Data

With the ship program's potential operating environment known an exhaustive list of threats and their capabilities can be developed. Important details to understand are a threat's delivery, capabilities in detecting a ship, and inflicting damage. Missile threats can be fired from land, ship, submarine, or aircraft and can be guided to a target using inertial navigation or have heat seeking or radar seeking guidance. Explosions from missiles, projectiles, or torpedoes can have a devastating effect on a ship's structure and internals. UNDEX mechanisms and damage propagation are well understood and documented in (Cole 1948) and their effects on naval ships in (Keil 1961) as discussed in Section 2.2.2. Understanding threat delivery, detection, and damage mechanisms allows a ship designer to propose design variables to mitigate the effects of those mechanisms.

A ship's operational environment and potential threats are documented in a ship program's POE and ICD. In addition to these documents OPNAV N81 assessments and intelligence from ONI, as discussed in Section 2.2.1, also support a ship designer in forming a database of potential threats and threat capabilities.

3.3.2 Develop Model of Threat Activity

Threat activity data is modeled for survivability assessment of ship concepts in subsequent steps. The threat encounter is a ship susceptibility concern and is modeled into the probability of activity and probability of detection portions of the susceptibility assessment. Damage mechanisms from various explosion types and locations are modeled into the vulnerability assessment. Design variables are proposed to address threats in terms of susceptibility reduction, vulnerability reduction, and recoverability enhancement. When a list of threats is gathered they can be ranked by level of importance or weighted by likelihood relative to each other to assist in determining design variables that address the matrix of threats.

3.4 Apply Survivability Variables and Finalize Design Vector

Step 4 of the process adds to the baseline design vector established in Step 2.3 and adds design variables specifically to address decision maker survivability requirements. Resources available to the ship designer are recommended survivability components to provide susceptibility reduction, vulnerability reduction, or recoverability enhancement. This step is a supplement to Step 2 and follows similar steps to propose survivability design variables, evaluate their ability to address survivability requirements and threats and to finalize the design vector. The sub-steps within this major step are:

1) Propose Survivability Design Variables
2) Map Design Variables to Threats
3) Establish Final Design Vector

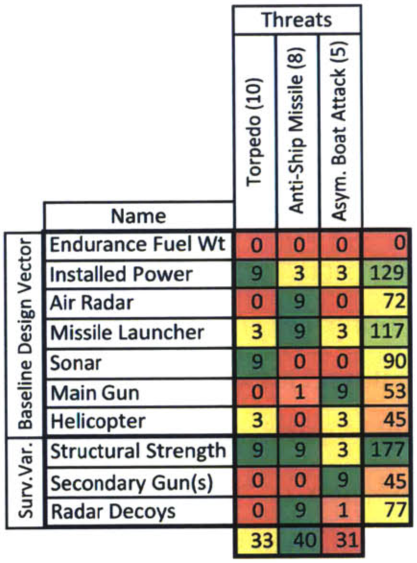
3.4.1 Propose Survivability Design Variables

A ship designer can propose strategies to mitigate the impact of the threat encounter and possible ship damage based on the ship program's survivability requirements, projected operating environment, and expected threats. The mitigation strategy originates from the three principle disciplines of survivability: susceptibility, vulnerability, and recoverability. Survivability components of surface ships categorized by susceptibility reduction, vulnerability reduction, and recoverability enhancement is provided in the Navy's survivability instruction, OPNAVINST 9070.1A, a list of which is provided in Appendix B. The components provided are not intended to be required or prescriptive in nature but serves as guidance to demonstrate survivability enhancement capabilities. The capabilities and components listed in the instruction are general descriptions leaving the ship designer to evaluate feasible design variables and alternatives.

3.4.2 Map Design Variables to Threats

The process for assessing additional design variables' effectiveness in addressing survivability requirements outlined by Richards (2009) is similar to that of the process described in Section 3.2.2 except the process considers threats for analysis instead of design attributes. A matrix is formed of design variables in rows and selected threats in columns. Again, similar to the process described in Section 3.2.2, a non-linear scale is used to describe the strength of the relationship between the design variable and its effectiveness in mitigating the threat. The baseline design variables chosen in Section 3.2.3 are included in this analysis to avoid having redundant design variables. Baseline design variables that address mission areas and design attributes can also contribute to the mitigation of expected threats and can eliminate the need for additional design variables for some threats.

Table 3-3 demonstrates the design value map including survivability design variables. In this example three threats are analyzed for and are ranked by importance on a scale of 0-10. The baseline design variables and survivability variables are included. The sums of the rows include the threat weighting factors to show the relative importance of each variable in addressing the analyzed threats. The sums of the columns show the adequacy of addressing each threat.



		Threats			
	Name	Torpedo (10)	Anti-Ship Missile (8)	Asym. Boat Attack (5)	
Baseline Design Vector	Endurance Fuel Wt	0	0	0	0
	Installed Power	9	3	3	129
	Air Radar	0	9	0	72
	Missile Launcher	3	9	3	117
	Sonar	9	0	0	90
	Main Gun	0	1	9	53
	Helicopter	3	0	3	45
Surv.Var.	Structural Strength	9	9	3	177
	Secondary Gun(s)	0	0	9	45
	Radar Decoys	0	9	1	77
		33	40	31	

Table 3-3: Survivability Design Value Map Matrix Example

3.4.3 Establish Final Design Vector

After analysis of the effectiveness of design variables to address selected threats, survivability variables are chosen to add to the tradespace. Filtering of the considered survivability design variables may be required after the analysis is performed to determine which variables will be included. One recommended method to choose survivability variables can be simply taking the highest value map scores among all design variables. Threats may be adequately addressed by the baseline design vector, which would require fewer added design variables to address the remaining threats. A ship designer could also consider design variables according to the three principle disciplines of survivability to ensure each is adequately represented. In the example, the secondary gun and radar decoys variables provided susceptibility reduction where the structural strength variable provides vulnerability reduction and recoverability enhancement. Another important consideration is tradespace size. The additional variables and their selected ranges can geometrically increase the size of the tradespace. A large tradespace size poses a problem for available computational power. After selecting the appropriate survivability design variables the variables are added to the tradespace for analysis. Continuing the example provided in Table 3-3 the additional survivability variables produce a tradespace of 23328 designs. The final design vector produced from this example is shown in Table 3-4.

Baseline Design Variables							Survivability Variables		
Fuel Wt	Power	Air Radar	Missile	Sonar	Main Gun	Helicopter	Structure	Sec. Guns	Decoys
200 Mt	30 MW	None	None	Passive System	57 mm	None	Commercial	None	None
500 Mt	50 MW	TRS-3D	Deck Mount	Active&Passive	76 mm	1 Embarked	Combatant	1-30 mm	Chaff
800 Mt	100 MW	Spy-3	VLS			2 Embarked		2-30 mm	Nulka
1200 Mt									

Table 3-4: Example Final Design Vector

A notable component of naval ship design is the interdependency between a design variable's contribution to mission capability and survivability performance. Baseline design variables contribute to survivability performance and survivability design variables can potentially contribute to mission area capability. This concept could be thought of in terms of offensive capability and defensive capability. A survivability variable can add defensive capability but can also be used offensively. Feedback may be required in the process to account for the additional mission capability provided by the proposed survivability variables.

3.5 Design Synthesis and Baseline Ship Performance

Step 5 of the process takes the final design vector and produces feasible ship designs through a design synthesis process and determines ship capability and cost. Data on each design variable is collected and used to determine ship performance parameters like ship range, ship speed, or ESWBS weight distribution. The performance parameters are translated to utility values to determine how well design attributes are met. The ESBWS weight distribution of each design is used to determine an estimated ship end cost for each design. Finally, the multi-attribute utility function developed in Section 3.1.2 is applied. The sub-steps within this major step are to:

1) Develop Software Architecture
2) Collect Design Variable Data

3) Perform Design Synthesis
4) Determine Multi-Attribute Utility
5) Determine Estimated Ship End Cost

3.5.1 Develop Software Architecture

A framework for processing design variable data and producing feasible ship designs is required to determine ship performance and evaluate utility and cost. A common tool used by the U.S. Navy for concept ship design is the Advanced Surface Ship Evaluation Tool or (ASSET), developed and maintained by NSWCCD. Data is entered into ASSET's editor and a feasible ship design is produced using a synthesis algorithm. ASSET is limited to a single design and does not have the capability to iterate through multiple designs. However, ASSET is useful for developing parametrics that can be used in a program that can iteratively analyze ship designs. Software for iteratively processing ship designs, determining performance, and display graphical results is accomplished with a commercial software package such as The MathWorks Inc's MATLAB.

3.5.2 Collect Design Variable Data

To produce a feasible concept ship design data must be collected on design variable size, weight, power required, and cost. This data is commonly referred to as "*SWaP-C*" data in military acquisitions. Providing the minimum volume and installed power for a feasible ship design that is stable is a function of the aggregated SWaP-C data. Size data is generally given by required deck area the total of which determines the minimum required arrangeable area in a ship design. The aggregated weight data not only determines the total weight that the ship must support but, depending on equipment location, determines the ship's center of gravity with the addition of the ship's structural center of gravity. Weight data is provided by single-digit ESWBS category according to which categories the load contributes. A gun system has fire control equipment that contributes to ESWBS 400 as well as armament weight that contributes to ESWBS 700. Variable loads that design variables produce such as fuel or other mission expendables like missiles are also accounted for.

A second component to the data collection step is to collect data on the design variable performance against the specified threats. A self-defense system selected as a design variable has performance parameters associated with detecting, targeting, and destroying incoming threats.

This performance data is important to determine a ship design's survivability performance against the characterized threat environment.

3.5.3 Perform Design Synthesis

The design synthesis portion of the process takes the accumulated design variable data, produces feasible ship designs using parametric data, and develops performance parameters that can be used in the multi-attribute utility function and cost estimation. The design synthesis process is dependent on the performance variables desired to determine utility and cost. From the weight data collected a weight distribution and total displacement by single-digit ESWBS can be determined for each design. To determine the mobility mission area requirement, for example, the concept ship design's speed and range is calculated from the design variables installed power and fuel weight and the performance parameter total displacement.

3.5.4 Determine Estimated Ship End Cost

Discussed in Section 3.4.3 an appropriate cost estimation model is determined. For concept ship design a NAVSEA Class F estimation method using single-digit ESWBS as input is appropriate. The single-digit ESWBS weight distribution is determined in the previous step and is used in conjunction with an appropriate set of CERs and GFM costs to determine the estimated total ship end cost of each design in the tradespace. Parametric cost estimation is used to develop CERs that relate the single-digit ESWBS weight distribution with ship cost. Existing CERs for current ship classes are useful as an analogous comparison and can be corrected to current year dollars and production conditions.

3.5.5 Determine Multi-Attribute Utility

Collated performance parameters from the design synthesis process are input into individual utility functions for each design. The resulting multi-attribute utility function assesses design performance and reflects fulfillment of decision maker requirements and preference. The multi-attribute utility score represents a concept ship design's mission area capability.

3.6 Survivability Assessment Model of Naval Ship Concepts

Step 6 of the process presents a concept ship design survivability assessment process. The process utilizes the threat characterization, final design vector variables, and design synthesis performance parameters to probabilistically determine a concept ship design's susceptibility, vulnerability and recoverability through modeling and simulation. The susceptibility, vulnerability, and recoverability results are combined into an overall probabilistic survivability assessment. The sub-steps within this major step are:

1) Susceptibility Calculation
2) Vulnerability Calculation
3) Recoverability Calculation
4) Overall Survivability Assessment

3.6.1 Susceptibility Calculation

As previously discussed in Section 2.2.3 susceptibility for naval ship design is the determination of the probability of taking a hit, P(Hit). Ball and Calvano, 1994, defined the P(Hit) for naval ship design with the following equation:

$$P(Hit) = P_A \cdot P_{DCT} \cdot P_{LFI}$$

The Ball and Calvano equation for probability of hit requires expansion to capture the survivability performance of design variables being sought for tradeoffs. Additionally, when considering tradeoffs, the susceptibility assessment should only consider threat encounters and not options employing strategies to reduce the likelihood of encounters as these strategies are beyond the scope of concept design where high-level system tradeoffs are explored.

The concept naval ship susceptibility assessment uses a probability of activity equal to 1 only considering actual threat encounters. A profile of independent threat activities can be modeled to represent the expected threats in a specific operational environment where the sum of the individual threat activity probabilities is equal to 1. Probability of detection, classification, and targeting by the threat is combined into P(Detection) = P_D and indicates the performance of design variables related to ship signature control. Probability of launch, fly out, and impact on the ship by the threat is combined into P(Impact)=P_I. The probability of impact indicates the survivability performance of ship self-defense systems and is decomposed into probabilities for the ship's ability to detect and target an incoming threat, P_{DT}, and the probability of destroying it or evading it, P_{KE}. The intersection of these two probabilities determines the ship's ability to avoid a hit and whose compliment is the probability of impact.

$$P_{DT} = P(Detect\ \&Target)$$

$$P_{KE} = P(Kill\ or\ Evade)$$

$$P(Hit\ Avoidance) = P_{DT}P_{KE}$$

$$P(Impact) = P(\overline{Hit\ Avoidance}) = 1 - P_{DT}P_{KE}$$

The final equation for naval ship susceptibility is:

$$P(Hit) = P_A \cdot P_D \cdot P_I = P_A \cdot P_D \cdot (1 - P_{DT}P_{KE})$$

The system tradeoffs being sought for a concept design are represented in the assessment by the P_D and P_I factors. The P_D factor represents performance of signature reduction design variables and the P_I factor represents performance of sensors and self-defense systems. A ship's self-defense system is a system of systems that is configured by detection and targeting systems (i.e. radars) and threat kill or evasion systems (i.e. missiles or decoys). The system is composed of parallel systems for detecting and targeting a threat in series with parallel systems for killing or evading a threat. Figure 3-4 gives an example of this configuration for an ASW threat event where the ship's electronic warfare system, sonar system, and any helicopter supported sensors contributes to the detection and targeting of the threat. The ship's speed demonstrates the ship's ability to evade the threat, and a ship fired torpedo or a helicopter delivered torpedo to kill the threat. Only one system in each parallel configuration is required to prevent a hit.

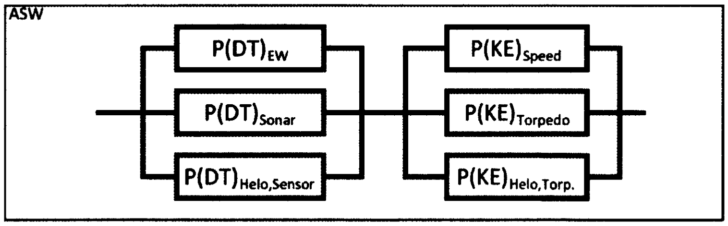


Figure 3-4: Parallel System Configuration for Detection and Targeting & Kill or Evade for an ASW Threat

The union of the individual system probabilities in each parallel configuration represents the ship's overall ability to detect/target a threat or destroy/evade a threat. The overall naval ship probability of detection & targeting and probability of destroying or evading are given below where 'n' and 'm' are the number of systems in each parallel configuration.

$$P_{DT} = 1 - \prod_{i=1}^{n} \left(1 - P_{DT,i}\right)^{n}$$

$$P_{KE} = 1 - \prod_{i=1}^{m} \left(1 - P_{KE,i}\right)^{m}$$

In effect, the probability of impact indicates the reliability of the self-defense system in preventing a hit. The final probability of impact and probability of hit equations are:

$$P(Impact) = 1 - P_{DT}P_{KE} = 1 - \left(1 - \prod_{i=1}^{n} \left(1 - P_{DT,i}\right)^{n}\right)\left(1 - \prod_{i=1}^{m} \left(1 - P_{KE,i}\right)^{m}\right)$$

$$P(Hit) = P_{A}P_{D}(1 - P_{DT}P_{KE}) = P_{A}P_{D}\left[1 - \left(1 - \prod_{i=1}^{n} \left(1 - P_{DT,i}\right)^{n}\right)\left(1 - \prod_{i=1}^{m} \left(1 - P_{KE,i}\right)^{m}\right)\right]$$

To determine a concept naval ship design's susceptibility a Monte Carlo analysis is conducted to generate a probability of hit for each design within the tradespace. For each design, hundreds of attack simulations are run using the activity profile and the individual system P_{DT} and P_{KE} values as input. The probability of activity profile, for example, is an expected 60% torpedo, 30% missile, and 10% asymmetric boat attack that determines, out of 1000 simulations, 600 are torpedo, 300 are missiles, and 100 boat attacks chosen randomly. The ability to model a naval ship's operating environment and expected threats is enabled by using an activity profile of independent threat events. Each threat simulation represents a different system configuration based on the type of threat as each type of threat has different systems to detect/target or kill/evade. In each simulation a hit or non-hit is determined and a distribution for each design is formed.

3.6.2 Vulnerability Calculation

Vulnerability is the ability of the ship to retain a defined amount of capability after taking a hit. Probabilistically, vulnerability is the probability of kill given a hit, $P\left({}^{Kill}/_{Hit}\right)$. The definition of a ship "kill" is defined in Step 1 as a decision makers desired capability after damage. Various levels of a "kill" can be defined by varying overall levels or targeted levels of mission capability required after a ship hit.

To determine $P\left({}^{Kill}/_{Hit}\right)$ an assumed two-dimensional ship profile is developed and arrangements of the major systems are assigned. A series of normally distributed hit simulations are run on each design. The damage effect on each system and the overall ship capability after damage is determined. Post hit utility is determined using the multi-attribute utility function establish in Section 3.1.2. Damage is simulated as degradation on each design attribute utility to accurately represent ship capability after a hit. For example, if a hit is simulated in an AW radar room then the AW mission area and its associated design attributes are degraded which reduces the multi-attribute utility score. Similarly to the susceptibility calculation in Section 3.6.1 the activity profile is used to determine a distribution of hit types on the ship. Torpedo hits use a normally distributed hit point along the longitudinal ship axis. Ship hits above the waterline use normally distributed longitudinal and vertical hit point locations. Impact points can also produce in internal explosion or an external explosion. A kill is counted if the calculated post hit utility is less than the utility requirement after damage for each design. After numerous hit simulations a distribution of kills given a hit can be determined. **Figure 3-5** shows a histogram of the number of simulations run on a single design and the resulting post hit utilities. With a desired post hit utility of 40%, for example, the hit simulations with resulting utilities below that value are considered "kills" and the probability of kill given a hit can be determined for this particular concept design.

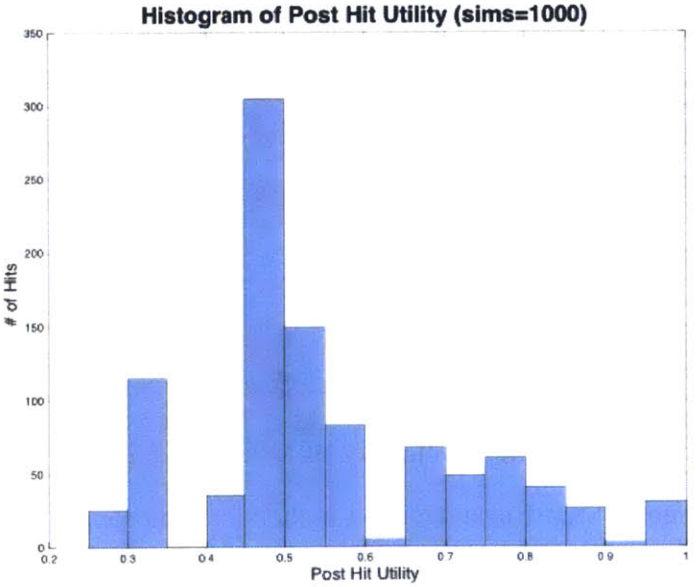


Figure 3-5: Histogram of Post Hit Utility for a Single Design

3.6.3 Recoverability Calculation

The probability of recovery, $P(\boldsymbol{Recovery})$, is determined similarly to and in conjunction with the vulnerability assessment described in Section 3.6.2. A recovery is defined in Step 1 by the decision maker's desired capability after ship recovery. With each hit simulation, after damage effects are determined in the vulnerability assessment, the utility post recovery is determined taking into account design variables established to enhance recoverability. Design variables such as damage containment through fire zones, watertight subdivision, and installed damage control systems enhance recoverability thus recovering capability. Crew response is accounted for by degrading the recoverability score if a command and control or accommodation space is hit or damaged. A recovery is determined if the post recovery utility calculated for each design is greater than the post recovery utility requirement. The probability of recovery is calculated exactly as the probability of kill given a hit in the previous section.

3.6.4 Overall Survivability Assessment

The assessment of the principle discipline survivability performance parameters produces three probabilities: the probability of hit, $P(Hit)$, the probability of kill given a hit, $P\left({}^{Kill}/_{Hit}\right)$, and the probability of recovery, $P(Recovery)$, the intersection of which gives the probability of kill. The overall survivability performance of a concept design is determined by the complement of the probability of kill, which is the probability of survival, $P(Survival)$, whose equation is:

$$P(Survival) = 1 - [P(Hit) \cdot P(Kill\ /\ Hit) \cdot (1 - P(Recovery))]$$

The probability of survival equation is useful to the process in that it provides a single holistic assessment of a concept design's survivability but the equation can be, at times, misleading. High performance scores in any of the three survivability discipline assessments can mask poor performance in another area. This is characteristic of ship designs that have a high degree of susceptibility reduction designed in while the ship is designed to commercial standards leaving poor performance in vulnerability and recoverability. An excellent $P(Hit)$ score can result in a relatively high $P(Survival)$ assessment while the $P\left({}^{Kill}/_{Hit}\right)$ and $P(Recovery)$ assessments are relatively poor. Seeking trades in capability, cost, and survivability results in a three dimensional tradespace. Optimizing a tradespace of 5 dimensions: capability, cost, susceptibility, vulnerability, and recoverability, can reveal optimized designs that not only optimize capability and cost but find the ideal balance in the performance of the principle disciplines of survivability.

3.7 Tradespace Exploration

Having assessed each design's capability, cost, and survivability, the last step in the process analyzes and explores the tradespace created with these parameters. The tradespace is optimized in three or five dimensions to generate a Pareto set of optimal designs. The Pareto set is projected onto a 2 dimensional plane where the space can be navigated and trades can be explored. The sub-steps within this last major step are to:

1) Perform Multi-Dimensional Optimization on Tradespace Designs
2) Navigate the Tradespace
3) Perform Capability, Affordability, Survivability Trades

3.7.1 Multi-Dimensional Optimization

The Pareto optimal designs in a tradespace are determined by their proximity to an optimal point. Traditionally in tradespace exploration two dimensions are explored, such as utility and cost, and optimal points are found to be the closest to an optimum (i.e. high utility, low cost). The optimal point when survivability is added as a third dimension becomes the high capability, low cost, high survivability point. The optimal designs are a surface of points in three-dimensional space. Figure 3-6 shows the three-dimension utility-cost-survivability tradespace, previously shown in Figure 2-12, with the 3D Pareto optimal designs highlighted in red.

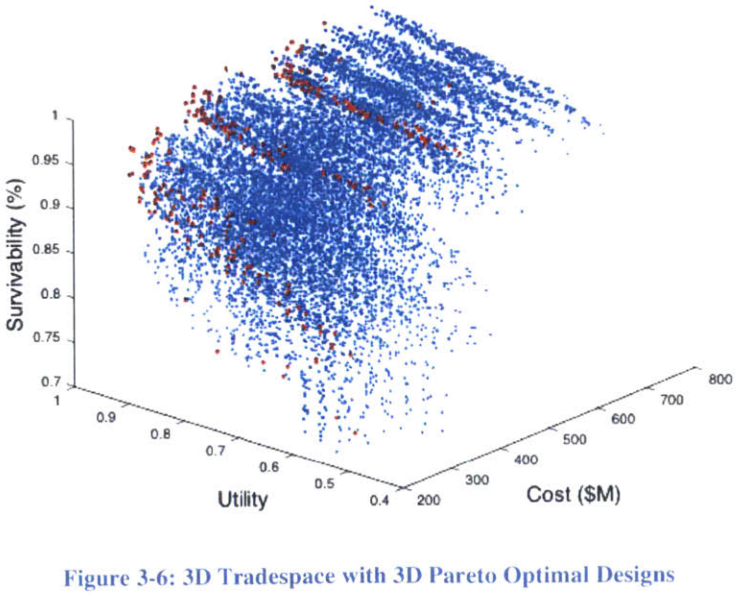


Figure 3-6: 3D Tradespace with 3D Pareto Optimal Designs

The number of dimensions determined for optimization is discussed briefly in Section 3.6.4. The number of optimal designs can increase by an order of magnitude as the number of dimensions increases which poses a problem in the size of the optimized set of designs to be explored. **Table 3-5** provides an example from the small surface combatant trade study of the increase in the number of optimal designs resulting from the additional dimensions of analysis given a constant set of analysis constraints and requirements.

Number of Dimensions	Dimensions for Analysis	# of Optimal Designs
2	Utility-Cost	47
2	Survivability-Cost	70
3	Utility-Cost-Survivability	350
5	Utility-Cost-Susceptibility-Vulnerability-Recoverability	1774

Table 3-5: Number of Optimal Designs Resulting from Number of Dimensions

Using a three-dimensional optimization approach can produce designs that have optimal overall survivability but have component survivability assessments that are disproportionate and do not reflect optimal design survivability. The three-dimensional optimized set is a more refined set of optimal designs that can represent approximately 1% to 2% of the tradespace. This assists designers in filtering large tradespaces to a relatively small set of optimized designs for further analysis. A five-dimensional optimization approach can produce designs that are optimized for all aspects of survivability but can conversely produce a much larger optimized set that could represent approximately 10% of the tradespace for analysis. **Figure 3-7** shows the same utility-cost-survivability tradespace with the five-dimensional optimized set of designs in red. The five-dimensional approach should only be used if additional filtering is applied to the optimized set.

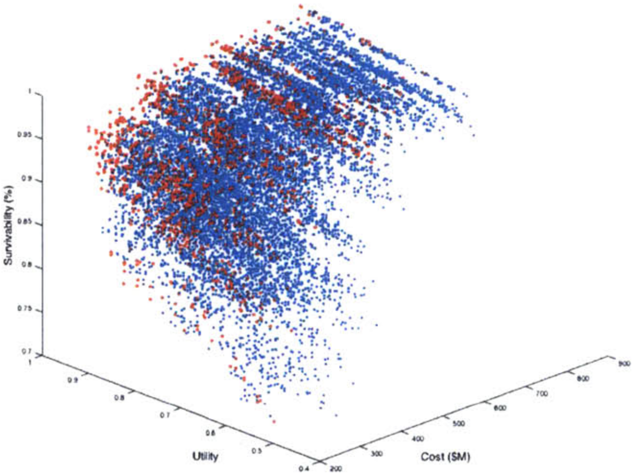


Figure 3-7: 3D Tradespace with 5D Pareto Optimal Designs

Apparent in **Figure 3-6** and **Figure 3-7**, even with the optimized set known the point cloud tradespace is still difficult to navigate. Methods to navigate the space bound by the optimized set of designs are needed.

3.7.2 Navigating the Tradespace

Traditionally, tradespace exploration is performed in two dimensions, utility and cost, where the optimal designs are easily identified and trades can be further analyzed. Adding dimensions to the design tradespace for analysis makes tradespace exploration a challenge. When multi-dimensional optimization is performed and an optimal set of designs is determined, the optimal designs are projected onto a two dimensional plane where the tradespace can be explored in a more traditional manner. The exception to tradition tradespace exploration being that every design represented on the two-dimensional plane is an optimal design, which requires additional techniques to explore tradeoffs. **Figure 3-8** shows the three-dimensional utility-cost-survivability Pareto surface designs projected onto the capability-cost plane.

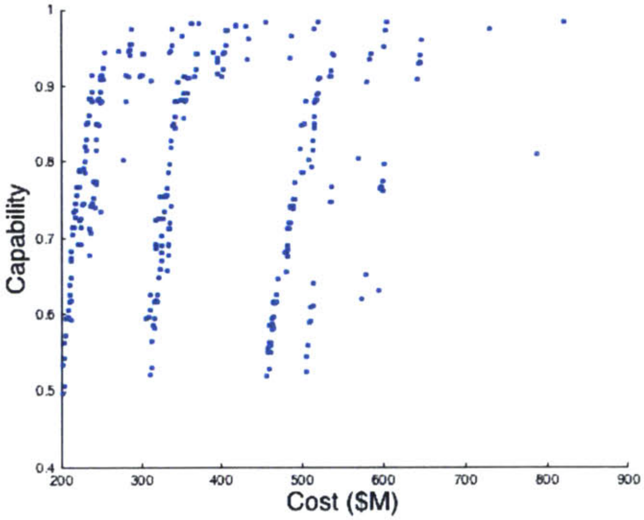


Figure 3-8: 3D Pareto Optimal Designs Projected on Capability-Cost Plane

One method of exploring the optimal designs on the capability-cost plane is to designate an iso-capability band to explore the trades between survivability and cost. Similarly, a second method of exploring the tradespace is to designate an iso-cost band to explore trades in capability and survivability. **Figure 3-9** demonstrates both iso-cost and iso-capability bands used to navigate the optimal tradespace in the capability-cost plane.

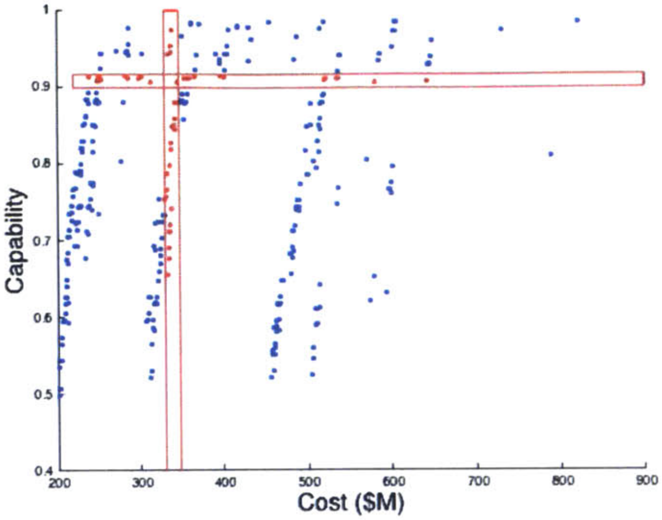


Figure 3-9: Optimal Tradespace Exploration with Iso-Cost & Iso-Capability Bands

Depending on the designer's preference, the combinations of different planes and iso-variable bands produces six methods to navigate the optimal tradespace, provided in Table 3-6. These methods are useful for designers where strict requirements can be placed on cost or predetermined levels of capability. The desired coupling of trades determines the projection plane.

Projected Plane	Tradespace Exploration Methods
Utility-Cost	*Iso-Utility: Survivability-Cost Trades*
	Iso-Cost: Survivability-Utility Trades
Survivability-Cost	*Iso-Survivability: Utility-Cost Trades*
	Iso-Cost: Survivability-Utility Trades
Utility-Survivability	*Iso-Utility: Survivability-Cost Trades*
	Iso-Survivability: Utility-Cost Trades

Table 3-6: Tradespace Navigation Methods of Multi-Dimensional Optimized Pareto Sets

3.7.3 Perform Capability, Affordability, Survivability Trades

In the last step of the process, after all assessments and evaluations have been performed, and the optimal designs have been identified and filtered, trades can take place to identify design concepts for further analysis and transition into detailed design. The designs identified within a desired iso-cost or iso-capability band are analyzed incrementally for design variable trades and design capability or survivability performance. Design selection is performed by plotting the tradeoff variables to determine optimal points or points of diminishing returns.

3.8 Process Overview: MATE for Naval Survivability

The MATE for Survivability process applied to US Navy Surface Ship survivability is a 23-step process that provides naval ship designers a systematic methodology to evaluate a concept naval ship design's capability, survivability, and cost, and high-level concept design tradeoffs. The process takes a traditional cost-benefit tradespace analysis and adds a naval ship's dynamic threat environment and takes into account the performance of a naval combatant design within that threat environment. The process accomplishes this through multiple contexts representing different states each having unique needs. Each context is defined and evaluated by a decision maker's requirements and preferences. In the case of naval combatant design, the contexts and needs considered are a ship design's performance in a normal state, damaged state, and recovered state. The process not only evaluates a design's mission area capability, estimated cost, and survivability but also demonstrates methods of exploring the tradespace developed by those performance parameters. The process identifies optimal designs and provides methods to navigate the space bound by the set of those designs. Optimal designs are selects for further analysis.

Figure 3-10 provides a flow chart of the functional MATE for US Navy surface ship survivability process described in this section. The MATE for naval ship survivability process applies the process outlined by (Richards 2009). Richards' process is an 8-phase, 29-step process and uses the survivability metrics of threshold availability and time-weighted average utility loss to evaluate design survivability. The MATE for naval ship survivability process uses the probability of ship survival, $P(Survival)$, as the survivability performance metric and incorporates performance assessments of the three principle disciplines of naval survivability; susceptibility, vulnerability, and recoverability. A probabilistic survivability assessment method is more applicable to naval ships and is modeled to simulate current Navy survivability assessment practices.

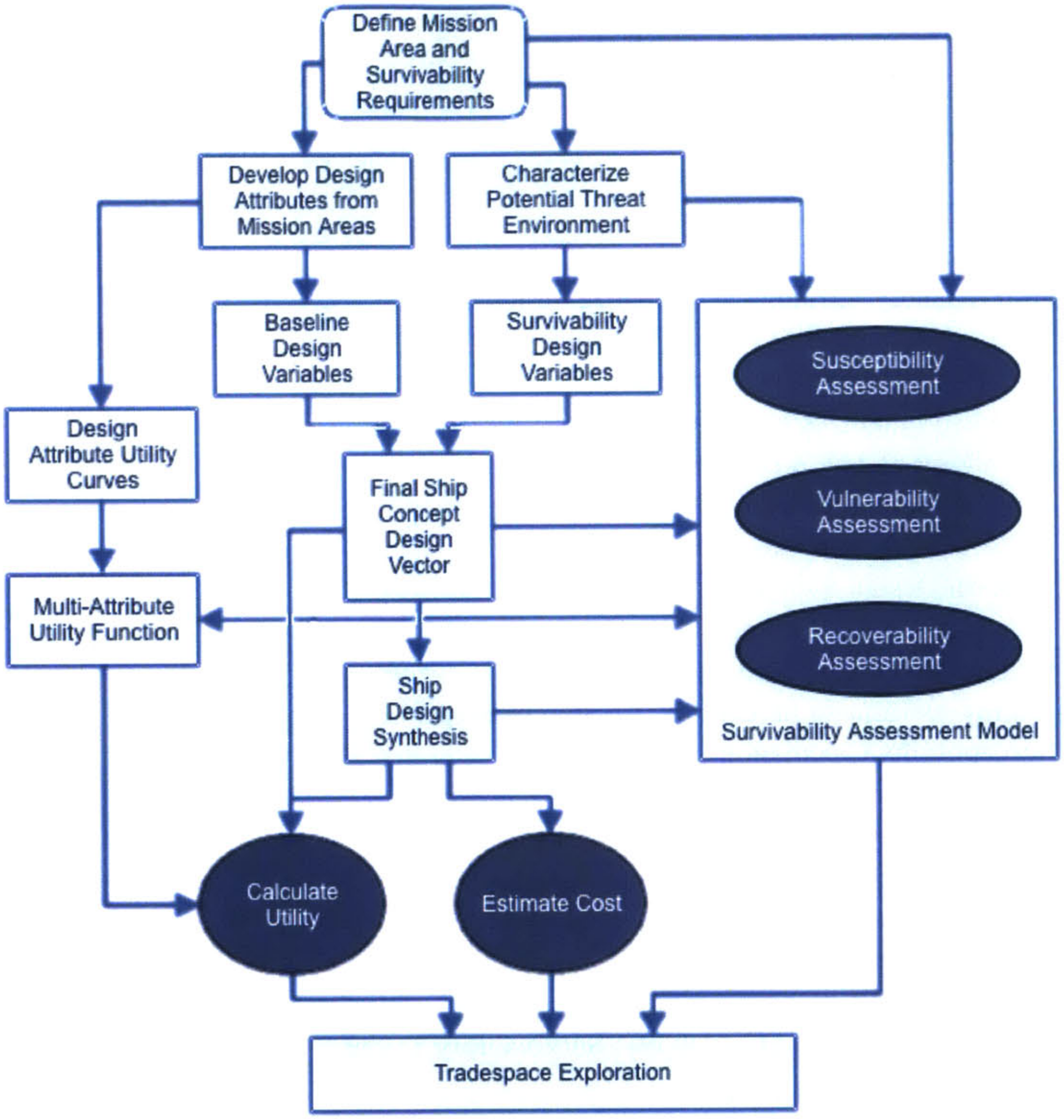


Figure 3-10: MATE for Survivability Applied to Naval Combatant Concept Design

Finally, this process allows ship designers to incorporate survivability in the earliest stages of the design process. Understanding the full effect of tradeoffs earlier in the design process avoids costly redesign and program disruptions. This is in contrast to the practice of designing for capability then seeking low-cost survivability reduction features to add on to a design. An overview of the major steps and sub-steps of the process are:

1. **Generate Ship Requirements**
    1.1. Determine Mission Area Requirements
    1.2. Establish the Multi-Attribute Utility Function
    1.3. Determine Survivability Requirements

2. **Generate Ship Concept Designs**
    - 2.1. Propose Design Variables
    - 2.2. Map Design Variables to Attributes
    - 2.3. Establish Baseline Design Vector
3. **Characterize Ship Threat Environment**
    - 3.1. Gather Threat Activity Data
    - 3.2. Develop Model of Threat Activity
4. **Apply Survivability Variables and Finalize Design Vector**
    - 4.1. Propose Survivability Design Variables
    - 4.2. Map Design Variables to Threats
    - 4.3. Establish Final Design Vector
5. **Design Synthesis and Ship Baseline Performance**
    - 5.1. Develop Software Architecture
    - 5.2. Collect Design Variable Data
    - 5.3. Perform Design Synthesis
    - 5.4. Determine Multi-Attribute Utility
    - 5.5. Determine Estimated Ship End Cost
6. **Survivability Assessment Model of Naval Ship Concepts**
    - 6.1. Susceptibility Calculation
    - 6.2. Vulnerability Calculation
    - 6.3. Recoverability Calculation
    - 6.4. Overall Survivability Assessment
7. **Tradespace Exploration**
    - 7.1. Perform Multi-Dimensional Optimization on Tradespace Designs
    - 7.2. Navigate the Tradespace
    - 7.3. Perform Capability, Affordability, Survivability Trades

4 TRADESTUDY: SMALL SURFACE COMBATANT CONCEPT

This section applies the MATE for naval surface ship survivability process developed in the previous section to a trade study of a future small surface combatant (SSC). The U.S. Navy is determined in its plans to increase the number of small surface combatants from 22 to 52 ships by FY2028. (DON 2015) This was to be accomplished through the LCS program, but the program has seen recent (at the time of writing) pressure from DOD to cut the total number of ships from 52 to 40 with the potential for future cuts and to eliminate one of the two shipbuilders. (SECDEF 2015) Regardless of the outcome of the LCS program a new design for a future small surface combatant is necessary to support the number of small surface combatants and eventually replace retiring LCS's. Considering the history of the LCS and the survivability tradeoffs that were made this trade study will demonstrate the concept generation of an SSC taking into account survivability in this early stage of design. The goal of the trade study is to not only demonstrate the process but to demonstrate the useful information for naval ship designers that can be gleaned from the process.

Limitations of the SSC trade study are available computing power and limited sensitive information. Available computing power limits the number of design attributes and variables for consideration. The final design vector forming a full-factorial tradespace can quickly diminish available computing power in an iterative analysis. In addition to the enumerated design vector, modeling and simulation within the survivability analysis model contributes to limiting available computing resources. Analyzing a tradespace of thousands of designs while simulating a thousand hit simulations per design could require tens of millions of computational operations, which have to be performed for different threat environments and varying requirements. Another limitation of the study is the availability of sensitive military information. Survivability performance suggests the combat performance of a military ship and is, understandably, controlled information. For the purposes of conducting a concept trade study and avoiding the use of sensitive information, all performance parameters and system characteristics that are otherwise classified will be estimated using unclassified sources or expert opinion.

The analytical value structure for this trade study is tailored using a combination of MAUT and AHP. The trades study accounts for design attributes that are both continuous variables and discrete variables. AHP pairwise comparison process is used to determine the mission area and design attribute weights based on decision maker inputs and activity profiles based on relative likelihood assumptions of threat encounters. Supplemental data for the trade study is provided in Appendix E.

4.1 SSC Requirements

4.1.1 Mission Area Requirements

Small surface combatants, synonymous with frigates and littoral combatants, have common missions and intended operational use. SSC's are undersea warfare platforms with added capability for surface and air warfare that operate in demanding littoral environments. The SSC is intended to operate in high-density multi-threat environments independently or part of a carrier strike group or surface action group. (DON 2014)

For the purpose of a concept trade study and available computing power the SSC concept will consider a limited number of mission areas. The SSC ROC, Table 4-1, designates the required primary and secondary mission areas for the SSC program. In addition to a traditional mission area designation, mission area weights are provided to reflect the Navy's preference between primary and secondary mission areas. Weights were determined using AHP pairwise comparison method. The selected mission areas are chosen to capture the performance of the high-level systems being sought for trades.

AW	ASW	EW	MOB	SUW
S	P	S	P	S
0.062	0.341	0.033	0.437	0.127

Table 4-1: SSC Required Mission Areas

The concept SSC's primary missions are mobility and anti-submarine warfare with surface warfare, air warfare, and electronic warfare as secondary missions. The weights demonstrate the preference between the ASW and MOB primary missions as well as the preference between AW, EW, and SUW secondary missions. The weights characterize an ASW platform that is capable of conducting SUW operations with limited AW capability. Pairwise comparison determination of the SSC mission area weights is provided in Appendix E.

4.1.2 Multi-Attribute Utility Function

The mission areas designated have typical sub-missions such as detection, targeting, and engagement in the case of AW, ASW, and SUW. Electronic warfare mission is composed of three sub-missions; to perform electronic support (ES), electronic protection (EP), and electronic attack (EA). For this trade study several design attributes are represented by system level architectures. Discussed in Section 3.2.1 the Navy relies on existing systems architectures that are developed in parallel to other ship design efforts and can be used commonly across different ship programs. The AW and ASW mission areas are represented with levels of concept system architectures that have detection, tracking, and engagement performance specifications. Weights for the design attributes were derived using AHP pairwise comparisons and the mission area weights. The pairwise comparison determinations for design attribute weights are provided in Appendix E. The selected design attributes, their weights, and ranges are provided in Table 4-2.

DESIGN ATTRIBUTE	k	RANGE
Ship Range	0.109	1000-7000 Nautical Miles
Maximum Ship Speed	0.328	25-40 Knots
ASW Combat System	0.256	Low-High
ASW Capable Helicopter	0.085	None-1 Embarked-2 Embarked ASW Helicopters
AW Combat System	0.062	None-Low-High
EW System	0.033	None - ES Only - ES/EP/EA System
SUW Gun Caliber	0.078	30-127mm
SUW Anti-Ship Missile	0.011	None - Medium Range
SUW Capable Helicopter	0.038	None-1 Embarked-2 Embarked SUW Helicopters

Table 4-2: SSC Design Attributes and Ranges

The ranges of the ship speed and endurance range attributes are derived from existing naval combatant capabilities and encompass a range that accounts for values above and below those capabilities. Speed, endurance range, and gun caliber are continuous attributes with the remaining attributes being desired discrete system architectures. The use of system architectures leverages existing systems and associated performance data, and avoids the design synthesis process producing designs that are infeasible (i.e. AW radar incompatible with AW missile). Utility curves are generated for each design attribute. Ship maximum speed utility curve was provided in Figure 3-2. The utility curves generated for the remaining design attributes are provided in Figure E-2.

4.1.3 Survivability Requirements

The SSC survivability requirements are identified by operational context and expected capability. The contexts applicable to naval ship survivability are normal operation, post-hit damaged operation, and post-recovery operation. The survivability requirement is defined as a percentage of the normal state design capability.

To demonstrate the flexibility of the process the trade study will consider multiple survivability requirement outcomes. One survivability requirement set will demonstrate an overall capability requirement where a concept design must provide a minimum amount of total capability after damage and recovery. These requirements are a minimum post-hit capability requirement of 50% and a minimum post-recovery capability requirement of 70%. The second set of survivability requirements will demonstrate targeted minimum capability requirements by mission area. This method allows a decision maker's preference for one mission area over other mission areas in damaged and recovered states. This set of requirements, provided in **Table 4-3**, demonstrates the desire for limited ship mobility as well as AW and SUW self-defense in a post-hit damaged state. The equivalent overall capability requirements are approximately 40% post-hit and 60% post-recovery.

	AW	ASW	EW	MOB	SUW
Post-Hit	100.00%	20.00%	20.00%	50.00%	50.00%
Post-Recovery	100.00%	50.00%	50.00%	70.00%	50.00%

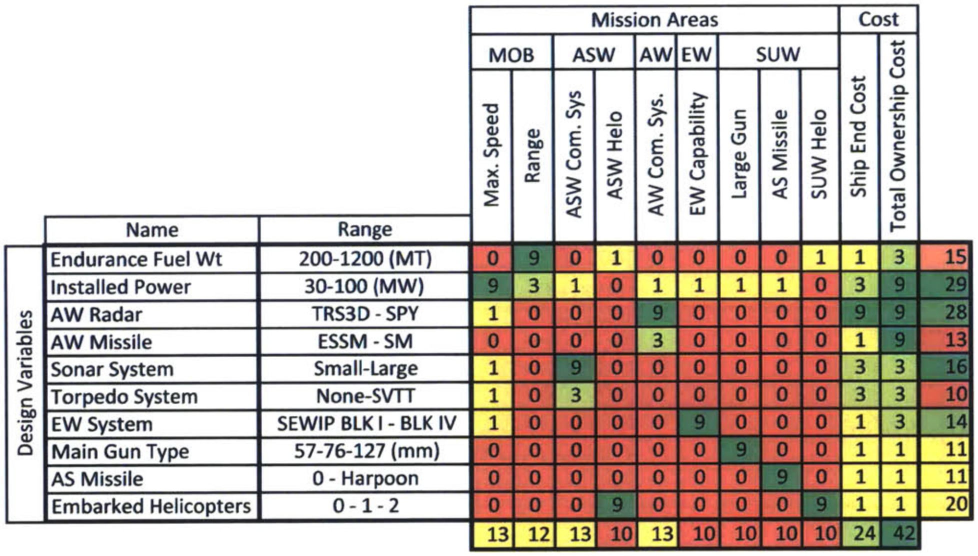
Table 4-3: SSC Survivability Requirements by Mission Area

4.2 Generate SSC Design Concepts

4.2.1 Design Variable Determination

Design variables are proposed to address the previously developed design attributes. For discretely defined design attributes system level architectures are developed as variables that satisfy detection, tracking, and engagement criteria. To assist in baseline design variable selection a design value matrix is developed to compare potential design variables to design attributes. Cost attributes are added to the matrix to reveal the importance of each design variable to ship end and total ownership costs.

Fuel weight and installed power ranges were established to provide ship speed and endurance range performance that satisfies the range and maximum ship speed attributes. Other design variable ranges were established using existing naval systems that provide capabilities that satisfy their design attributes.

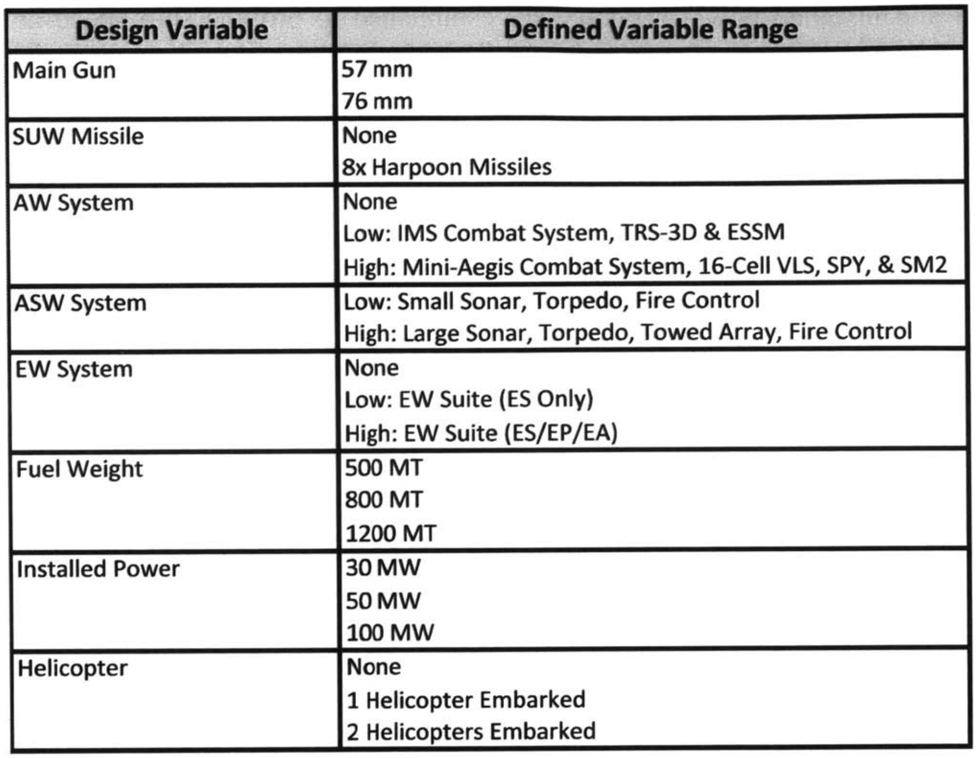


			Mission Areas									Cost		
			MOB		ASW		AW	EW	SUW					
	Name	Range	Max. Speed	Range	ASW Com. Sys	ASW Helo	AW Com. Sys.	EW Capability	Large Gun	AS Missile	SUW Helo	Ship End Cost	Total Ownership Cost	
Design Variables	Endurance Fuel Wt	200-1200 (MT)	0	9	0	1	0	0	0	0	1	1	3	15
	Installed Power	30-100 (MW)	9	3	1	0	1	1	1	1	0	3	9	29
	AW Radar	TRS3D - SPY	1	0	0	0	9	0	0	0	0	9	9	28
	AW Missile	ESSM - SM	0	0	0	0	3	0	0	0	0	1	9	13
	Sonar System	Small-Large	1	0	9	0	0	0	0	0	0	3	3	16
	Torpedo System	None-SVTT	1	0	3	0	0	0	0	0	0	3	3	10
	EW System	SEWIP BLK I - BLK IV	1	0	0	0	0	9	0	0	0	1	3	14
	Main Gun Type	57-76-127 (mm)	0	0	0	0	0	0	9	0	0	1	1	11
	AS Missile	0 - Harpoon	0	0	0	0	0	0	0	9	0	1	1	11
	Embarked Helicopters	0 - 1 - 2	0	0	0	9	0	0	0	0	9	1	1	20
			13	12	13	10	13	10	10	10	10	24	42	

Table 4-4: SSC Design Value Matrix

4.2.2 Baseline Design Vector

From the design value matrix in Table 4-4 variables are proposed for the baseline design vector. The proposed baseline design variables and their defined ranges are provided in Table 4-5. The defined variable ranges produce a wide array of design options. Included within several design variable ranges are the "none" option to explore design choices that exclude systems that could address design attributes to provide options for potential design affordability. Other variable definition ranges include high options that are not traditionally included in small surface combatant designs. These high-low options are demonstrated by the AW system variable where the defined ranges include the option to not have an AW system, having a self-defense combat system, or having a "mini-Aegis" system that is expensive and typically installed on large surface combatants that have a required primary AW mission area. The baseline design vector addresses design attributes and produces a tradespace of 1944 concept designs. Several "none" options were used in mission areas with low relative mission area weight factors.



Design Variable	Defined Variable Range
Main Gun	57 mm 76 mm
SUW Missile	None 8x Harpoon Missiles
AW System	None Low: IMS Combat System, TRS-3D & ESSM High: Mini-Aegis Combat System, 16-Cell VLS, SPY, & SM2
ASW System	Low: Small Sonar, Torpedo, Fire Control High: Large Sonar, Torpedo, Towed Array, Fire Control
EW System	None Low: EW Suite (ES Only) High: EW Suite (ES/EP/EA)
Fuel Weight	500 MT 800 MT 1200 MT
Installed Power	30 MW 50 MW 100 MW
Helicopter	None 1 Helicopter Embarked 2 Helicopters Embarked

Table 4-5: SSC Baseline Design Vector

The core of a naval combatant's SUW capability is the large caliber naval gun. The naval guns selected for consideration are currently in use by the U.S. Navy, the 57 mm used on LCS and the 76 mm used on FFG-7. Both naval guns were considered for the LCS design. (Work 2012) Implied with the main gun design variable are the applicable sub-systems for detection and tracking such as the fire control radar and fire control system. Similarly, the AW and ASW system architectures were built using variables selected through the design value matrix process with each possessing a sensor, processing system, and engagement weapon. The EW system variable considers a "none" option, a passive only system variant, and an active and passive system variant.

Several design variable ranges were determined using performance estimates derived from ship modeling in ASSET. Fuel weights selected provided estimated ship endurance ranges between 1000 and 7000 NM. The average endurance range between FFG-7, both LCS variants, and a DDG-51 is approx. 4000 NM. Ship installed power is also comparable to existing small surface combatant designs. The FFG-7 class has approx. 30 MW of installed power with a max speed over 29 knots with the LCS having approx. 85 MW of installed power and a max speed over 40 knots. The defined range for installed power is estimated to achieve design speeds up to 40 knots. The design synthesis process determines the exact range and speed based on weight distribution and electrical loading and will be discussed in Section 4.5.1.

4.3 Characterize SSC Threat Environment

4.3.1 Threat Environment

The most demanding projected operating environment for the SSC is the littoral environment. Undersea threats from torpedoes or mines, coastal anti-ship missiles, and asymmetric attack from small boats or other surface combatants characterize the threats the SSC expects to face in littoral waters. This trade study considers three enumerated threat types; coastal anti-ship missiles, submarine launched torpedoes, and surface boat attack. For these enumerated threats additional information on their specific damage mechanisms and a determination of their relative probabilities of activity is needed.

4.3.2 Damage Mechanisms

In addition to the types of threats the SSC will face the damage mechanisms from these threats must be understood so adequate mitigation can be applied. The predominant categories of damage mechanisms are UNDEX from torpedoes, internal explosions from missiles, and contact external explosions from asymmetric boat attack. The effects of a torpedo UNDEX can be mitigated through vulnerability reduction by use of high strength ductile materials, shock hardening/isolation of equipment and machinery, watertight compartmentalization to minimize the extent of flooding, and increased hull girder strength. (Keil 1961) Susceptibility reduction against torpedoes includes destroying the launch vehicle, high design speeds to outrun the torpedo, or use of acoustic or magnetic decoys or countermeasures.

The anti-ship missile is a versatile weapon fired from air, land, sea, or undersea vehicles that employs various guidance and homing techniques to lock onto a ship. The intention of an anti-ship missile is to penetrate the ship's hull and explode internally causing severe damage and fire. Susceptibility reduction for anti-ship missiles includes point defense systems like the Navy's close-in weapon system (CIWS) to defeat the missile or thermal or radar signature reduction efforts to limit the ability of the missile to lock on to the ship. Susceptibility reduction also includes destroying the delivery vehicle prior to missile launch. Damage effects from an internal explosion can be mitigated through vulnerability reduction by use of blast-hardened structure, and shock isolation of equipment and machinery. To prevent the spread of fire naval ships are designed with fire zones. Structurally reinforced and insulated bulkheads form the fire zone boundaries and contain damage and limit the spread of fire. Each fire zone contains redundant fire fighting systems such as seawater systems for fire hoses and ventilation for de-smoking.

Asymmetric small boat attacks utilize high speed "hit and run" tactics to harass and cause damage that results in a "mission kill" usually from a swarm of several boats. The tactic employs a large number of small agile boats that are lightly armed and dispersed from different locations then converge on a target. The small boat swarm is difficult to detect and defend against. (Haghshenass 2006) A small boat possesses light armament of small caliber shells or rocket propelled grenades intended to damage systems external to the ship like radars, masts, and weapons. Evolving asymmetric small boat tactics are utilizing missiles or torpedoes but for this trade study will only consider engagements from lightly armed small boats. Susceptibility reduction for asymmetric small boat attack includes high design speeds to limit the closing velocity of approach and point defense systems. Vulnerability reduction methods for the damage effects from external explosions are similar to previously discussed methods to improve structure, shock isolate equipment, and damage control and containment.

4.3.3 Model Threat Activity

The identified threats, their damage mechanisms, and the probability of activity are determined for the threat activity model. The first, provided in Table 4-6, models threat activity for the projected littoral environment. The P(Activity) is determined by examining the likelihood of each threat relative to the others within the project environment. A similar process to pairwise comparisons is used with likelihood scores rather than importance rankings. Each threat represents an independent threat encounter with the total probability of activity equal to one. The survivability assessment model will only consider actual threat encounters and does not account for strategies utilizing CONOPS to avoid threat activity.

Threat	Mechanism	P(Activity)
Anti-Ship Missile	Internal Explosion	0.32
Torpedo/Mine	Proximity UNDEX	0.56
Surface Boat Attack	External Explosion	0.12

Table 4-6: SSC Littoral Threat Model

To demonstrate the flexibility of the process the trade study will consider a second threat activity model. The second, provided in **Table 4-7**, models threat activity for a less demanding open ocean, or "blue water" environment. In the open ocean environment, anti-ship missiles are twice as likely to be encountered as torpedoes and the chance of small boat attack is virtually non-existent.

Threat	Mechanism	P(Activity)
Anti-Ship Missile	Internal Explosion	0.62
Torpedo/Mine	Proximity UNDEX	0.32
Surface Boat Attack	External Explosion	0.06

Table 4-7: SSC Blue Water Threat Model

Likelihoods of threat encounters relative to each other are provided to the ship program via official assessments by OPNAV N81 or ONI but are sensitive material and assumed for the purposes of this trade study.

4.4 Survivability Variables and Final SSC Design Vector

4.4.1 Survivability Design Variable Analysis

After the expected threats have been accounted for and modeled the survivability components of surface ships, given in Appendix B, are consulted to generate a list of systems or design features to mitigate the effect of the modeled damage mechanisms. A survivability design value matrix, Table 4-8, is formed from the list of components generated relative to the modeled threats. The list includes baseline design variables, shown in bold in Table 4-8, to account for the contribution of baseline performance to survivability performance. The modeled threat damage mechanisms are weighted according to the littoral environment activity profile in Table 4-6.

	Survivability Design Principle	Survivability Design Variable	Variable Range	Threat			Total Impact
				Anti-Ship Missile	Torpedo/ Mine	Asymm. Boat	
Susceptibility	Detection & Targeting	Acoustic Signature	Equipment Isolation, Prairie/Masker	0	9	0	5.0
		Magnetic Signature	Degaussing System	0	3	0	1.7
		Thermal Signature	Stack Cooling, Rerouting, Insulation	9	0	3	3.2
		Radar Cross Section	Hull Design and Enclosures	9	0	9	4.0
		AAW Detection	***TRS-3D, SPY-3***	9	0	0	2.9
		ASW Detection	***None, Sonar, Towed Array, Helicopter***	0	9	1	5.2
		Installed Power (Speed)	***Low-Med-High***	0	9	9	6.1
		Installed Power (Detection)	***Low-Med-High***	9	3	9	5.6
	Hit Avoidance	***Active Defense (AAW)***	***ESSM, SM***	9	0	1	3.0
		Active Defense (ASuW)	***Main Gun,*** Secondary Deck Guns	3	0	9	2.0
		Active Defense (ASW)	***Helicopter, Towed Array, Nixie***	0	9	1	5.2
		Decoys	NULKA, Chaff	9	0	1	3.0
		Electronic Warfare (Active & Passive)	***Active, Passive***	9	0	3	3.2
Vulnerability	Damage Tolerance	Structural Strength	Commercial-Combatant	9	9	9	9.0
		Magazine Armor	Ballistic Plating, Blast Hardening	9	9	3	8.3
		Side Protection	Hull Design	9	9	9	9.0
		Bottom Protection	Hull Design	1	9	1	5.5
		Compartmentalization	Watertight Subdivision	3	9	1	6.1
		Shock Hardening	Equipment Isolation, Rafting	9	9	3	8.3
	Separation	Equipment Separation	Ship Length, Separation Distance	9	9	9	9.0
	Redundancy	Equipment Redundancy	Vital Equipment Redundacy, Watertight Subdivision	9	9	9	9.0
		Primary & Alternate Power Sources	Primary, Alternate, Casualty Power Systems	9	9	9	9.0
Recover.	Damage Containment	Crew Size	Minimal - Full Manning	3	3	3	3.0
		Distributed & Redundant Seawater & Ventilation	Fire Zones	9	9	9	9.0
		Watertight Subdivisions	Watertight Subdivision	9	9	9	9.0

Table 4-8: Survivability Variable Design Value Matrix

Susceptibility reduction design variables tend to be threat specific where as vulnerability reduction and recoverability enhancement features tend to fit the entire threat profile. Also evident from the design value matrix is the baseline design variables selected for their mission area effectiveness contribute only to susceptibility reduction. A holistic design tradespace includes design variables that encompass all three disciplines of survivability, their baseline and survivability performance, and cost. This comprehensive tradespace enables efficient survivability component tradeoffs that provide a balance of capability, overall survivability, and cost. The design value matrix also demonstrates the contribution of several vulnerability reduction design variables adequately addressing all the threats considered. The survivability variables added to the tradespace are signature controls, decoys, secondary deck guns, watertight subdivision, machinery redundancy and separation, primary structural strength, equipment shock isolation, fire fighting (FF) and protection. These additional nine variables can potentially grow the tradespace into the millions of designs, which becomes computationally expensive.

	Commercial	Mixed-Spec Low	Mixed-Spec High	Combatant
Watertight Subdivision	1-Compartment Flooding	2-Compartment Flooding	12.5% Length	15% Length
Primary Structure	ABS SVR	ABS SVR	ABS NVR	ABS NVR
Machinery Redundancy & Separation	Twin-Screw Single Machinery Room	Separated Auxiliary Systems	Two Machinery Rooms w/ Commercial Equipment	Two Machinery Rooms w/ Combatant Equipment
Equipment Shock Isolation	None	Command & Control, Int. Comms, Casualty & DC Equipment	Command & Control, Int. Comms, Casualty & DC, Limited Ship Control, & Navigation Equipment	Command & Control, Int. Comms, Casualty & DC, Ship Control, Navigation Equipment, and Mission Area Systems
Fire Fighting and Protection	No Fire Zones SOLAS CO2	No Fire Zones, Commercial DC Lockers & FF Material & Equipment	Combatant Fire Zone Bulkheads, Commercial DC Lockers, Combatant FF Material & Equipment	Combatant DC Repair Stations & Fire Zone Bulkheads, Redundant Firezone Systems, Combatant FF Material & Equipment
Signature Reduction	None	Degaussing System	Degaussing, Masker Systems, Reduced RCS	Degaussing, Masker Systems, Reduced RCS, Sound Isolation Mounts, Exhaust Cooling

Table 4-9: SSC Survivability Design Variables by Design Specification Category

In consideration to the tradespace size survivability design variables for the SSC are aggregated into four categories based on the design standard. Discussed in Section 2.3.1 the set of design standard specifications increase design complexity and cost through additional strength, redundancy and separation, shock isolation, and quality control. The four categories are commercial specifications on the low end, combatant specifications on the high end, with two mixed-specification categories in between. For these four categories, six survivability design variables are considered; watertight subdivision, machinery redundancy and separation, primary structural strength, equipment shock isolation, fire fighting and protection, signature reduction. For each survivability design variable a range is determined across the design specification categories.

4.4.2 SSC Final Design Vector

To complete the final design vector the design standard variable and remaining survivability variables not used in a design standard category are either added as a variable or included into existing system architectures. In addition to the design standard variable secondary deck guns are added as a survivability variable and decoys were added to the ASW and EW system architectures. The final design vector, provided in **Table 4-10**, grew from a baseline of 1944 designs to 23328 designs. If each design standard variable is included into the trade space the number of designs grows geometrically to approx. 24 million designs which is computational prohibitive considering the pending process constraints in modeling and simulation for each design.

Design Variable	Defined Variable Range
Design Standards*	Commercial Mixed Specification - Low Mixed Specification - High Naval Combatant Standards
Main Gun	57mm 76mm
Secondary Gun*	None 1 - 30mm 2 - 30mm
SUW Missile	None 8x Harpoon Missiles
AW System	None Low: IMS Combat System, TRS-3D & ESSM High: Mini-Aegis Combat System, 16-Cell VLS, SPY, & SM2
ASW System	Low: Small Sonar, Torpedo, Fire Control, Decoys* High: Large Sonar, Torpedo, Towed Array, Nixie*, Fire Control, Decoys*
EW System	None Low: SEWIP BLK I (ES Only) with Chaff Decoys* High: SEWIP BLK III with Nulka Decoys*
Fuel Weight	500 MT 800 MT 1200 MT
Installed Power	30 MW 50 MW 100 MW
Helo	None 1 Helicopter Embarked 2 Helicopters Embarked

*Survivability Design Variable

Table 4-10: SSC Final Design Vector

4.5 SSC Design Synthesis and Baseline Performance

To analyze the final design vector a computer model was developed using MathWorks' MATLAB to perform design synthesis and to assess each design's performance. The computer model forms the tradespace by full-factorial combination of the final design vector. Collected design variable SWaP-C data is entered into the model for the design synthesis process determining each design's weight distribution and displacement, max electrical load, maximum speed, and endurance range. Survivability performance data, P_D, P_{DT}, and P_{KE} values, were also entered into the model for each applicable design variable for use in the survivability assessment model in a later step. The model applies the multi-attribute utility function and the cost estimation model to each design to determine baseline performance. Finally, the process model determines Pareto optimal designs for the capability-cost tradespace.[4]

4.5.1 Design Synthesis

The design synthesis model determines ship weight distribution, total ship displacement, and maximum power load. From these parameters the ship's endurance range based on displacement, fuel weight, and installed power is calculated. Ship's maximum speed is calculated based on power available minus loads and the ship's displacement.

4.5.1.1 ASSET Models

Parametrics used in computer modeling were generated from concept models in ASSET. Twelve models were created, one for each design standard arrangement and for each installed power design variable. The design standard variable determines the structural design by determining the number of transverse bulkheads, girder supports, frame spacing, and type of stiffeners. For every design, the hull structural material was constant with the hull being high strength steel and the super structure and mast being aluminum. The propulsion plant was designed with an integrated power system (IPS) architecture using three gas turbine engines. The power rating of each gas turbine determined the amount of installed power. The design standard variable also designated propulsion equipment location, either co-located in the same machinery room or located in separate machinery rooms. From these models weight, power, speed, and range data was obtained for development of parametrics.

4.5.1.2 Weight Distribution

Design variable load weight, in metric tons, is collect by single digit ESWBS and variable loads added. The synthesis processes each design in the tradespace and sums the single digit ESWBS weights in addition to an assumed baseline set of weights. Hull structural weight is determined from a parametrically determined percentage of the ESWBS 200-700 weights and the F00 load weight taking into account the design standard variable. The design standard influences the structural weight through the number of watertight subdivisions and structural strength standards. The parametrically determined structural weight embodies an "inside-out" hull design where the

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[4] MATLAB function to determine multi-dimensional Pareto sets was graciously provided by the MIT Systems Engineering Advancement Research Initiative (SEAri). Website: seari.mit.edu

hull structure is determined by the internal loads. The sum of the collected single-digit ESWBS weights gives the total displacement. The tradespace produces designs that are 4350 to 7142 MT in total displacement.

Design # 23328		
W100	Hull Structure	2474
W200	Propulsion Plant	1534
W300	Electric Plant	290
W400	Command & Surveillance	367
W500	Auxiliary Systems	550
W600	Outfit and Furnishings	373
W700	Armament	104
F00	Loads	1450
Total Displacement		7142 MT

Table 4-11: SSC Design Weight Distribution for Design #23328

4.5.1.3 Maximum Electrical Loading

Maximum electrical loading is determined from the summed design variable electric loads in addition to an assumed base load. The base load accounts for standard ship electrical loads minus the design variable loads. The base load power across all designs is 3400 kW. The tradespace includes designs with max electrical loading ranging from 3470 kW to 4640 kW.

4.5.1.4 Maximum Ship Speed

The SSC's propulsion plant configuration is assumed to be an integrated power system for all designs. An IPS is an all-electric propulsion plant architecture where ship propulsion is an electrical load. Maximum ship speed is determined from the power available, which is equal to the installed power minus the maximum power loading. Ship power and speed have a cubic relationship where the power required to achieve a certain speed is a function of the speed cubed. (Woud and Stapersma 2008)

$$P = C \cdot V_{Ship}^{3}$$

Model experiments conducted in ASSET created ship designs of varying displacements from a common hull form. From these models, power-speed data was obtained and modeled as power-law functions with power available as the independent variable, illustrated in Figure 4-1. Maximum ship speed is determined with power available as the input and interpolated from the determined design total displacement relative to the displacement speed-power curves. Speeds observed in the trade study range from 26 to 38 knots.

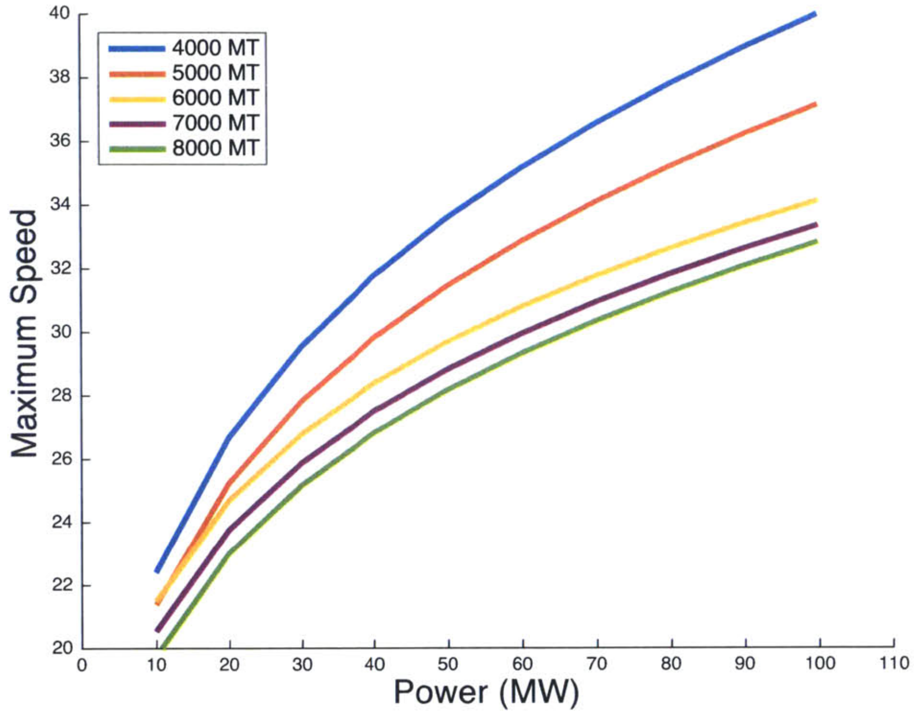


Figure 4-1: SSC Power-Speed Curves for Various Displacements

4.5.1.5 Endurance Range

ASSET model experiments performed in Section 4.5.1.4 were used to collect data points for installed power, fuel weight, displacement, and the calculated endurance range. Installed power and displacement variables were chosen to account for the approximate rate of fuel consumption and ship resistance respectively. A multiple linear regression was determined for each installed power variable with fuel weight and displacement as independent variables and endurance range as the dependent variable. Regression error based on the collected data points is less than ±3%.

$$RANGE_{30MW} = 4812.9 + 8.7766(FUELWT) - 0.799(DISP)$$

$$RANGE_{50MW} = 3127.4 + 8.7533(FUELWT) - 0.522(DISP)$$

$$RANGE_{100MW} = 1543.8 + 6.1685(FUELWT) - 0.235(DISP)$$

4.5.2 Estimated Ship End Cost

The cost estimation model uses the single-digit ESWBS weight distribution determined by the design synthesis model and applies a set of CERs to determine the estimated total ship end cost. The cost model is comparable to a navy Class F feasibility estimate as it relies on single-digit

ESWBS weights. The CERs for the cost model were developed using the analogy estimation method using cost data from similar ship classes. The cost model assesses ships designed to different standards, which have different material and labor costs. CER's for the different design standard variables are analogous to ship classes designed to the same standard. Analogous CERs to the commercial category were developed from T-AKE class and to the combatant category developed from DDG-51 class. The CERs developed account for basic construction (materials and labor) and GFM costs. The cost model predicts total ship end unit costs in the trade study between \$217M and \$906M.

4.5.3 Baseline Performance

The baseline SSC tradespace, shown in **Figure 4-2**, evaluates each designs utility and estimated ship cost. The process applies the multi-attribute utility function to each design accounting for design variables and the performance parameters determined through design synthesis. The cost estimation model is applied to each design's single-digit ESWBS weight distribution. All 23328 designs are plotted in terms of capability and cost. Each point in the tradespace cloud represents a unique ship design.

The baseline SSC tradespace has 81 Pareto optimal designs, shown in red in **Figure 4-2**, that give the best capability for a given cost. This set of optimal designs is characterized by commercial standard designs representing a range of capabilities. After approx. \$450M in ship cost there is a point of diminishing returns where there is no increase, or a decrease in some cases, in capability with cost. This is due to increasing design standards and resulting increase in cost with no accompanied increase in capability. Another effect of decreasing capability at higher costs is a result of decreased mobility performance with increasing loads and ship displacement.

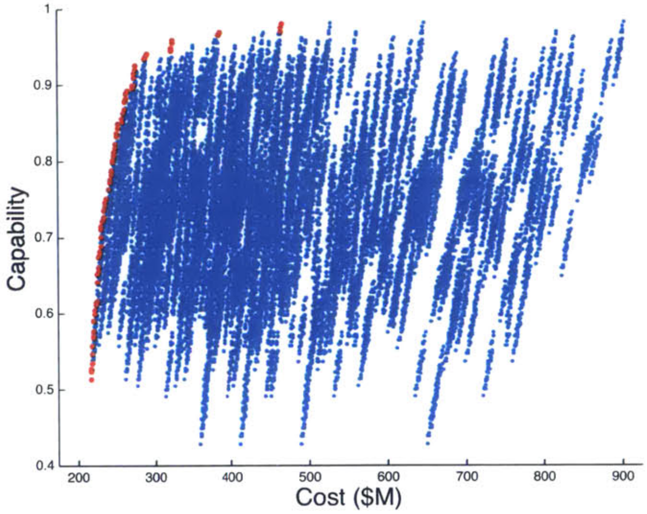


Figure 4-2: Baseline SSC Tradespace

4.6 SSC Survivability Assessment

The Pareto optimal designs of the baseline tradespace demonstrate the need to incorporate design survivability performance into a multi-dimensional tradespace. The survivability assessment model iteratively processes each design in the tradespace and determines susceptibility, vulnerability, and recoverability performance through Monte Carlo analysis. The analysis determines probability distributions for the amount of capability remaining in each context relative to the number of hit simulations to derive probabilities of hit, kill given a hit, and recovery.

4.6.1 SSC Susceptibility Assessment

The first step in determining susceptibility performance is to model the design variable systems within a self-defense system of systems framework composed of parallel detection and tracking systems in series with parallel destroying or evasion systems. This framework for the SSC, Figure 4-3, illustrates the path dependent nature of a system in preventing an impact, or the probability of hit avoidance. The framework is separated by threats defined by the activity profile with the left hand column of systems being detection and targeting systems and the right hand column being destroying or evasion systems relative to the type of threat. The P_{DT} and P_{KE} values used for the tradespace study are provided in Table E-1.

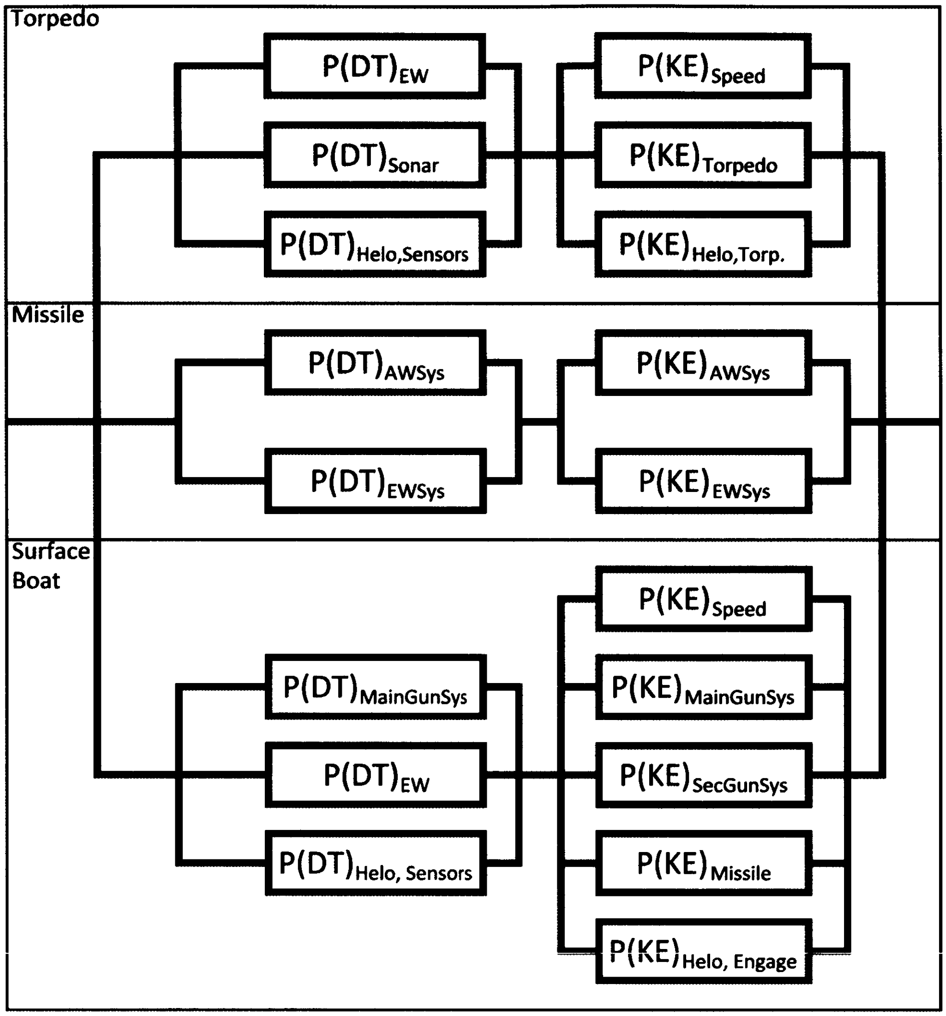


Figure 4-3: Hit Avoidance System of Systems Framework

To determine susceptibility performance the survivability assessment model determines what systems each design has and figures the deterministic probability of hit avoidance for each threat for every design. A simulation is run with randomly determined threat engagements regulated by the threat activity profile. For each engagement a hit is determined with respect to the P(Detection) and the P(Impact) or the compliment of the P(Hit Avoidance). The number of hits recorded relative to the number of simulations determines the probability of hit for the design. The distribution for the P(Hit) for the entire tradespace of designs using the littoral threat environment and targeted mission survivability requirements is provided in Figure 4-4. The distribution was fit to a lognormal distribution and shows a mean P(Hit) across the tradespace of approximately 22%.

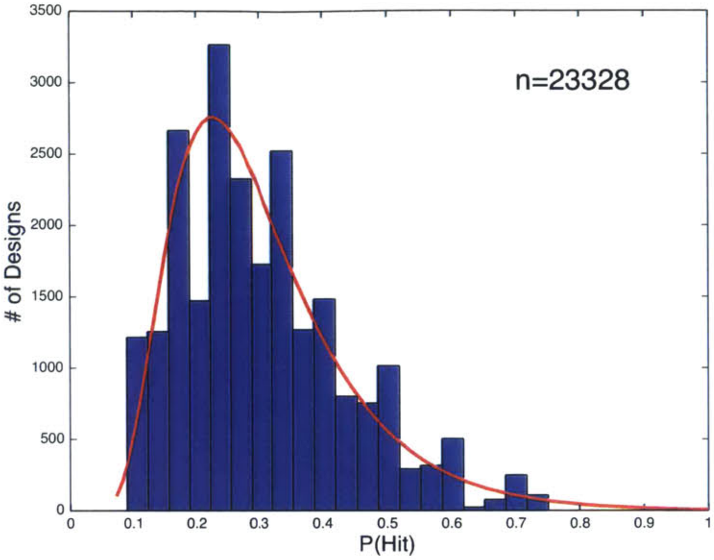


Figure 4-4: Distribution for P(Hit)

4.6.2 SSC Vulnerability and Recoverability Assessment

The survivability assessment model performs the vulnerability and recoverability assessments concurrently by Monte Carlo analysis. The model conducts hit simulations on each design where the hit location determines the amount of lost capability. The amount of lost capability depends on the physical arrangement of the design variables in addition to the vulnerability reduction and recoverability enhancement variables. Recall from the final design vector that the vulnerability reduction and recoverability enhancement variables are collated into the design standard variable. The post-hit and post-recovery utilities are determined with the multi-attribute utility function.

For the MATLAB model to conduct hit simulations the physical arrangements of the ship internals must be known. In naval architecture, ship arrangements are dependent on multiple design considerations but, for the SSC trade study, depend mainly on the design standard variable. The design standard variable determines the watertight subdivision, the number of and separation of machinery rooms, and the number of fire zones. Four physical arrangements were determined for the SSC trade study. Each design was assigned an arrangement determined by its design standard. The arrangement for the SSC combatant design is provided in Figure 4-5. The remaining SSC detailed design arrangements are provided in Figure E-7.

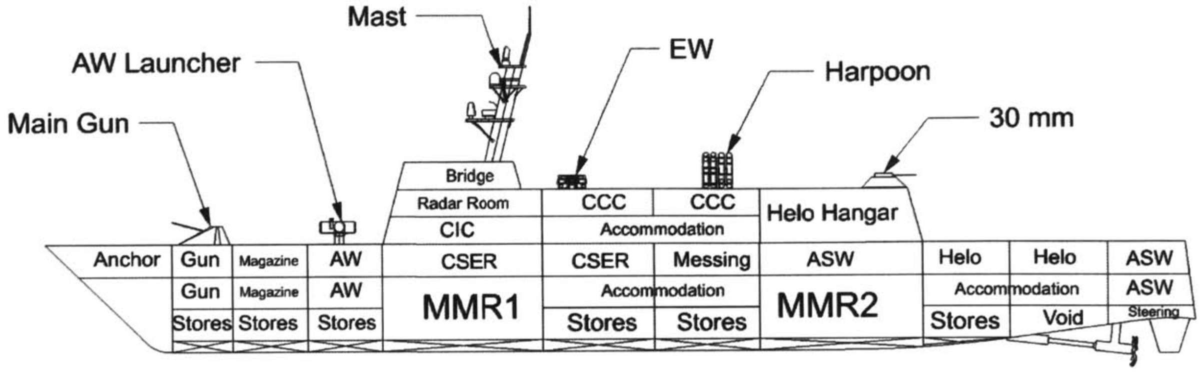


Figure 4-5: Arrangements for SSC Combatant Design

Each arrangement diagram, beginning with commercial, represents increasing levels of vulnerability reduction. The commercial arrangement has four watertight subdivisions, no fire zones, and one large engine room for all propulsion equipment. The major compartments bound by the watertight bulkheads are larger, more open, spaces that can be subdivided. The single machinery room presents a large vulnerability, as a hit in this room would result in a complete loss of mobility and electrical power resulting in a complete loss of mission capability. The subdivided spaces within a subdivision are not considered watertight. The mixed low specification arrangement has six watertight subdivisions, no fire zones, one main machinery room and a separate auxiliary machinery room for separated auxiliary propulsion equipment. The mixed high specification arrangement has eight watertight subdivisions, four fire zones, and two separated main machinery rooms each containing half of the propulsion plant equipment. The combatant arrangement has ten watertight subdivisions, four fire zones, and two separated main machinery rooms similar to the mixed-high arrangement. The difference between mixed-high and combatant being that the mixed-high arrangement only has structural fire zones for damage containment where the combatant arrangement has the structural fire zones and redundant fire fighting systems (seawater and ventilation) within each zone.

The process model, with the design arrangements known, simulates one thousand hit points on each design. The hit locations are spread in a normal distribution both longitudinally and vertically for hits above the waterline and normal distributed longitudinally for UNDEX. Figure 4-6 illustrates a modeled ship arrangement with normally distributed hit locations. The mean of distributed hit points is shown with the black marker in the figure. Hit locations outside the boundaries of the ship were treated as air explosions.

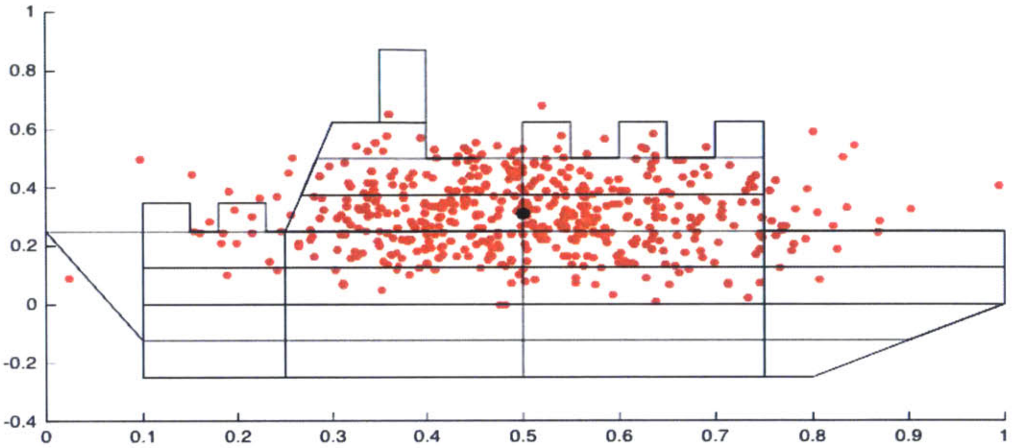


Figure 4-6: Computer Model of a Ship Arrangement with Normally Distributed Hit Locations

With each hit simulation the probability of kill given a hit and the probability of recovery is determined concurrently. The hit location determines lost mission capability and the post-hit utility is determined. Simultaneously, the amount of restored capability is figured and the post-recovered utility is determined. The post-hit utility and the post-recovered utility are determined using the multi-attribute utility function. If the post-hit utility is less than the required post-hit utility a kill resulting from the hit is recorded. Similarly, if the post-recovered utility is greater than the recovered capability requirement a recovery resulting from the hit is recorded. A distribution for the probability of kill and the probability of recovery is then determined. Figure 4-7 shows the distribution for P(Kill/Hit) for the entire tradespace using the littoral threat environment and the 50% post-hit capability survivability requirement with a mean P(Kill/Hit) of approximately 65%. The relatively high mean P(Kill/Hit) reflects a more demanding post-hit capability requirement of 50%. The mean P(Recovery) is 20% which is also relatively low and reflects the demanding 70% post-recovery capability requirement.

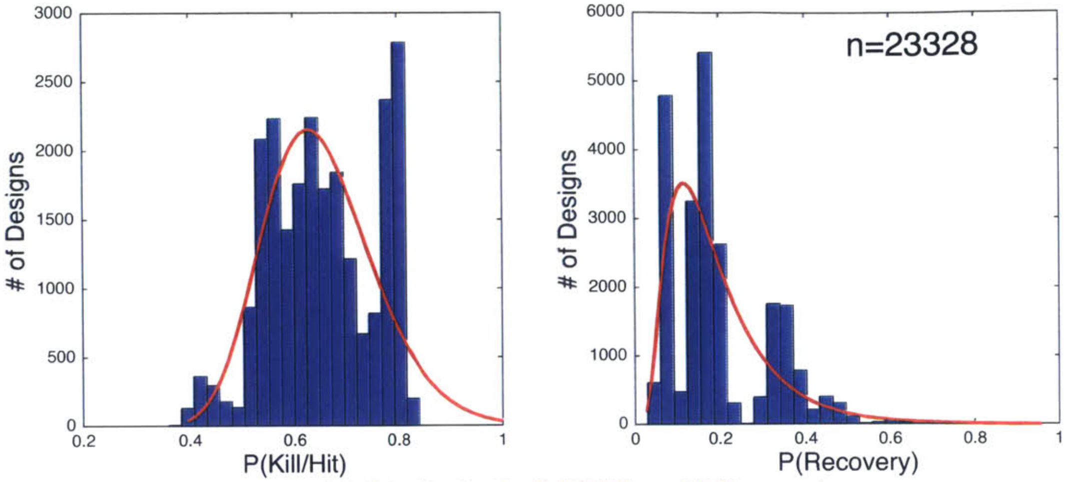


Figure 4-7: Distribution for P(Kill/Hit) and P(Recovery)

4.6.3 SSC Overall Survivability Assessment

The probability of survival for each design was calculated from the $P(Hit)$, $P\left({}^{Kill}/_{Hit}\right)$, and $P(Recovery)$ values calculated in the previous sections. An overall distribution was determined for the P(Survival) for all designs for each threat activity profile and each set of survivability requirements. The P(Survival) distribution for the littoral threat environment and 50%/70% survivability requirements tradespace is provided in Figure 4-8.

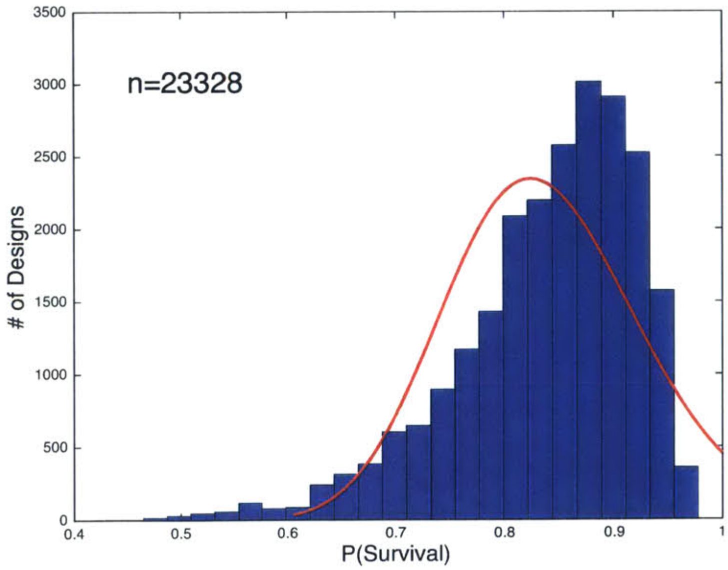


Figure 4-8: Distrbution for P(Survival)

Figure 4-9 shows the tradespace of survivability versus cost and 76 survivability-cost Pareto designs highlighted in red. The survivability-cost Pareto set represents designs with varying utilities ranging from 0.515 to 0.957. This Pareto set, similar to the utility-cost Pareto set, gives little insight to the overall capability-survivability performance of the tradespace.

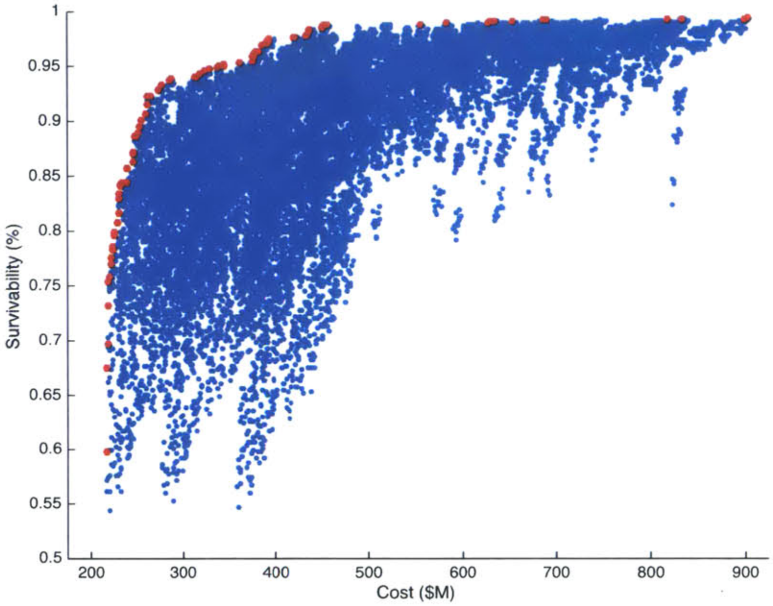


Figure 4-9: Survivability vs. Cost Tradespace

4.7 SSC Tradespace Exploration

4.7.1 Multi-Dimensional Tradespace Optimization

Illustrated in Figure 4-2 and Figure 4-9, the Pareto optimal sets of designs for the utility-cost and the survivability-cost planes do not provide sufficient insight for a ship designer seeking an economical balance of capability and survivability. The utility-cost designs ignore survivability and produce an optimal set of low survivability designs while the survivability-cost designs ignore capability and produce an optimal set of designs with capabilities that are not optimal and would not be considered for further analysis. The multi-dimensional optimized set of Pareto designs provides a cost-effective balance of capability and survivability. The multi-dimensional tradespace analysis provides a Pareto set optimizing capability, cost, and survivability and generates 247 3D optimal designs and 2097 5D optimal designs. Figure 4-10 shows the Pareto surface for each analysis overlaid on the utility-cost-survivability tradespace.

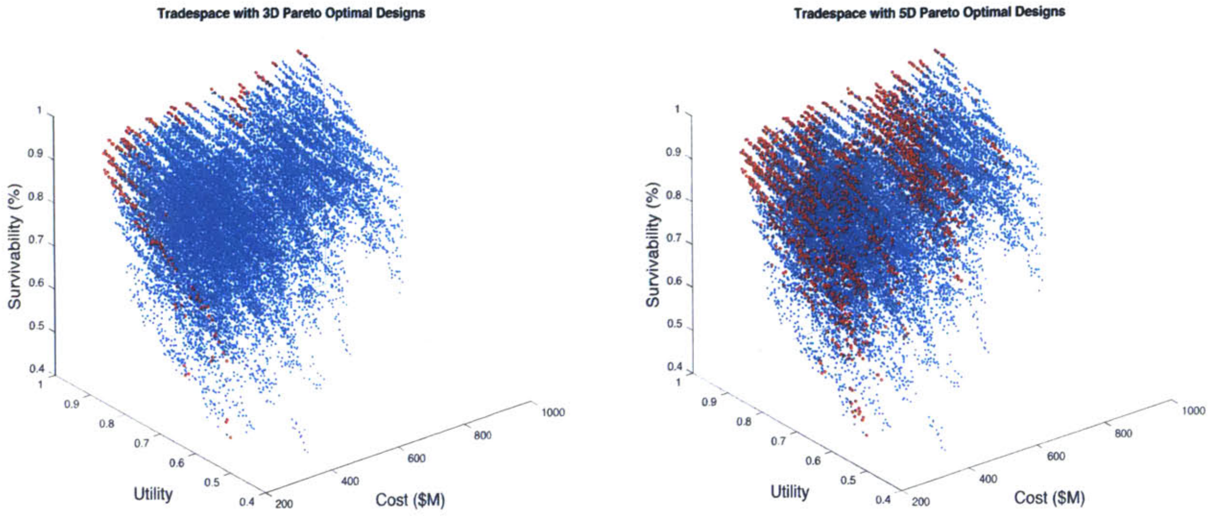


Figure 4-10: Utility-Cost-Survivability Tradespace with 3D and 5D Optimal Designs

The three-dimensional Pareto set is then projected onto the capability-cost plane, shown in Figure 4-11. The 3D Pareto set of designs projected onto a two-dimensional plane reveals additional optimal designs in the interior of the tradespace and allows for ease in navigating the optimal tradespace.

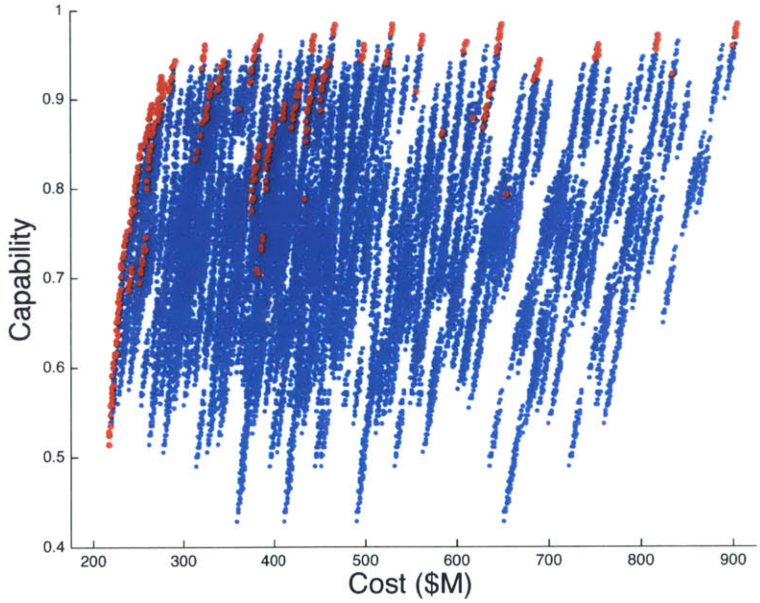


Figure 4-11: 3D Pareto Set Projected on Capability-Cost Plane

4.7.2 3D Tradespace Navigation and Exploration

The optimal designs, projected onto the capability-cost plane, are navigated using iso-capability bands or iso-cost bands. For example, designs with capability greater than 90% are isolated and, from the plot in **Figure 4-12**, runs of iso-capability or iso-cost bands can be analyzed for tradeoffs. An iso-capability and an iso-cost band are illustrated in red.

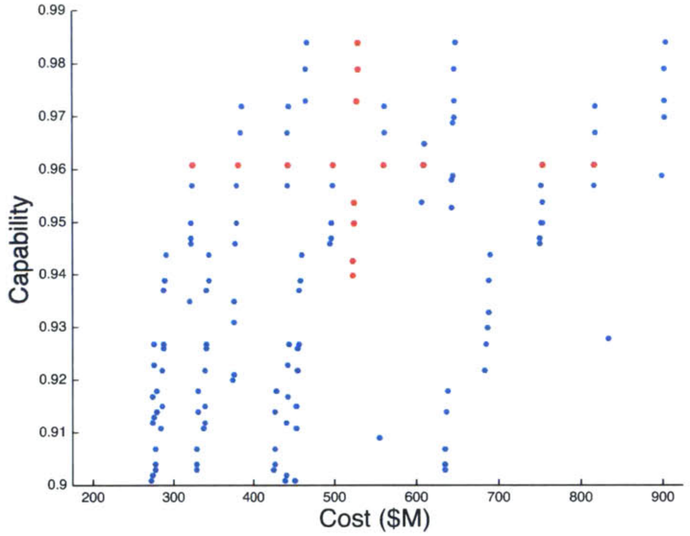


Figure 4-12: 3D Pareto Design with Greater than 90% Capability

Survivability-cost tradeoffs for an iso-capability line, 0.927, are shown in **Table 4-12**. The trades observed are in design standards, main and secondary gun systems, inclusion of an anti-ship missile, fuel weight and resulting endurance range, and the number of embarked helicopters. Consistent across this specific capability band are the ASW, AW, and EW warfare systems, and installed power. Capability-survivability tradeoffs for an iso-cost line, approx. $525M, are shown in **Table 4-13**. Similar tradeoffs are observed for the iso-cost line.

Design Variable	Variable Range	13773	21509	21510	13775	21511	21512	23252
Design Standard	Commercial-Combatant	Commercial	Commercial	Mixed-Low	Mixed-High	Mixed-High	Combatant	Combatant
Main Gun Type	57mm,76mm	76mm	76mm	76mm	76mm	76mm	76mm	57mm
Secondary Gun	None,1-30mm,2-30mm	2-30mm	None	None	2-30mm	None	None	2-30 mm
Harpoon Missile	No,Yes	Yes	No	No	Yes	No	No	No
AW System	None, TRS3D ,SPY	TRS3D/ESSM	TRS3D/ESSM	TRS3D/ESSM	TRS3D/ESSM	TRS3D/ESSM	TRS3D/ESSM	TRS3D/ESSM
ASW System	Low,High	High	High	High	High	High	High	High
EW System	None, Low, High	High	High	High	High	High	High	High
Fuel Weight	500, 800, 1200 MT	500	500	500	500	500	500	1200
Range	Calculated	3300	3300	3300	3300	3300	3300	7400
Power	30,50,100 MW	100	100	100	100	100	100	100
Helicopter	None, 1, 2 Embarked	1-Helo	2-Helos	2-Helos	1-Helo	2-Helos	2-Helos	2-Helos
Displacement	Calculated	5595	5696	5696	5595	5696	5696	6742
Speed	Calculated	36	36	36	36	36	36	34
Cost	Calculated	$276.9	$288.1	$341.8	$445.0	$457.1	$685.6	$834.5
Utility	Calculated	0.927	0.927	0.927	0.927	0.927	0.927	0.928
Susceptibility	Calculated	15.510%	11.040%	10.760%	15.860%	10.860%	10.960%	10.840%
Vulnerability	Calculated	72.100%	64.800%	57.800%	13.500%	16.000%	13.800%	11.800%
Recoverability	Calculated	5.700%	8.200%	16.400%	18.200%	16.800%	37.700%	51.000%
Survivability	Calculated	89.460%	93.440%	94.800%	98.250%	98.560%	99.060%	99.370%

Table 4-12: Demonstrated Survivability-Cost Tradeoffs for Iso-Capability Band (0.927)

Design Variable	Variable Range	13735	13751	13767	13775	22446	22438	22454
Design Standard	Commercial-Combatant	Mixed-High	Mixed-High	Mixed-High	Mixed-High	Mixed-Low	Mixed-Low	Mixed-Low
Main Gun Type	57mm,76mm	76mm	76mm	76mm	76mm	76mm	76mm	76mm
Secondary Gun	None,1-30mm,2-30mm	None	2-30mm	1-30mm	2-30mm	None	2-30mm	1-30mm
Harpoon Missile	No,Yes	No	No	Yes	Yes	Yes	No	Yes
AW System	None, TRS3D ,SPY	TRS3D/ESSM	TRS3D/ESSM	TRS3D/ESSM	TRS3D/ESSM	SPY/SM2	SPY/SM2	SPY/SM2
ASW System	Low,High	High	High	High	High	High	High	High
EW System	None, Low, High	High	High	High	High	High	High	High
Fuel Weight	500, 800, 1200 MT	500	500	500	500	800	800	800
Range	Calculated	3300	3300	3300	3300	4900	4900	4900
Power	30,50,100 MW	100	100	100	100	100	100	100
Helicopter	None, 1, 2 Embarked	1-Helo	1-Helo	1-Helo	1-Helo	2-Helos	2-Helos	2-Helos
Displacement	Calculated	5563	5579	5588	5595	6516	6515	6524
Speed	Calculated	36	36	36	36	34	34	34
Cost	Calculated	$441.4	$443.0	$444.3	$445.0	$443.6	$443.0	$444.3
Utility	Calculated	0.902	0.917	0.923	0.927	0.957	0.961	0.967
Susceptibility	Calculated	16.41%	16.04%	15.59%	15.86%	9.38%	9.42%	9.50%
Vulnerability	Calculated	12.10%	12.30%	12.80%	13.50%	54.10%	55.30%	56.50%
Recoverability	Calculated	19.90%	19.00%	17.50%	18.20%	18.70%	15.60%	16.00%
Survivability	Calculated	98.41%	98.40%	98.35%	98.25%	95.87%	95.60%	95.49%

Table 4-13: Demonstrated Capability-Survivability Tradeoffs for Iso-Cost Band (~$445M)

The tradeoff tables ultimately inform a ship designer which design variables should be incorporated into a design and which design variables should be considered for further analysis and potential tradeoff. The consistent variables indicate the relative insensitivity of those design variables to the capability or cost constraints. For this example, the analysis demonstrates the sensitivity of the design standard, anti-ship missile, large and small caliber deck guns, and fuel weight variables are to changes to the environment and requirements.

4.7.3 5D Tradespace Navigation and Exploration

The five-dimensional utility-cost-susceptibility-vulnerability-recoverability tradespace analysis produced 2097 optimal designs. The large set of 5D designs is approx. 9% of the tradespace and lacks refinement, illustrated in **Figure 4-13**, which is not conducive to efficient exploration of design tradeoffs for survivability. The primary reason for lack of refinement in a five-dimension Pareto set is the large variance between the susceptibility, vulnerability, and recoverability values for each design. The large variance between the principle survivability components suggests a limitation of the probabilistic assessment model where strength in one of the three component survivability assessments can "carry" the overall survivability value and mask poor performance in the other two survivability components. The survivability variance effect is observed in the tradeoff tables in Section 4.7.2 where the low cost commercial designs have acceptable susceptibility performance but poor vulnerability and recoverability performance. The effect of the survivability variance precluded use of the 5D Pareto set exploration for the trade study.

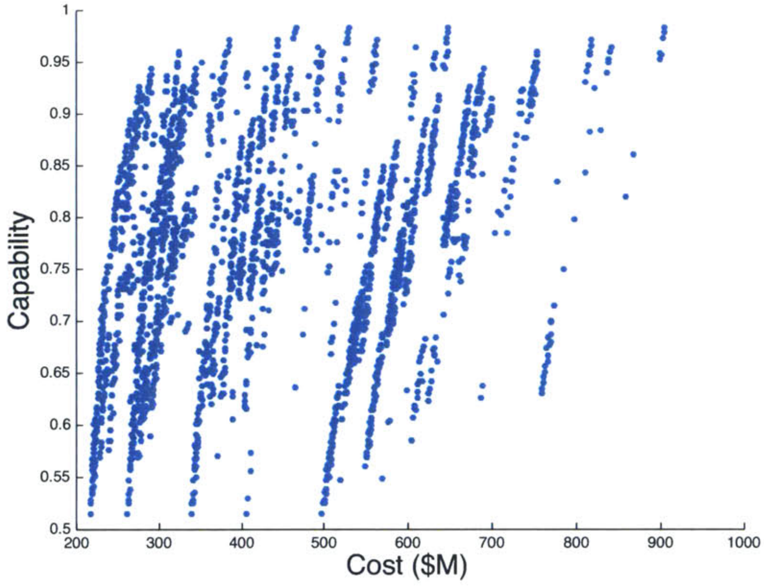


Figure 4-13: 5D Pareto Optimal Designs Projected onto Capability-Cost Plane

5 RESULTS AND ANALYSIS

This section analyzes the trade study results from the considered threat activity profiles and survivability requirements. Two activity profiles modeled after two projected operating environments and two sets of survivability requirements generate four sets of data. Four data runs were conducted on the static tradespace model for a comparison of results and a discussion of the insights the process provides for a future SSC. Sensitivity of the design variables, threat activity profile, and survivability requirements on the trade study results is discussed in greater detail. The reasoning for requiring survivability being considered in a three-dimensional tradespace is also discussed.

5.1 Survivability Tradespace Exploration Results

5.1.1 Tradespace Sensitivity to Design Standards

The design standard variable is shown to have an immense influence on survivability and cost. The optimal designs determined in the baseline SSC tradespace are an obvious result of considering design standard changes in the tradespace. Design standards have a substantial impact on cost with no change in ship mission capability. The resulting optimal capability-cost set reveals the most capable designs at the lowest cost producing an optimal set of exclusively commercial designs with relatively weak survivability performance, specifically weak vulnerability and recoverability performance. This effect necessitates the need for the survivability performance parameter to be included in a multi-dimensional tradespace to reveal cost effective designs that are capable and survivable. Figure 5-1 shows the same baseline SSC tradespace and Pareto optimal designs with the design standard shown in blue scale (Lighter: Commercial, Darker: Combatant).

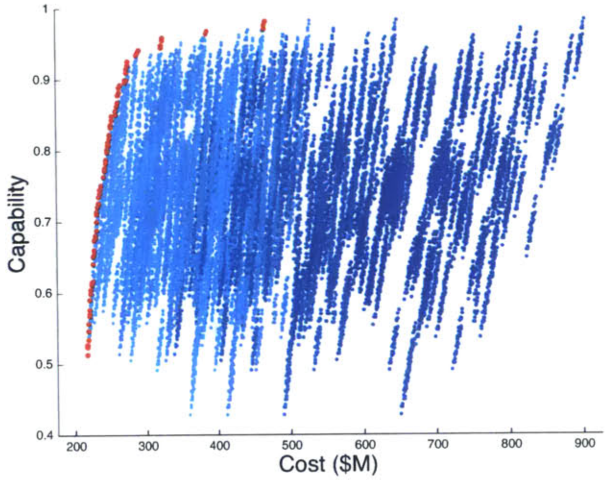


Figure 5-1: Baseline SSC Tradespace with Design Standards

Figure 5-2 shows the utility-cost plane with the two-dimensional and three-dimensional Pareto sets for a side-by-side comparison. The plots illustrate the expansion of the optimal design space by incorporating the survivability dimension. Initially, the optimal utility-cost set of designs only included commercial ship designs but now includes additional designs throughout the interior of the capability-cost tradespace representing all of the design standard variables. At this juncture, the three-dimensional set of optimal designs can be further analyzed to determine the cost premium that must of paid for increased survivability for a constant level of capability all while maintaining a cost-effective balance of capability and survivability.

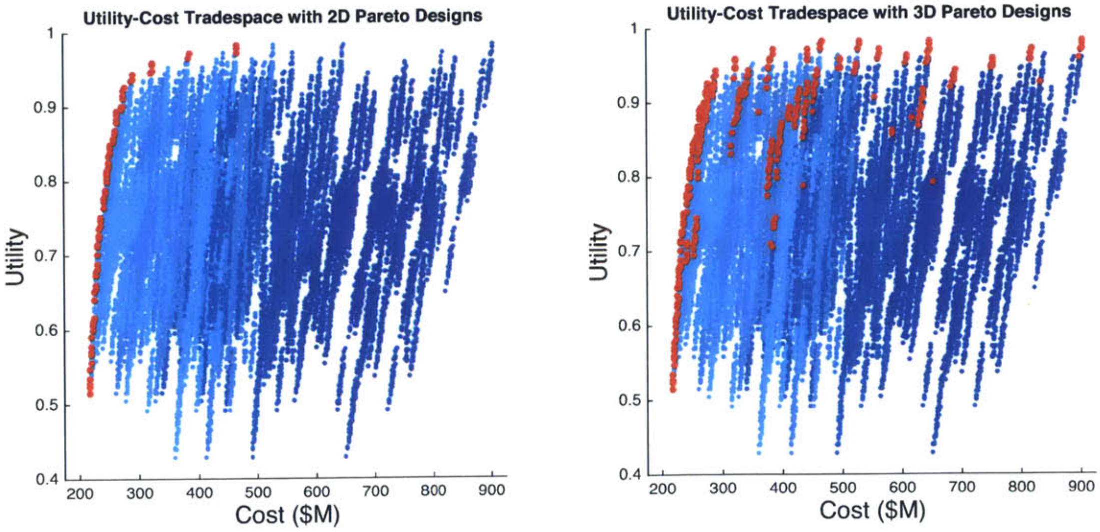


Figure 5-2: 2D & 3D Pareto Designs on Utility-Cost Plane for Side-by-Side Comparison

The design standard variable also has a prominent effect on the survivability-cost tradespace. **Figure 5-3** shows the same survivability-cost tradespace shown in **Figure 4-9** with the design standard variable highlighted in blue scale in addition to the survivability-cost Pareto optimal designs. Observed from the figure is the overlapping nature of the varying design standards across the tradespace. The commercial designs dominate the low cost area of the Pareto frontier upwards to an inflection point, or "knee" in the curve. The higher survivability area of the Pareto frontier is a mix of standards from the mixed-low specification to combatant after a point of diminishing returns.

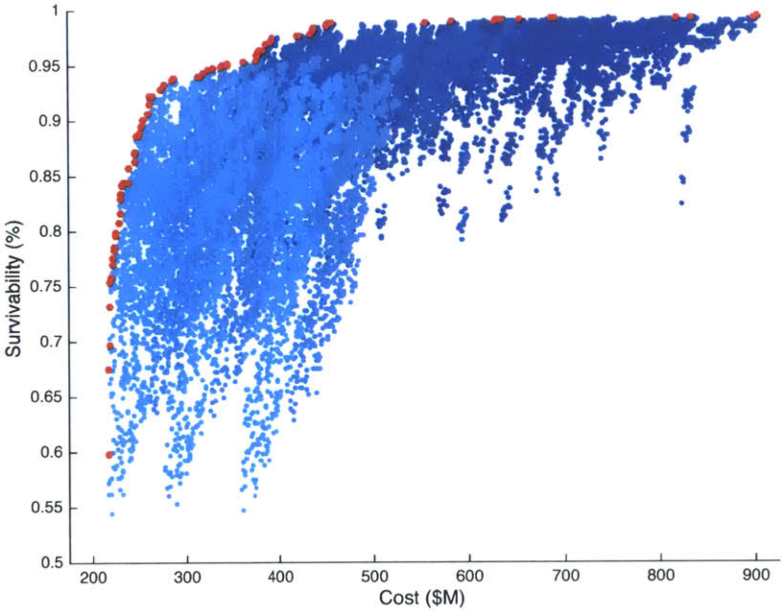


Figure 5-3: Survivability-Cost Tradespace with Highlighted Design Standard Variable

The three-dimensional Pareto set reveals designs at the extreme points of the areas of designs separated by design standard in blue scale. **Figure 5-4** shows the survivability-cost tradespace with the optimal 3D Pareto set and **Figure 5-5** characterizes the survivability-cost Pareto front. **Figure 5-6** further illustrates this point with polygon regions defined by design standard including the 3D Pareto set to demonstrate the optimal designs on the boundaries of the design standard regions. The plots reveal that optimally survivable designs exist within the mixed-standard regions of the survivability-cost tradespace.

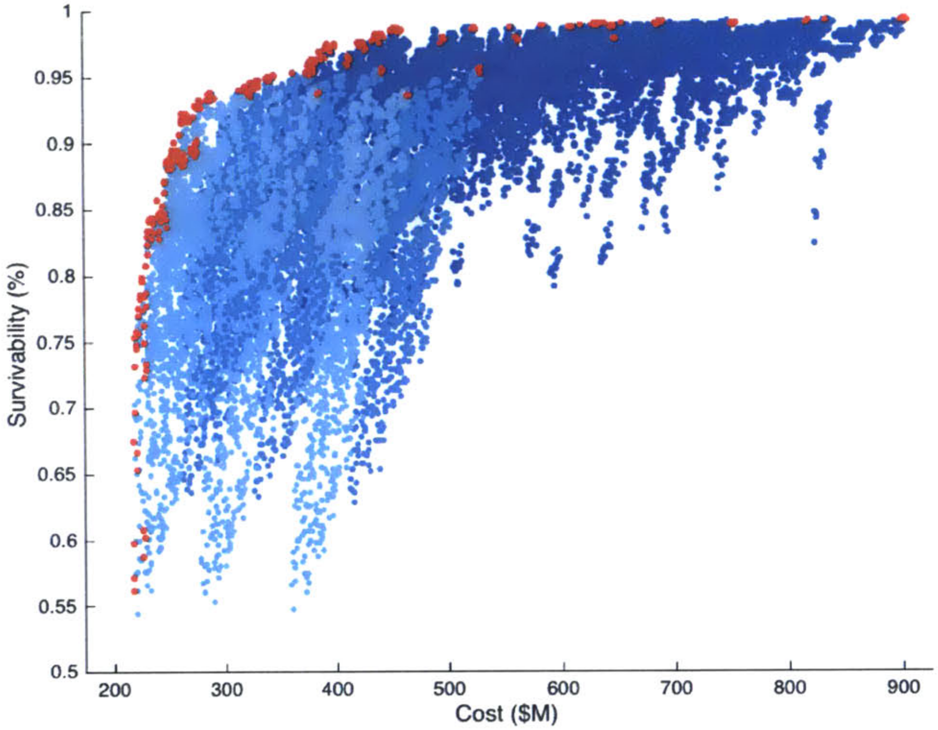


Figure 5-4: Survivability-Cost Tradespace with 3D Pareto Set and Highlighted Design Standard

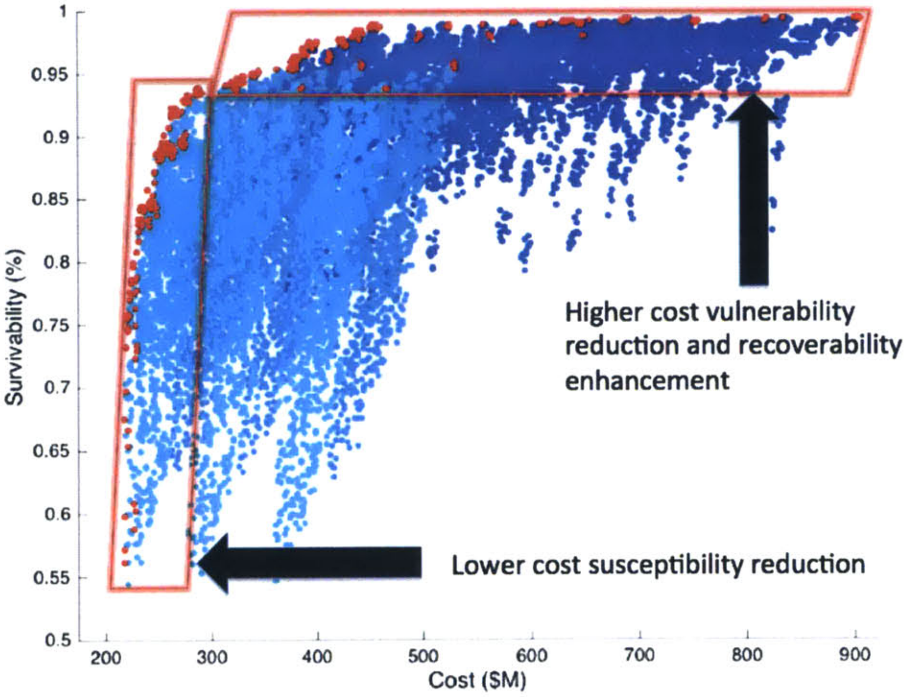


Figure 5-5: Survivability-Cost Tradespace with Cost Regions

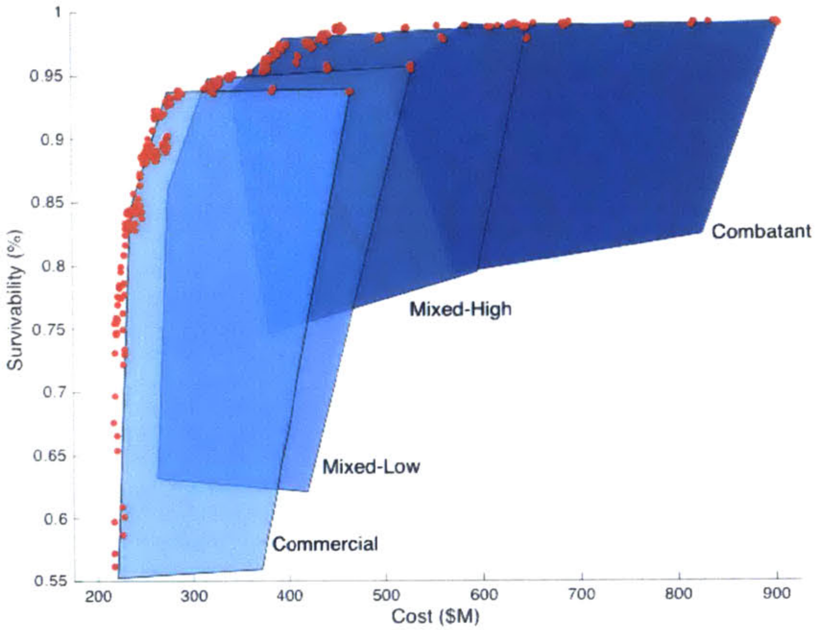


Figure 5-6: Survivability-Cost Tradespace with Design Standard Regions Showing 3D Pareto Optimal Designs on Region Boundaries

5.1.2 Tradespace Sensitivity to Operating Environments and Survivability Requirements

The defined threat activity profile and the requirements defining post-hit and post-recovery capability affect the outcome of the survivability assessment analysis. The four data runs considered are the littoral environment or open ocean, blue water environment each considered with the overall 50%/70% requirement or the targeted capability requirement.

Running the simulation with both the littoral and blue water environment threat activity profiles and 1000 simulations per design results in the P(Hit) distributions provided in Figure 5-7. The P(Hit) distribution only depends on the operating environment and resulting threat activity profile. The figures illustrate the effect of changing the threat activity profile from littoral to blue water shifting the P(Hit) distribution to the left. This effect demonstrates the increase in susceptibility for a ship operating in a littoral environment.

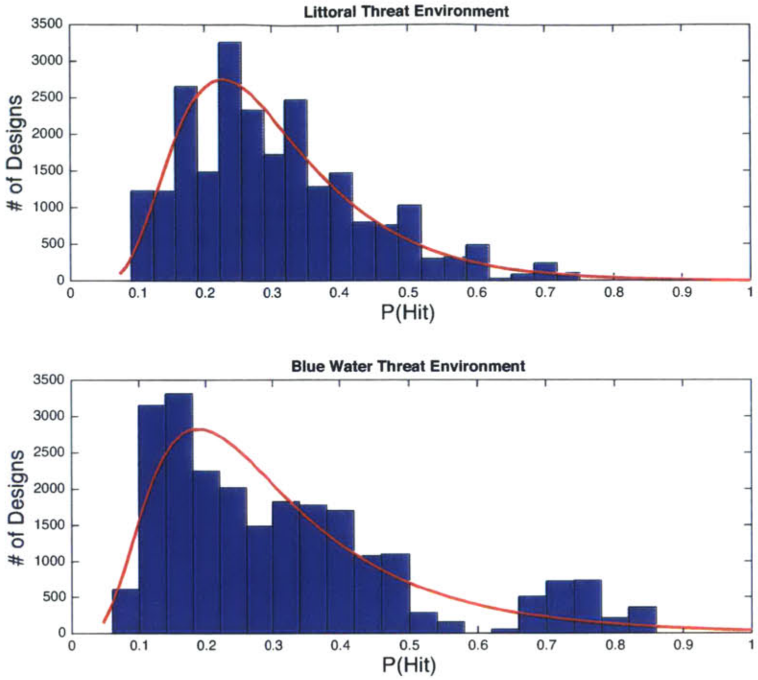


Figure 5-7: SSC Tradespace P(Hit) Distributions

Figure 5-8 shows the distributions for the probability of kill given a hit for both sets of survivability requirements discussed in Section 4.1.3 and both sets of threat environments. The figures illustrate that the threat environment and the survivability requirements can result in varying levels of acceptable overall capability after a hit as evident by the distribution shifting to the left with a lower mean P(Kill/Hit). The littoral environment with the overall 50% post-hit and 70% post-recovery survivability requirements gives the worst vulnerability performance. The results from a particular ship trade study can give ship designers insight into how the design will perform in different environments with different requirements. Similarly to vulnerability, recoverability results demonstrate the same effect of varying performance based on the threat environment and survivability requirement.

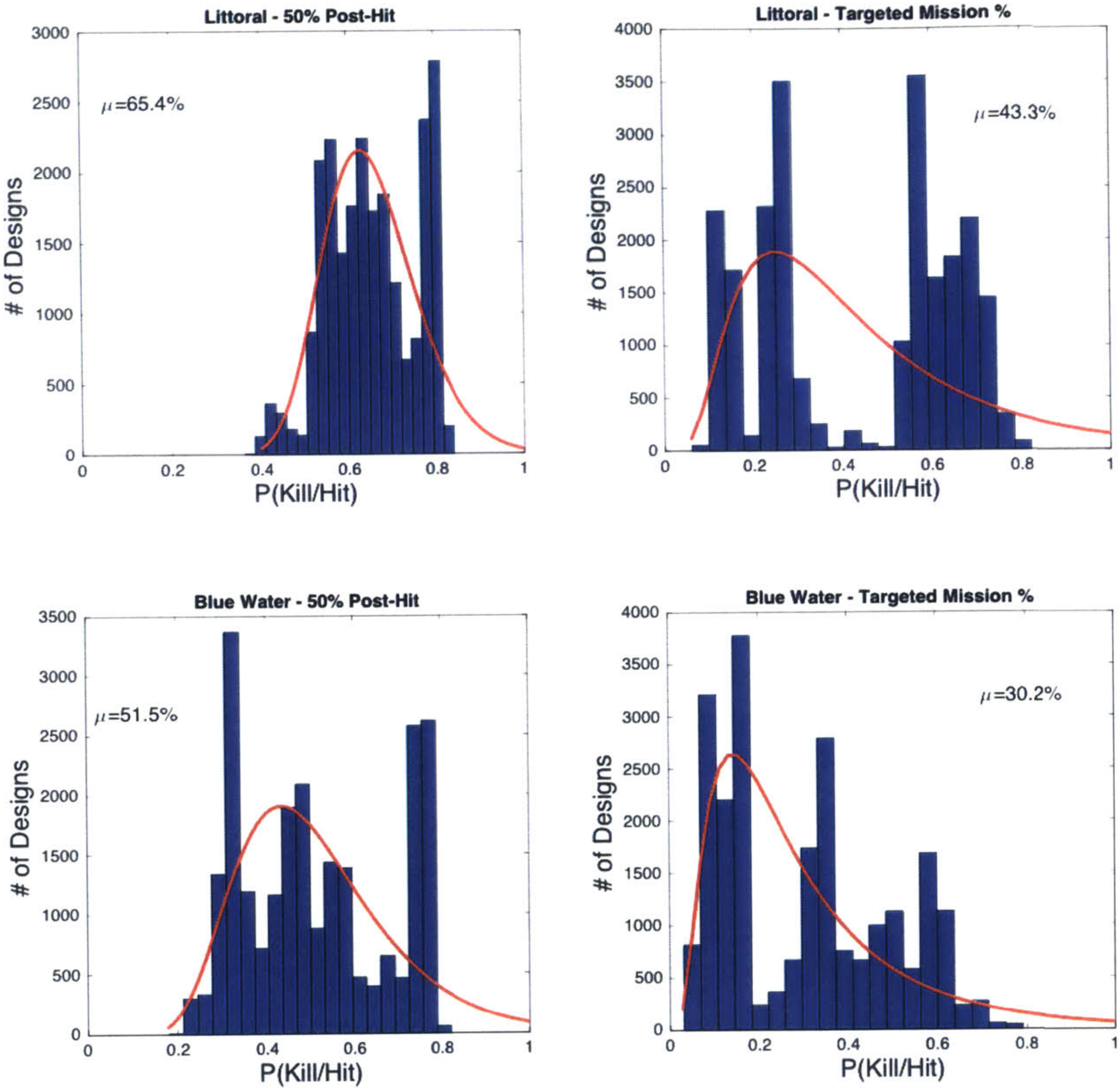
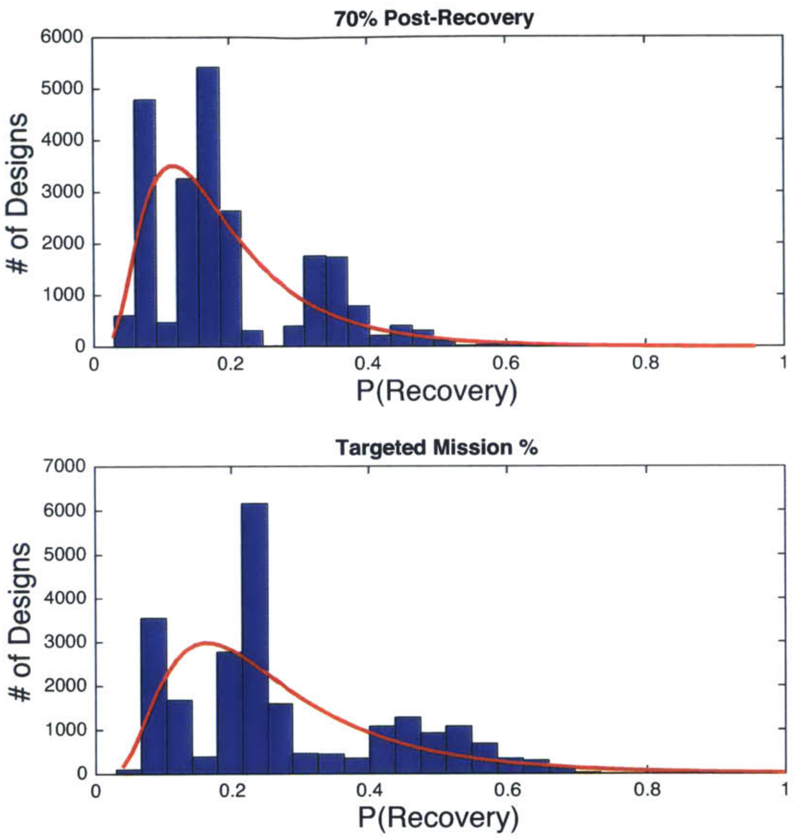


Figure 5-8: Distribution for P(Kill/Hit) for Threat Environment and Survivability Requirement

The P(Recovery) distributions showed little sensitivity to the threat activity profile with the post-recovery capability requirements having the greatest effect on the outcome of the recoverability assessment. The type or severity of damage, determined by the threat activity profile, is not as important as the amount of capability that can be recovered by the ship.

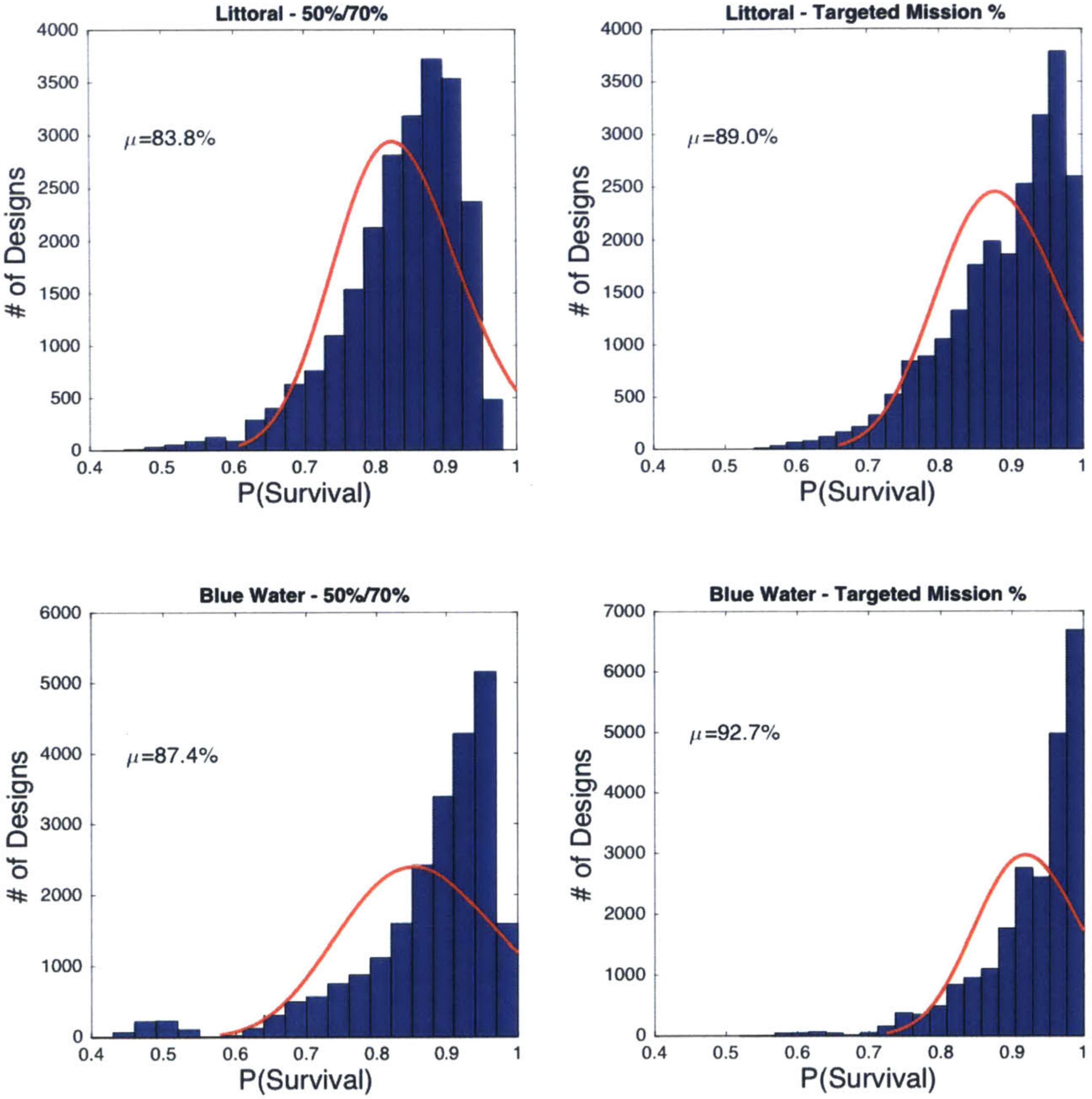

70% Post-Recovery

Targeted Mission %

Figure 5-9: Distributions for P(Recovery) by Survivability Requirement

The P(Survival) distributions and their respective mean values are provided in Figure 5-10. The effects of the threat activity profile and survivability requirements on the P(Survival) distributions are similar to the P(Kill/Hit) distributions. The figure shows how overall survivability performance can vary based on the operating environment and survivability requirements. The effect of the threat activity profile and survivability requirements on the survivability-cost tradespace can be seen in Figure 5-11. These figures show that, as the threat environment and survivability requirements get less stringent, the tradespace shifts up and begins to saturate the 99%-100% survivability performance region. This effect can cloud the survivability performance of vast regions of the tradespace and dictates the need to design to the most demanding operating environment and rigorous of survivability requirements.

In summary, the threat activity profile and survivability requirements affect the outcome of the individual survivability assessments and overall survivability performance. Susceptibility performance was only affected by the threat activity profile, as the goal defined by susceptibility performance is to prevent a ship hit. Vulnerability performance was affected by both the threat activity profile and the post-hit capability requirement. The type of threat and its damage mechanism determines the magnitude and extent of damage while the capability after damage determines if the ship is "killed" due to a hit. Recoverability performance was only affected by the post-recovery capability requirement.


Littoral - 50%/70%

Littoral - Targeted Mission %

Blue Water - 50%/70%

Blue Water - Targeted Mission %

Figure 5-10: Distribution of P(Survival) by Threat Environment and Survivability Requirements

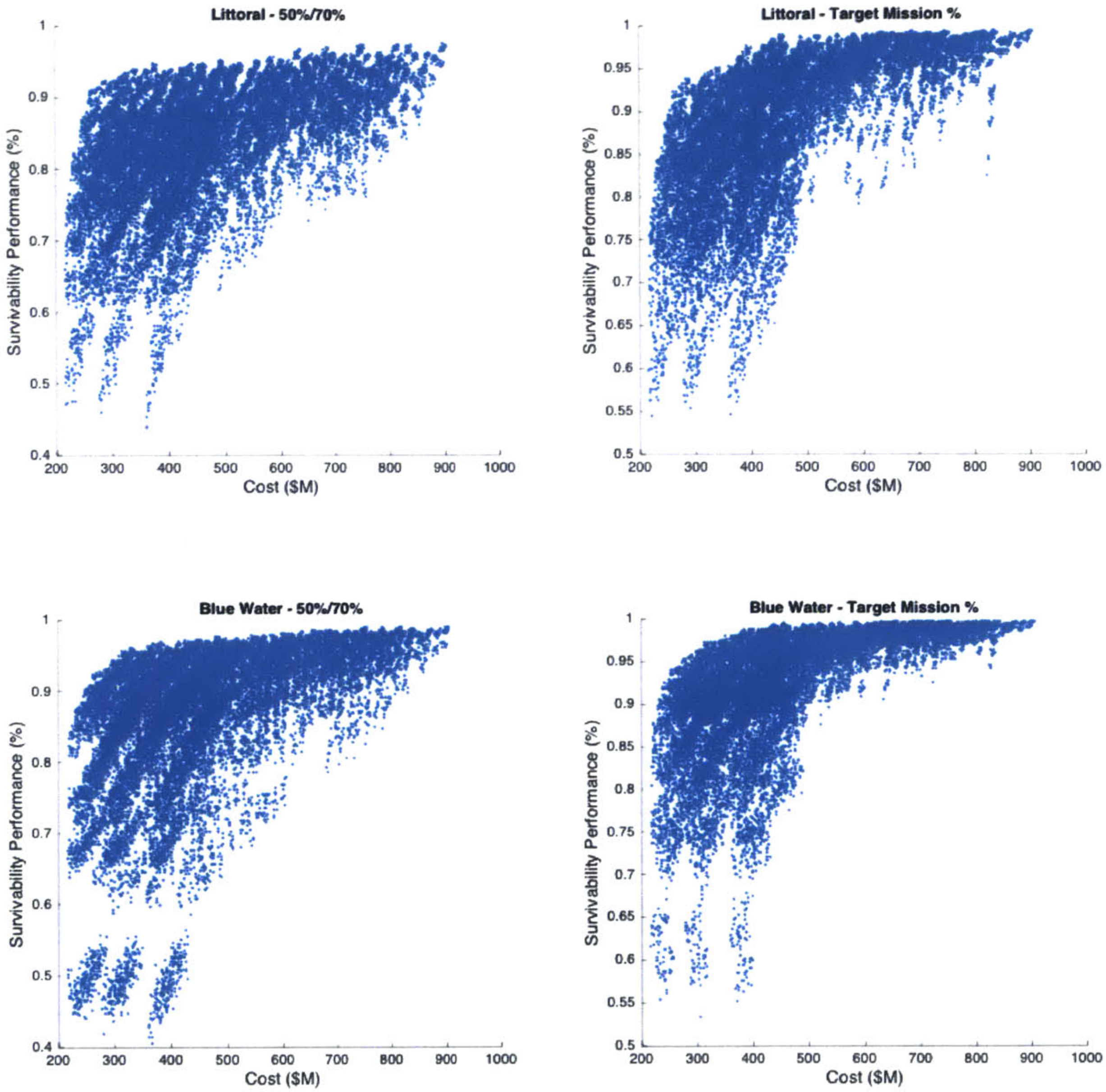


Figure 5-11: Survivability-Cost Tradespace by Threat Environment and Survivability Requirement

5.1.3 Insights for Survivability Tradeoff Trends

5.1.3.1 Tradespace Navigation Tradeoff Trends

Survivability tradeoffs are explored by analyzing the optimal Pareto surface of designs projected onto the capability-cost plane. When using iso-capability bands designs can be considered for survivability-cost tradeoffs and when using iso-cost bands designs can be considered for capability-survivability tradeoffs. The 3D Pareto optimal set of designs collectively has the optimal balance of capability, survivability, and cost. Due to the fact that only the 3D Pareto optimal set of designs is being considered, trends in the survivability-cost and capability-survivability tradeoffs are identified. When exploring an iso-capability band, survivability performance always increases with cost. When exploring an iso-cost band, capability-survivability tradeoffs have an inverse relationship. For a constant cost, capability increases as survivability decreases, or vice-versa, with tradeoffs.

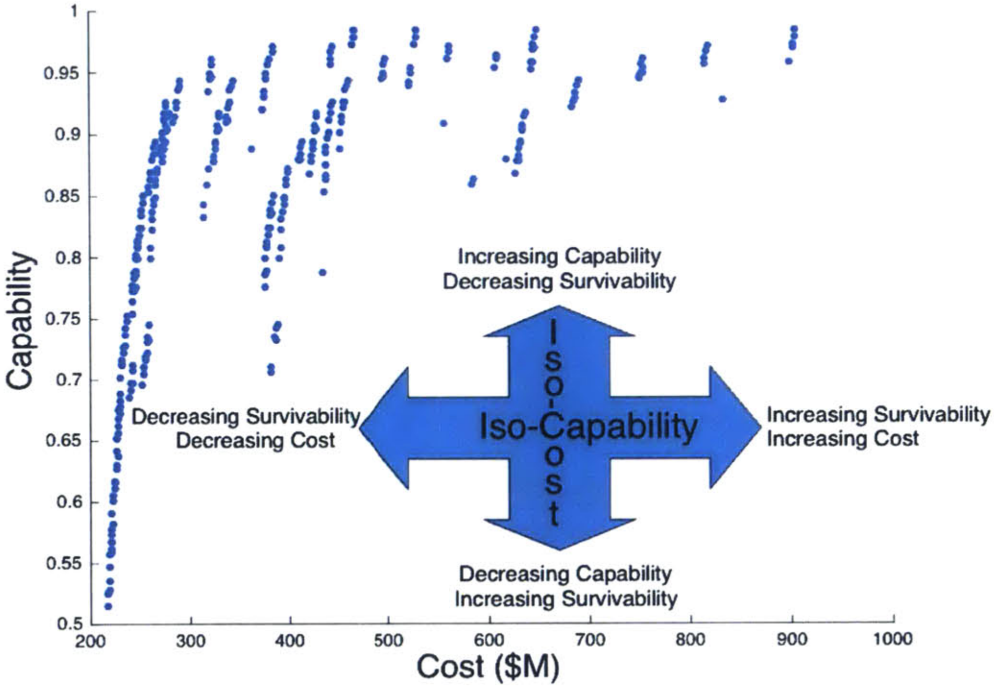


Figure 5-12: Capability-Cost Plane Tradeoff Trends

Further analysis of the iso-capability bands reveals trends in survivability performance. Iso-capability survivability performance is characterized by high susceptibility performance on the lower cost designs with increases in vulnerability and recoverability performance with increases in ship cost. This is due to the inherent dependency between ship mission systems and susceptibility performance. Survivability increases are achieved with additional investment in vulnerability reduction and recoverability enhancement. An "off-axis" trend line with either slightly changing cost or capability has a mixed effect. Understanding the survivability-cost and survivability-capability trend vectors allows for a path dependent method of navigating the tradespace, illustrated in Figure 5-13. The trend vectors allow navigation of the optimal tradespace within affordability limits. Navigation can be accomplished in two parts, by desired increase in cost followed by capability-survivability tradeoffs. In Figure 5-13, moving from points 1 to 2 in the shows a desired increase in cost for an increase in survivability and moving from points 2 to 3 shows in increase in capability for an acceptable decrease in survivability.

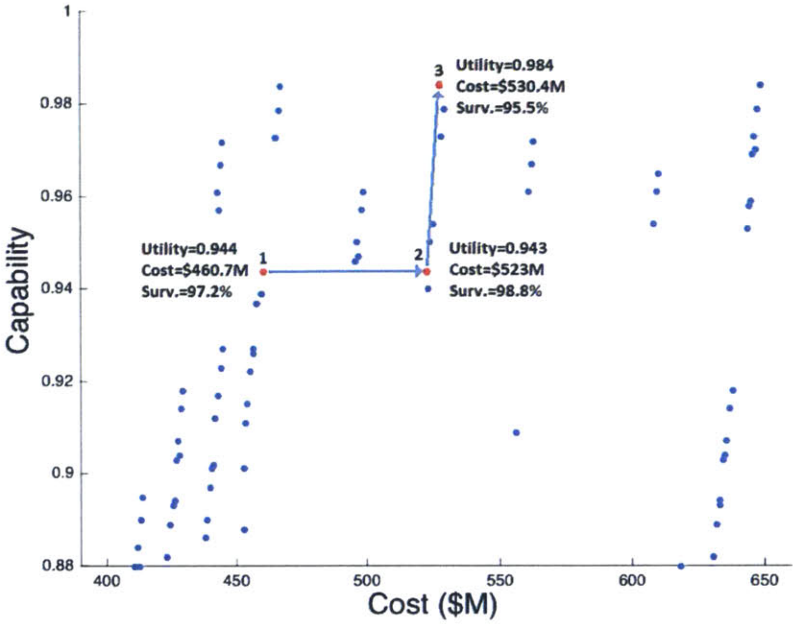


Figure 5-13: Path Dependent Tradespace Navigation

5.1.3.2 Capability-Survivability-Cost Relationships

Analysis of several iso-capability bands for survivability-cost performance reveals a capability dependent behavior for the relationship between survivability and cost. Within each iso-capability band the increase in survivability relative to the increase in cost diminishes as capability increases. At lower capability levels increased spending on survivability results in greater survivability returns than at higher capability levels. Figure 5-14 illustrates the increase in survivability for the increase in cost relative to a constant capability level. The iso-capability bands were analyzed for the littoral operating environment and targeted mission survivability requirements.

The survivability-cost trends in Figure 5-14 are dependent on many factors. Design of a combatant class, ship mission capability, the projected operating environment and expected threats, and the survivability requirements all have an effect on the survivability-capability-cost relationship. The logarithmic relationship between increased survivability and increased cost also demonstrates the inherent dependency between a naval combatant's capability and its survivability. The survivability-cost relationship may change for a non-combatant class whose mission requirements are not combat related. The relationships can also be explained by additional investment in susceptibility reduction relative to vulnerability reduction and recoverability enhancement. With lower capability designs, survivability can be improved with relatively low-cost susceptibility reduction efforts. As capability increases and susceptibility decreases, additional investment is required in vulnerability reduction and recoverability enhancement through higher-cost design standard improvements.

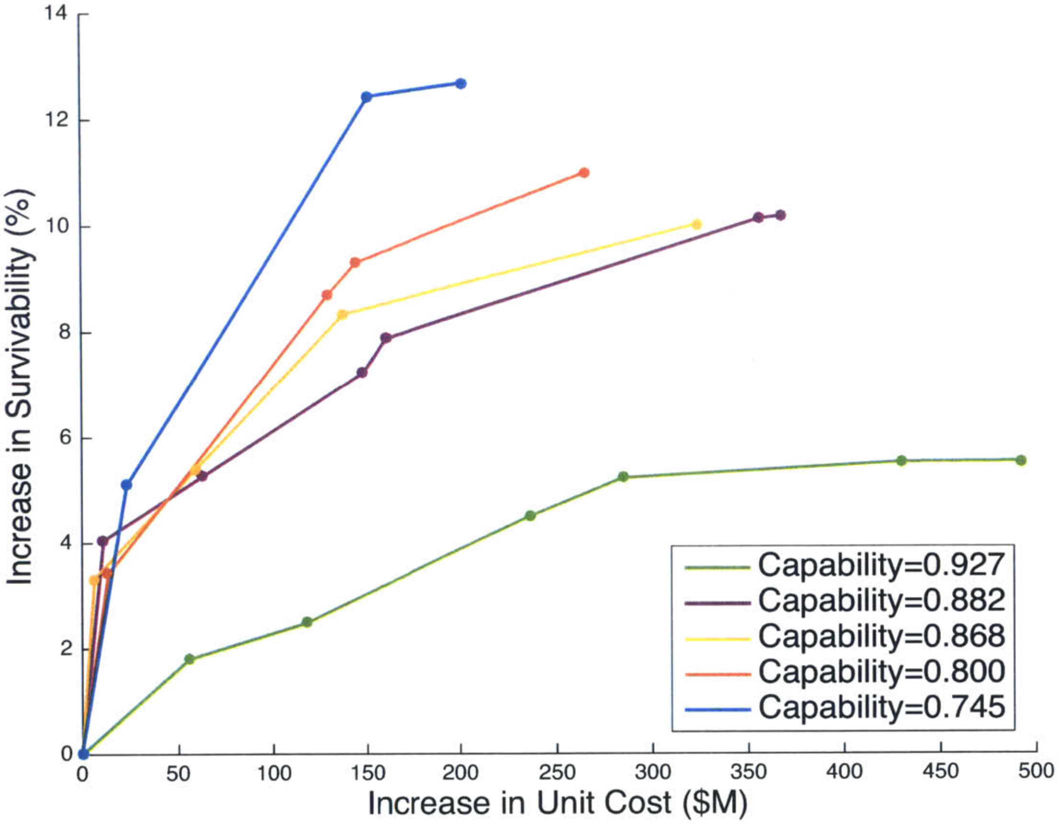


Figure 5-14: Increase in Survivability for Increasing Cost Relative to Desired Capability

5.1.3.3 Design Standard Sensitivity and Tradeoff Trends

The design standard variable has a massive impact on survivability and cost but also has great influence on potential tradeoffs. Reducing the design standard one variable step can provide an opportunity to increase capability for relatively constant cost and survivability performance. To demonstrate this effect a relatively constant cost cluster in Figure 5-12 is analyzed. The design cluster being considered is shown in Figure 5-15 and the tradeoff table provided in Table 5-1.

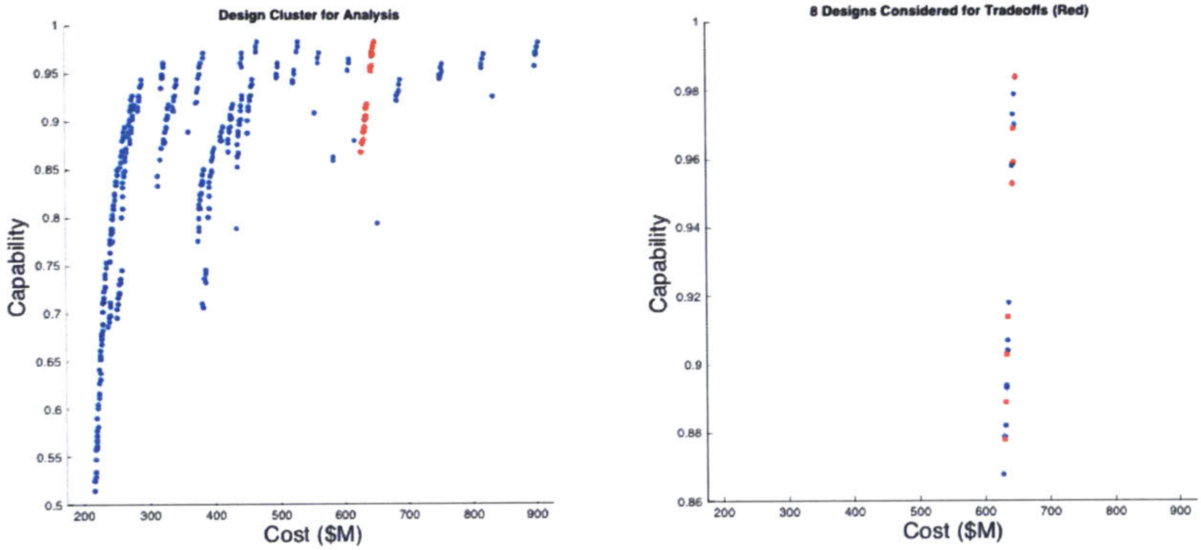


Figure 5-15: Relatively Constant Cost Cluster (Red) for Design Standard Analysis

Design Variable	Variable Range	18924	18948	18928	18952	23323	23287	23311	23303
Design Standard	Commercial-Combatant	Combatant	Combatant	Combatant	Combatant	Mixed-High	Mixed-High	Mixed-High	Mixed-High
Main Gun Type	57mm,76mm	57mm	57mm	76mm	76mm	57mm	76mm	76mm	76mm
Secondary Gun	None,1-30mm,2-30mm	1-30mm	1-30mm	1-30mm	1-30mm	2-30mm	None	None	2-30mm
Harpoon Missile	No,Yes	No	Yes	No	Yes	Yes	No	Yes	No
AW System	None, TRS3D ,SPY	TRS3D/ESSM	TRS3D/ESSM	TRS3D/ESSM	TRS3D/ESSM	SPY/SM2	SPY/SM2	SPY/SM2	SPY/SM2
ASW System	Low,High	High	High	High	High	High	High	High	High
EW System	None, Low, High	High	High	High	High	High	High	High	High
Fuel Weight	500, 800, 1200 MT	500	500	500	500	1200	1200	1200	1200
Range	Calculated	4800	4800	4700	4700	7300	7300	7300	7300
Power	30,50,100 MW	50	50	50	50	100	100	100	100
Helicopter	None, 1, 2 Embarked	2-Helos	2-Helos	2-Helos	2-Helos	2-Helos	2-Helos	2-Helos	2-Helos
Displacement	Calculated	5239	5256	5280	5296	7104	7112	7128	7127
Speed	Calculated	31	31	31	31	34	34	34	34
Cost	Calculated	$630.0	$632.3	$634.7	$637.0	$644.8	$645.3	$647.4	$646.9
Utility	Calculated	0.878	0.889	0.903	0.914	0.958	0.959	0.970	0.973
Susceptibility	Calculated	11.95%	11.61%	11.54%	11.53%	9.32%	9.54%	9.38%	9.47%
Vulnerability	Calculated	13.50%	13.30%	12.60%	13.40%	13.00%	12.70%	12.80%	14.50%
Recoverability	Calculated	47.60%	48.10%	46.50%	47.70%	20.20%	18.80%	18.20%	18.10%
Survivability	Calculated	99.16%	99.20%	99.22%	99.19%	99.03%	99.02%	99.02%	98.88%

Table 5-1: Design Standard Tradeoff Table

The design cluster considered in Figure 5-15 has slightly increasing cost ranging from $630 to $647M per ship with a relatively constant survivability at approx. 99±0.2%. As capability increases few tradeoffs are made within the combatant designs with slight increase in capability. When the design standard variable is reduced from combatant to mixed-high standards several more up-select tradeoffs are made that improve capability by 10%. Down-selecting the design standard allowed for the inclusion of the "mini-Aegis" AW mission system, increased fuel capacity and range, and up-selection of propulsion plant power and resulting maximum ship speed. These up-selected systems improve mission capability for relatively constant cost and survivability. The survivability tradeoff occurs in susceptibility and recoverability. Susceptibility performance is improved with improved mission systems while recoverability performance decreases with the design standard down-selection.

5.1.3.4 Threat Activity and Tradeoff Trends

The effect tradeoffs have on survivability performance is a function of the threat activity profile. The resulting survivability performance from tradeoffs is sensitive to the proportion of threat activities relative to each other. Asymmetric SUW attack probability within the littoral and blue water operating environments was relatively low. Tradeoffs in mission systems contributing to reduced susceptibility to an asymmetric SUW threat resulted in little change in susceptibility performance or changes within a small margin of error. This was due to the relatively low representation of the SUW attack probability within the activity threat profile. Observed in Table 5-1, tradeoffs in the first 4 designs occurred in SUW mission systems with little change in susceptibility or survivability. The up-selection of the AW system from fourth to fifth designs results in a more pronounced change in susceptibility as anti-ship missile attack was more represented in both threat activity profiles.

5.2 Multi-Dimension Analysis Discussion

5.2.1 Effect of Design Standards on Survivability

The standards a ship is designed to have a dominating effect on its vulnerability and recoverability performance. A naval combatant's mission systems are inherently linked to a ship's susceptibility performance requiring additional costs to be paid for improved survivability. Design standards define a ships structural strength, compartmentalization, and shock isolation of equipment. Design standards are survivability design variables that add considerable cost with no additional utility. The additional cost from design standards is due to increased material and labor costs, additional quality control and non-recurring engineering work.

In a traditional two-dimensional cost-benefit tradespace analysis, including design standards to improve survivability leads to the obvious result of an optimal set of entirely commercial designs. In this two-dimensional optimal set of designs, survivability performance is characterized by adequate ship susceptibility with relatively poor vulnerability and recoverability performance. For these designs, the ship's susceptibility performance sustains the overall ship survivability performance. Expanding the optimal set to include more survivable designs in a two-dimensional tradespace would require aggregating survivability performance into a value function or considering the tradespace in three dimensions. Combining survivability into the value function does not give an accurate representation of design performance. To explore other designs that have optimal survivability performance the tradespace must be considered three-dimensionally.

5.2.2 Incorporating Naval Ship Survivability into Tradespace Exploration

Incorporation of "ilities" in tradespace exploration was discussed by McManus, et al., 2007, and Richards, 2009, and was discussed in this thesis in Section 2.4.3. The "ility" describes the ability of a design or system to continue to provide value across different contexts. An "ility" can be ambiguously defined and difficult to assess. A design or system "ility" is not an independent performance parameter the way a design attribute is and should not be integrated into a utility function. Aggregating metrics for an amount value with metrics describing the ability to deliver value in different contexts over time is not an accurate representation of overall design performance. In concept ship design there is a need for exploring design spaces that consider different "ility" parameters, such as flexibility, modularity, or survivability, that indicate the performance of a ship design over time under varying conditions.

Survivability in naval ship design was defined in Section 1.3 but within an "ilities" framework is defined as "The ability of a ship to continue to provide a defined amount of mission capability after a disturbance while operating in a normal state, damaged state, and post-damage recovered state." Ship performance in these three states is, by definition, Susceptibility, Vulnerability, and Recoverability respectively. Aggregating survivability and capability within a two-dimension tradespace framework does not give an accurate indicator of ship design performance. Ship mission capability is a value metric where ship survivability is a description of providing mission capability in normal, damaged, and recovered states over time. Aggregating survivability into an overall value metric raises several issues. First, survivability is time dependent when traditional tradespace exploration is static. Second, weighting the value of survivability relative to capability is subjective and difficult to appropriately determine. Third, applying a utility curve to survivability levels effectively levies a survivability constraint instead of treating survivability as a parameter for potential tradeoff.

Performing active tradeoffs between capability and survivability relative to cost requires the multi-dimensional approach. Rather than aggregating survivability performance into a design's overall utility, survivability is added as a third dimension and then optimized. In three dimensions a Pareto surface of optimal designs is determined and evaluated for tradeoffs. The Pareto surface reveals designs that have an optimal balance of capability and survivability for a given cost.

5.2.3 Five-Dimensional Optimization and Survivability Variance

Discussed in Section 4.7.3, the variance between components of the survivability assessments produced an 5D optimal set of designs approx. 10 times the size of the 3D Pareto surface designs and precluded use of the five-dimensional optimization approach in the trade study. The 5D Pareto optimal set of designs analyzed for an iso-capability band, shown in Figure 5-16, shows that the set includes designs not optimal for the capability and survivability for a given cost. The iso-capability band considered for this analysis is the same iso-capability band in Table 4-12, 0.927 utility, with the same design conditions.

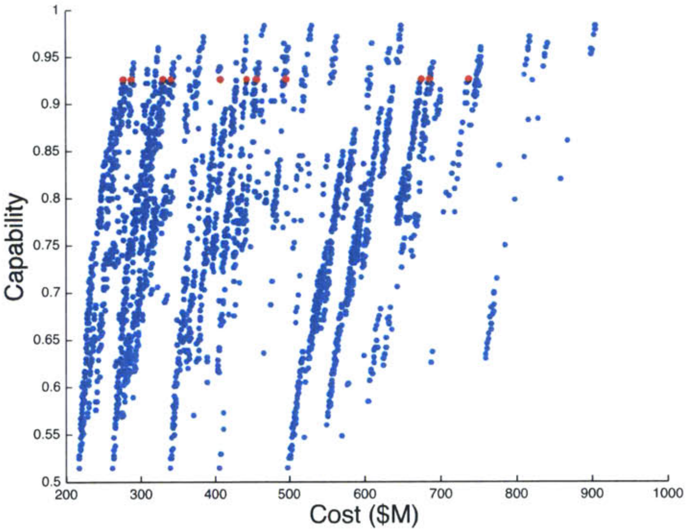


Figure 5-16: Iso-Capability Band in 5D Pareto Space

The iso-capability band tradeoffs, provided in Table 5-2, shows additional designs from the designs included in Table 4-12, highlighted in red, and have decreases in survivability for increases in cost, which are not optimal tradeoffs. The variance of the P(Hit), P(Kill/Hit), and (1-P(Recovery)) was calculated and provided for these designs.

Design Variable	Variable Range	13773	21509	13774	21510	22118	13775	21511	21287	13776	21512	14616
Design Standard	Commercial-Combatant	Commercial	Commercial	Mixed-Low	Mixed-Low	Mixed-Low	Mixed-High	Mixed-High	Mixed-High	Combatant	Combatant	Combatant
Main Gun Type	57mm,76mm	76 mm	76 mm	76 mm	76 mm	76 mm	76 mm	76 mm	76 mm	76 mm	76 mm	76 mm
Secondary Gun	None,1-30mm,2-30mm	2-30 mm	None	2-30mm	None	1-30 mm	2-30mm	None	2-30mm	2-30mm	None	2-30mm
Harpoon Missile	No,Yes	Yes	No	Yes	No	Yes	Yes	No	No	Yes	No	No
AW System	None, TRS3D ,SPY	TRS3D/ESSM	TRS3D/ESSM	TRS3D/ESSM	TRS3D/ESSM	TRS3D/ESSM	TRS3D/ESSM	TRS3D/ESSM	SPY/SM2	TRS3D/ESSM	TRS3D/ESSM	TRS3D/ESSM
ASW System	Low,High	High	High	High	High	High	High	High	High	High	High	High
EW System	None, Low, High	High	High	High	High	Low	High	High	Low	High	High	High
Fuel Weight	500, 800, 1200 MT	500	500	500	500	800	500	500	500	500	500	800
Range	Calculated	3300	3300	3300	3300	5000	3300	3300	3200	3300	3300	5100
Power	30,50,100 MW	100	100	100	100	100	100	100	100	100	100	100
Helicopter	None, 1, 2 Embarked	1 Helo	2 Helos	1 Helo	2 Helos	2 Helos	1 Helo	2 Helos	2 Helos	1 Helo	2 Helos	1 Helo
Displacement	Calculated	5595	5696	5595	5696	6171	5595	5696	6049	5595	5696	6038
Speed	Calculated	36	36	36	36	34	36	36	35	36	36	35
Cost	Calculated	$276.9	$288.1	$329.7	$341.8	$407.7	$445.0	$457.1	$496.1	$674.8	$685.6	$737.1
Utility	Calculated	0.927	0.927	0.927	0.927	0.927	0.927	0.927	0.927	0.927	0.927	0.927
Susceptibility	Calculated	15.510%	11.040%	15.660%	10.760%	12.480%	15.860%	10.860%	10.260%	15.930%	10.960%	15.460%
Vulnerability	Calculated	72.100%	64.800%	58.600%	57.800%	53.600%	13.500%	16.000%	25.700%	15.200%	13.800%	13.700%
Recoverability	Calculated	5.700%	8.200%	15.700%	16.400%	16.400%	18.200%	16.800%	18.600%	45.200%	37.700%	51.600%
Survivability	Calculated	89.460%	93.440%	92.260%	94.800%	94.410%	98.250%	98.560%	97.850%	98.670%	99.060%	98.980%
Variance	Calculated	0.1651	0.1690	0.1203	0.1364	0.1275	0.1503	0.1629	0.1400	0.0513	0.0833	0.0382

Table 5-2: Iso-Capability Band for 5D Pareto Design Tradeoffs

The effect of the survivability variance on the 3D Pareto set of optimal designs characterizes the component survivability performance across design standards. Survivability performance with low variance represents a design with balanced levels of susceptibility, vulnerability, and recoverability performance. The survivability variance suggests a limitation of the probabilistic survivability assessment method. The variance in survivability performance is observed to be large in commercial designs with high susceptibility performance and low vulnerability and recoverability performance. The high variance commercial designs characterize a "disposable" warship, which have relatively small likelihoods of sustaining a hit with relatively large likelihoods of sustaining a mission kill or total kill given a hit. The survivability variance is observed to decrease with additional investment as the design standard increases and vulnerability and recoverability performance improves.

6 SUMMARY AND CONCLUSIONS

This final section summarizes the process developed and applied to naval ship survivability, the processes applicability to DON acquisitions, proposes areas for future work, and draws conclusions from the process and its application in the SSC trade study.

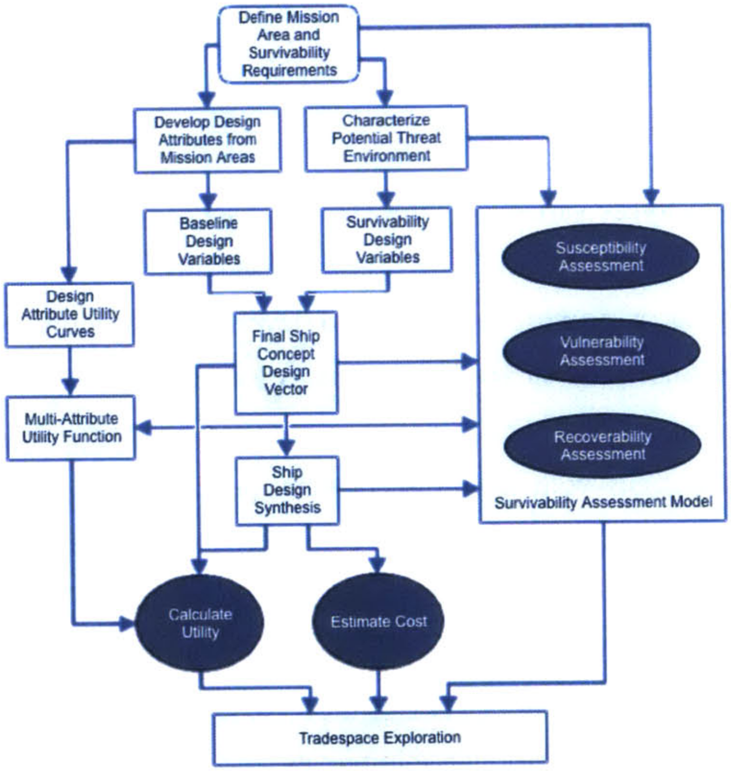


Figure 6-1: MATE for Survivability Applied to Naval Combatant Concept Design

6.1 Summary of Tradespace Process Applied to Naval Ship Survivability

This thesis presented the background and process to evaluate a new naval ship design for capability, survivability, and cost tradeoffs. The process for exploring the survivability tradespace for naval ship design was applied from the MATE for Survivability process developed by Richards, 2009. Applying Richards' MATE for Survivability process to a complex system of systems like a naval warship required process adjustments and modifications. The MATE for Naval Survivability process incorporates system level architectures in the form of combat mission systems designed in parallel and used on multiple ship platforms. The process treats these systems as discrete design variables and evaluated them through discrete design attributes that are derived from decision-maker system preferences. The process defines decision-maker requirements for normal operation and requirements in damaged and post-damage recovered states. A dynamic feature of the process models projected operating environments and their expected threats. Variations of different environments and threats can be considered and their effects on survivability performance understood. Considering survivability from the earliest stages of requirements definition enables early design systems tradeoffs and provides opportunities for affordability. Early identification of tradeoffs for survivability is in contrast to the practice of designing for capability then seeking cost-effective design features to add on to a design for improved survivability. As seen in the LCS case study in Section 1.4, design changes later in the design and acquisition process can result in severe cost overruns and ship program disruptions.

The MATE for Naval Survivability process uses the probability of ship survival, P(Survival), as the survivability performance metric and incorporates performance assessments of the three principle disciplines of naval survivability. Susceptibility, vulnerability, and recoverability are assessed probabilistically with the P(Hit), P(Kill/Hit), and the P(Recovery) all of which are determined through modeling and simulation. A probabilistic survivability assessment method is more applicable to naval ships and is modeled to simulate current Navy survivability assessment practices. The survivability assessment process in this tradespace model is unique from Navy survivability assessments in that it processes large numbers of concept designs rather than a relatively small number of detailed designs, which enables consideration of survivability tradeoffs earlier in the design process. The survivability assessment also combines the individual susceptibility assessments based on individual threats into one overall score so the global effects of tradeoffs for susceptibility reduction on survivability are understood. The combined susceptibility score represents susceptibility in a projected operating environment rather than susceptibility to a specific threat, which also enables informed survivability tradeoffs. The differences in the survivability assessment coupled with the need to consider survivability early in the design process necessitates the demand for a concept design survivability assessment tool within the U.S. Navy.

The tradespace exploration process mandates a three-dimensional analysis and optimization approach for identifying a Pareto surface of designs for further analysis. A three-dimensional analysis avoids combining capability and survivability into a single value function which results in a value function that does not accurately represent design performance. Additionally, combining capability and survivability into a single metric treats survivability as a design constraint rather than a performance parameter for tradeoffs. A three-dimensional analysis reveals optimal designs across the spectrum of survivability and cost rather than an optimal set that is designed entirely to commercial standards. Ultimately, a three-dimensional analysis approach enables survivability tradeoffs.

6.2 Tradespace Process within DON Acquisitions

Within Department of the Navy acquisitions the tradespace process outlined is valuable in the Materiel Solution and Analysis phase, specifically the AoA and CONOPS/CDD approval processes between requirements Gates 1 and 3. The process assists the organization conducting the AoA, NAVSEA 05D Future Surface Ship Concepts for example, to rapidly assess and navigate large tradespaces for gaining insight into tradeoffs that ultimately influence the design alternative selection. The tradespace process also assists the acquisitions process after gate 2 in defining a ship design's CONOPS through the insights gained from simulating the projected operating environment and its effect on survivability performance. Ultimately, the insights gained from the tradespace process assist a new ship program up to and including program approval at Milestone A and transition from program requirements to program acquisition.

6.3 Future Work

6.3.1 Optimized Design Standards

The process developed to explore the tradespace of naval ship survivability has limitations. These limitations, previously discussed for the SSC trade study, are computing power and available sensitive data. For the SSC trade study, computing power limitations were overcome by limiting the size of the tradespace. The tradespace size was limited by collating related survivability variables into the design standard variable. As a result, tradeoffs were limited to four very specific sets of design standard specifications. These specific sets of design standards may be appropriate for concept ship design but the next step in expanding the process is to consider these design standard variables individually in a larger tradespace. Considering the identified sensitivity that the design standards variable has within the tradespace results, individual design standard variables could result in further optimizing the set of design standards for a new ship design.

Adding individual design standards to the final design vector will result in geometric growth of the number of designs in the tradespace. The number of designs could potentially grow from the tens of thousands to millions of designs. The number of tradespace designs in the millions is problematic for modeling and simulation with the survivability assessment process conducting 1000 hit simulations per design. Obviously, this limitation could be overcome with the computing power available to the U.S. Navy. Reducing the number of simulations or the number of design variables reduces the necessary amount of computing power. A multi-tiered tradespace exploration process could overcome this effect where design variables are filtered for sensitivity to changes in requirements and operating environments after an initial baseline analysis.

The sensitive data limitation provided another reason for collated design standard blocks. Available cost data limited the cost estimation model used in the SSC trade study. The SSC trade study cost model for total ship end cost using single-digit ESWBS weights produced simple, analogously derived, CERs applicable to each design standard block. Individual design standard variables in the tradespace requires a more complex cost estimation model that accounts for changing material, labor, and non-recurring engineering costs applicable to each specification.

6.3.2 Multiple Threat Encounters

The process model assesses survivability across three contexts: normal operation, post-hit damaged operation, and post-damage recovered operation. These three contexts involve a single encounter from one threat and its damage mechanism. A realistic assessment of naval ship survivability would include multiple threat encounters from the same or different threats employing different damage mechanisms. Considering successive attacks would require expanding the assessment of survivability with additional contexts and defining additional survivability requirements. Figure 6-2 illustrates a five-context model for survivability similar to the three-context model in (McManus, et al. 2007) that would be necessary to model two successive ship hits. Improvement of the process is needed in clarifying additional survivability requirements, operational environments, threats, and damage mechanisms for successive hits and recoveries.

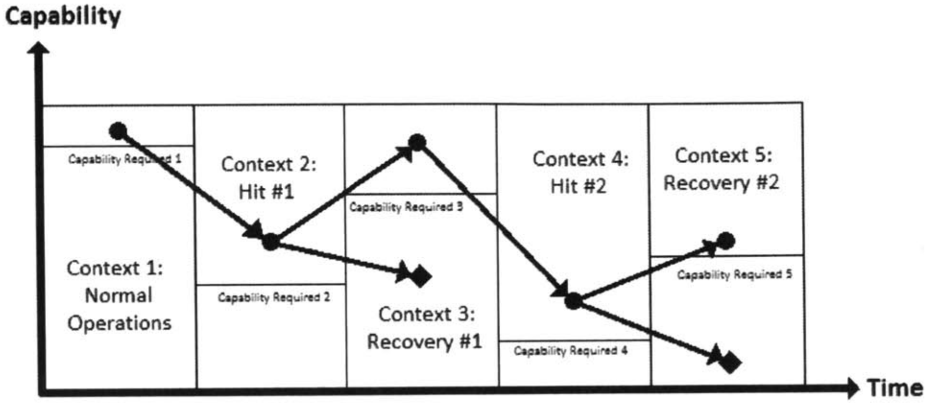


Figure 6-2: Five-Context Model of Naval Ship Survivability

6.3.3 Consideration of other "ilities" in Concept Ship Design Tradespace Exploration

Navy leadership desires strategies for maintaining naval ship capability and relevance as requirements change over time. Ship requirements can change due to new mission areas, rapidly evolving technology, or the development and proliferation of lethal threats. Naval ships must maintain capability and relevance over a ship's lifecycle spanning 30-40 years. There is a need in naval ship design to understand the benefits associated with design and implementation of flexibility strategies. The process application demonstrated in this thesis was for a specific "ility", survivability, but can be applied to any "ility" applicable to naval ship design.

The difficulty with incorporating "ilities" into design is that they're ambiguously defined and difficult to assess. Further research is required to identify methods to model evolving requirements or missions over a ship's lifecycle, identify design variables applicable to flexible ship design and their cost, and methods to assess the tenets of flexibility, i.e. modularity, commonality, growth margins, and design open architecture. Having an assessment of ship flexibility relative to the ship's capability or survivability produces a multi-dimensional tradespace where optimal designs can be identified and explored. Incorporating flexibility into the current tradespace exploration process can provide insight into naval ship performance over its lifecycle. Understanding tradeoffs for naval ship flexibility early in design can reduce lifecycle costs and reduce or potentially eliminate a naval ship's mid-life modernization.

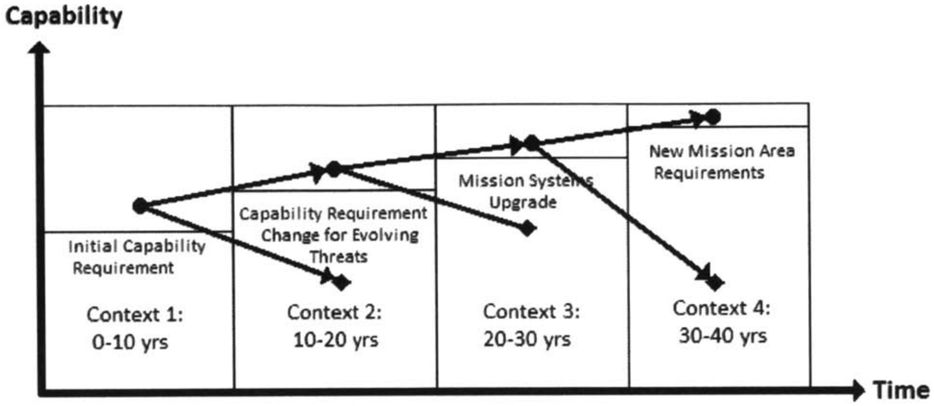


Figure 6-3: Four-Context Model of Naval Ship Flexibility

Figure 6-3 demonstrates an example of varying contexts for naval ship flexibility over a 40-year service life.

6.3.4 Improved Survivability Assessment Method

Limitations of the probabilistic assessment method for naval survivability were discussed in Section 5.2.3. The survivability variance between component survivability assessments results in designs with disproportionate susceptibility, vulnerability, and recoverability performance. The survivability variance effect was noted in commercial designs that possess high susceptibility performance with poor vulnerability and recoverability perform characteristic of a "disposable" warship. Further research is necessary to develop a survivability assessment model that accounts for the survivability variance between component assessments. The probabilistic model can account for the survivability variance by applying a penalty for designs that have a relatively large variance between component assessments by using the variance, standard deviation, or coefficient of variation. The following equation provides an example.

$$P(Survival)_{Overall} = P(Survival) \cdot \left(1 - \sqrt{Variance(Sus, Vul, 1 - Rec)}\right)$$

6.4 Conclusion

The MATE for Survivability process applied to Navy ship design provides keen insight into survivability-cost tradeoffs. This thesis proposes a method to answer the research question of how much additional investment is required to improve naval ship survivability. The short answer to this research question is "it depends." Analysis of the trade study results shows that the optimal survivability-cost relationship for a specific ship class depends on its projected operating environment, survivability requirements, and desired mission capability. The relationships identified are specific to the type of ship considered in the trade study, a naval combatant. Desired mission capability determines the amount of survivability performance being supported by mission systems. To account for dependencies between capability and survivability a naval combatant's survivability cannot be considered for cost tradeoff without regard to its capability.

Considering capability and survivability for potential cost tradeoffs requires a multi-dimensional approach. The multi-dimensional approach enables survivability tradeoffs by considering survivability independently from capability and not treating survivability as a design constraint. A multi-dimensional analysis produces a Pareto surface of optimal designs. The identified optimal designs relative to the operating environment and survivability requirements are analyzed for potential capability and survivability cost tradeoffs. The optimal tradespace can be navigated in iso-capability bands where survivability-cost relationships can be determined for specific capability levels. The survivability-cost relationships observed are determined to behave logarithmically and is dependent on a naval combatant's capability where increasing desired capability diminishes survivability returns for an given increase in cost. Figure 5-14 illustrated the increase in survivability with increase in cost for five iso-capability bands. These survivability cost curves are specific to the naval combatant considered in the trade study with exact mission and survivability requirements in a particular projected operating environment.

Determining the survivability-cost relationship for a new concept naval ship design allows tradeoffs to be made in the earliest stages of design. Understanding the desired levels of capability and survivability relative to imposed affordability constraints prevents costly design changes and program disruptions. Affordability of naval vessels has become essential in the current environment of shipbuilding budget constraints and high-priority ship procurement programs coupled with aggressive shipbuilding plans and will remain a priority for the next 20 years. The process and analytic techniques proposed in the thesis seeks to address these affordability concerns.

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APPENDICES

A. Navy Mission Areas and Operational Capabilities

Appendix A defines all 21 Navy mission areas and operational capabilities. OPNAVINST C3510.2K is the source document but contains sensitive material and is restricted. The following mission area descriptions contain only public information and was taken from Commander Operational Test and Evaluation Force (COMOPTEVFOR) Policy and Information Notice 11-04 (DON 2011) with the exception of the electronic warfare definition. Not all the mission areas described are applicable to ships and not all mission areas are applicable to all ship classes.

AMW - Amphibious Warfare - The employment of a combination of a land and maritime forces/capabilities, and other forces/capabilities, as required, to take or defend a military objective.

ASW – Antisubmarine Warfare - Operations conducted with the intention of denying the enemy the effective use of submarine.

AW – Air Warfare - Operations conducted with the intention to destroy or neutralize enemy aircraft or missiles in the atmosphere, including nullify or reduce their effectiveness.

CCC/C3 – Command, Control, and Communications - The exercise of authority and direction by a properly designated commander over assigned and attached forces in the accomplishment of the mission. C3 function are performed through an arrangement of personnel, equipment, communications, facilities, and procedures employed by a commander in planning, directing, coordinating, and controlling forces and operations in the accomplishment of the mission.

CON – Construction - Operations in building or assembling of infrastructure.

EW - Electronic Warfare - Any action involving the use of the electromagnetic spectrum or directed energy to control the spectrum, attack of an enemy, or impede enemy assaults via the spectrum. The purpose of electronic warfare is to deny the opponent the advantage of, and ensure friendly unimpeded access to, the EM spectrum. (JCS 2007)

EXW – Expeditionary Warfare - Operations conducted by maritime forces in the littoral, riparian, or coastal environments.

FHP – Force Health Protection - Measures to promote, improve, or conserve, the mental and physical well being of Service members. These measures enable a healthy and fit force, prevent injury and illness, and protect the force from health hazards.

FSO – Fleet Support Operations - Those support operations (e.g., repair, inspection, maintenance, administrative, logistics, utilities, services, refueling, towing, search, salvage, Search and Rescue (SAR), explosive ordnance disposal, port control, medical training, navigation, icebreaking, Tactical Development and Evaluation (TAC D&E), scheduling, Public Affairs (PA), and legal that are available and provided to assist other units in the execution of their missions.

INT – Intelligence Operations - The variety of intelligence and CI tasks that are carried out by various intelligence organizations and activities within the intelligence process. Intelligence includes planning and direction, collection, processing and exploitation, analysis and production, dissemination and integration, and evaluation and feedback.

IO – Information Operations - Integrated employment of core capabilities of electronic warfare, computer network operations, psychological operations, Military Deception (MILDEC), and Operations Security (OPSEC), in concert with specified supporting and related capabilities to influence, disrupt, corrupt, or usurp adversarial human automated decision making while protecting our own.

IW – Irregular Warfare - A violent struggle among state and non-state actors for legitimacy and influence over relevant populations. Naval forces employ indirect and asymmetric approaches, as well as the full range of military capabilities, to erode an adversary's power, influence, and will.

LOG – Logistics - The science of planning and carrying out the movement and maintenance of forces. In its most comprehensive sense, those aspects of military operations that deal with : (a) design and development, acquisition, stowage, movement, distribution, maintenance, evacuation, and disposition of material; (b) movement, evacuation, and hospitalization of personnel; (c) acquisition or construction, maintenance, operation, and disposition of facilities; and (d) acquisition or furnishing of services.

MIW – Mine Warfare - The strategic, operational, and tactical use of mines and Mine Countermeasures (MCM). MIW is divided into two basic subdivisions: the laying of mines to degrade the enemy's capabilities to wage land, air, and maritime warfare; and the countering of enemy-laid mines to permit friendly maneuver or use of selected land or sea areas.

MOB – Mobility - A quality or capability of military forces, which permits them to move from place to place while retaining the ability to fulfill their primary mission.

MOS – Missions of State - Those operations that support strategic, operational, and tactical objectives to include, but not limited to: diplomacy, humanitarian assistant, peacekeeping, interdiction, Foreign Internal Defense (FID), CT, counterdrug operations, forward presence, civil military/assistance operations, Foreign Humanitarian Assistance (FHA), Functional Specialty (FS) support, and other forms of assistance.

NCO – Noncombat Operations - Selected operations of a noncombat nature not clearly categorized in any other warfare mission area. Included in this category are the necessary support requirements and/or special mission that are required of a unit, but not directly related to the other warfare mission areas.

NSW – Naval Special Warfare - NSW is a designated naval warfare specialty that conducts operations primarily in the coastal and riverine environments and maritime domain. NSW emphasizes small, flexible, mobile units operating under, on, and from the sea. These operations are characterized by stealth, speed, and precise, violent application of force.

STS – Strategic Sealift - The afloat prepositioning and ocean movement of military material in support of U.S. and multinational forces. Sealift forces include organic and commercially acquired shipping and shipping services, including chartered foreign-flag vessels and associated shipping services.

STW – Strike Warfare - Naval operations to destroy or neutralize enemy targets ashore, including attacks against strategic or tactical targets such as manufacturing facilities and operating bases, from which the enemy is capable of conducting or supporting air, surface, or subsurface operations against friendly forces.

SUW – Surface Warfare - That portion of maritime warfare in which operations are conducted to destroy or neutralize enemy naval surface forces and merchant vessels.

B. Survivability Components of Surface Ships

Enclosure (2) of OPNAVINST 9070.1A " Survivability Policy and Standards for Surface Ships and Craft of the U.S. Navy" contains several tables of survivability components categorized by reducing a ship's susceptibility, vulnerability, or increasing a ship's recoverability. This all-inclusive set of core capabilities is used as a guideline to establish a ship's minimum survivability baseline with respect to its mission requirements and CONOPS and is not intended to be prescriptive in nature. Included in this appendix are collated tables, **Table B-1** and **Table B-2**, of surface ship survivability components from the OPNAVINST Enclosure (2). (DON 2012)

Table B-1: Survivability Components of Surface Ships
(DON 2012)

	Type	Mitigation	Capability or Component
Susceptibility Reduction	Detection and targeting avoidance	Signature reduction	Absorbent materials, ship design, insulation, cable shielding, silencing, degaussing, mechanical masking
	Hit avoidance and reduction	Active and passive defenses	SAM systems, active EW measures, point defense, decoys
	Information integrity and accessibility	Active and passive defenses	Information systems and C4ISR
	Mitigation of CBRN attack	Passive defenses	Countermeasure washdown system, decon stations
Vulnerability Reduction (Damage Tolerance)	Ship Loss	Magazine Mass Detonation Prevention	Passive protection, armor, ballistic plating, side and bottom protection
	Conventional Damage Reduction	Structural and Equipment Design Improvements	Hull, structural and equipment strength improvements
	Nuclear Damage Reduction	Nuclear Protection	Hull, structural, and equipment strengthening, shielding and hardened equipment, CMWD system
	Fallout Removal	Removal of Nuclear Radiation from Exterior of the Ship	A system capable of removing radiological contamination
	Chem and Bio Liquid and Particulate	Remove all chem and bio liquid and or particulate matter from ship exterior	System capable of removing contamination
	CBR and Toxic Gases	A network of chem, bio, toxic gas, and radiological sensors internal and external to the ship	Sensors placed in critial interior and exterior airflow paths
	EMP and HEMP	EMP Protection	EMP hardening, equipment, shielding, filtering, protective devices, & spares
	CBR, Toxic Gases, and TICs	Identification, warning, monitoring	Automatic fixed and portable detection and identification systems and alarms
		Protect personnel	CMWD system, collective protection system, individual protection equipment, circle william and purging procedures
		Collective protection system	Air purification and monitoring system designed to provide fresh air to critical portions of the ship: C&C, medical, and crew rest and recovery spaces
		Identification, warning, monitoring	Automatic fixed and portable detection and identification systems and alarms
	Munitions Sensitivity	Damage Reduction	Insensitve explosives
	Loss of Mission Critical and Vital Systems	Redundancy, alternate systems	Pri and alt power sources, separation of pri and alt mission systems, ships drawings and common diagrams
	Cyber Attacks and Hacking	Information Assurance	Information Systems
	Malware and Malicious Code	Information Assurance	Information Systems

	Type	Mitigation	Capability or Component
Vulnerability Reduction (Environmental)	Sea State	Structural design improvements	Hull, structural and equipment strength improvements
	Icing	Coatings	Paints, composites
	Sea Water Temperature	Temperature regulation systems	Coolings
	Air Temperature	Air regulation systems	Air conditioners, heat exchangers
	Sand and Dust	Airtight structures, filtration	Ship design, filtering systems
Vulnerability Reduction (Accidents)	Collisions & Groundings	Indications and warnings	Sensors and alarms
		Structural design improvements	Hull and structural strength improvements
Recoverability (Fire and Damage)	Smoke	Detection	Sensors
		Desmoking	Smoke ejection system, porable blowers, ventilation, shipboard training
	Fire	Detection	Sensors, shipboard training
		Fire suppression and extinguishing	Distributed and redundant seawater sprinkling and hoses, freshwater, AFFF and hoses, hi-expansion foam, water mist, gaseous agents, portable extinguishers, training
	Flooding	Dewatering	Main drainage, portable eductors
		Structural design improvements	Increased watertight subdivisions
	Heat and Fire Spread	Structural design improvements	Compartmentalization
		Fire resistant materials, reduced fire load	Insulation, paints, coatings, interior finishes, cables, habitability materials, outfitting
		Fire resistant bulkheads and decks, penetrations	N-class divisions, fire insulation, shipboard training
Recoverability (Personnel Protection and Capability Restoration)	Heat and Fire	Detection, rsistance	Sensors, FF ensemble, FF equipment
	CBR	Detection, monitoring, protect personnel	Individual protective equipment, automatic fixed and portable detection and indentification systems, collective protection systmes, medical prophylaxis
	CBR Decontamination	One or more decontamination stations which allow passage from exterior into interior of ships which are clean of liquid or particulate contamination	Decontamination stations should be capable of processing ambulatory personnel and the processing of litter borne causalities
	Hazardous Atmospheres	Detection, ventilation	Sensors, emergency breathing devices, portable blowers, ventilation, training
	Loss of Mission Critical and Vital Systems	Reconfiguration and reconstruction	Casualty power, ships drawings and common diagrams, portable communications, spares, redundancy and separation of systems

Table B-2: Survivability Components of Surface Ships (Cont.)
(DON 2012)

C. Expanded Ship Work Breakdown Structure and Total Ship End Cost Estimation

The primary means of communication between ship designers, cost estimators, and shipbuilders is the Expanded Ship Work Breakdown Structure. ESWBS relates physical ship properties categorized by a coded structure. A cost estimating relationship (CER) is used to relate physical ship weight by ESWBS group to cost. CERs also exist to varying levels of detail based on the ESWBS detail provided. ESWBS is divided into ten major groups, ESWBS 000-900. The ESWBS group names and descriptions are shown in Table C-1.

Group #	ESWBS Name	Group Description
000	Administrative Support	Include guidance and administration for operational, logistic, management, and planning functions
100	Hull Structure	Includes shell plating, decks, bulkheads, framing, superstructure, pressure hulls, and foundations
200	Propulsion Plant	Includes boilers, reactors, turbines, gears, shafting, propellers, steam piping, lube oil piping, and radiation shielding
300	Electric Plant	Includes ship service power generation equipment, power cable, lighting systems, and emergency electrical power systems.
400	Command and Surveillance	Includes navigation systems, interior communications systems, fire control systems, radars, sonars, radios, teletype equipment, telephones, and command and control systems.
500	Auxiliary Systems	Includes air conditioning, ventilation, refrigeration, replenishment-at-sea systems, anchor handling, elevators, fire extinguishing systems, distilling plants, cargo piping, steering systems, and aircraft launch and recovery systems
600	Outfit and Furnishings	Includes hull fittings, painting, insulation, berthing, sanitary spaces, offices, medical spaces, ladders, storerooms, laundry, and workshops
700	Armament	Includes guns, missile launchers, ammunition handling and stowage, torpedo tubes, depth charges, mine handling and stowage, and small arms.
800	Integration/Engineering	Includes all engineering effort, both recurring and nonrecurring. Nonrecurring engineering is generally recorded on the Construction Plans category line of the end cost estimate while recurring engineering is recorded in Group 800 of the Basic Construction category.
900	Ship Assembly and Support Services	Includes staging, scaffolding, and cribbing; launching; trials; temporary utilities and services; materials handling and removal; and cleaning services

Table C-1: ESWBS Groups and Descriptions
(NAVSEA 05C 2005)

The quality of a cost estimate using ESWBS is determined by the level of detail defined by the number of ESWBS digits. A single digit EWSBS code represents the major functional technical areas of a ship. ESWBS codes 100-700 encompass the entire ship minus ship variable loads. Ship variable loads are the ships personnel, mission related expendables like ammunition, ship's stores, liquids, and cargo. Additional ESWBS digits represent a higher level of detail. Table C-2 demonstrates the varying degrees of detail in an ESWBS description. (SAWE 2011)

One-Digit	100 - Hull Structure	200 - Propulsion Plant	300 - Electric Plant	400 - Command and Surveillance	500 - Auxiliary Systems	600 - Outfit and Furnishings	700 - Armament
Two-Digit	120 - Hull Structural Bulkheads	230 - Propulsion Units	330 - Lighting Distribution	450 - Surface Surveillance	530 - Freshwater Systems	640 - Berthing Spaces	720 - Missiles and Rockets
Three-Digit	122 - Transverse Structural Bulkheads	234 - Gas Turbine Unit	332 - Lighting Fixtures	451 - Surface Search Radar	533 - Potable Water	641 - Officer Berthing and Messing	727 - Missile Launcher Control

Table C-2: Example of Varying Degrees of ESWBS Details (ESWBS 100-700)

In a total ship end cost estimate ESWBS groups 100-900 are used to determine basic construction costs. The basic construction cost is the center of the cost estimation process and requires the most time and attention. CERs, at the appropriate digit level, are used with the provided ESWBS 100-900 weights to arrive at the basic construction cost. The cost of detailed drawings and specifications from the ship builder or design agent are charged to the construction plans category. Reimbursement to the shipbuilder for inflation occurring over the contract period is accounted for in the contract escalation category. Change orders are typically an assumed percentage of the basic construction costs and accounts for any contract changes due to technology improvements or correcting deficiencies over a lengthy construction period. Materials and equipment provided by the government such as electronics hardware and software, mission systems (radars, fire control systems, etc.), special craft, or certain propulsion items are designated Government Furnished Material (GFM). GFM costs are accounted for in addition to any other support costs to determine the total ship end cost. The cost to install GFM is accounted for in the basic construction cost. (NAVSEA 05C 2005)

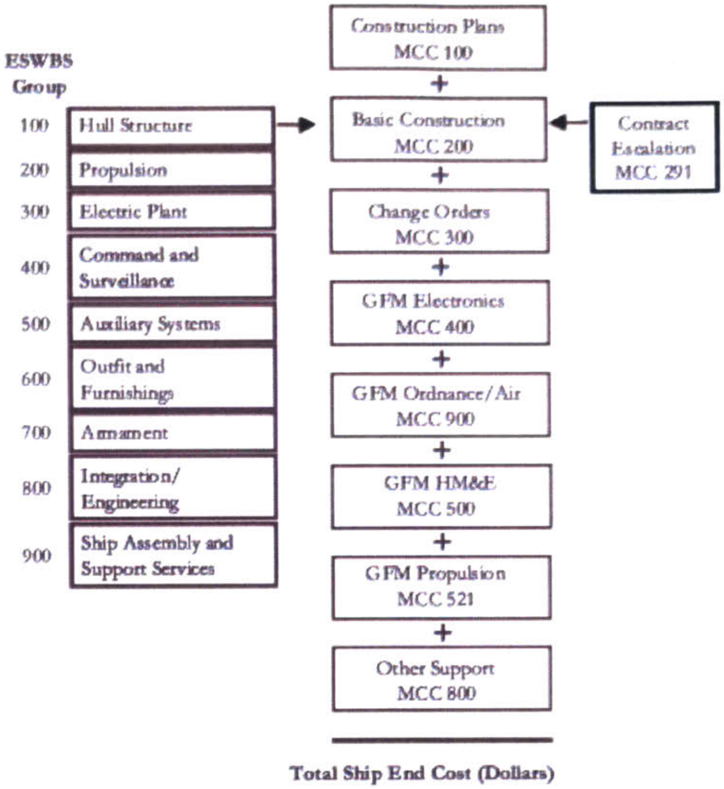

Figure C-1: Total Ship End Cost Process

(NAVSEA 05C 2005)

D. MATE for Survivability Methodology Overview

Appendix D provides an overview of Multi-Attribute Tradespace Exploration for Survivability process as defined by (Richards 2009). The process is illustrated in Figure 0-2 and shows the 8 phases of the process and the interdependencies between phases. The 8 phases and tasks within each phase are provided in the list below.

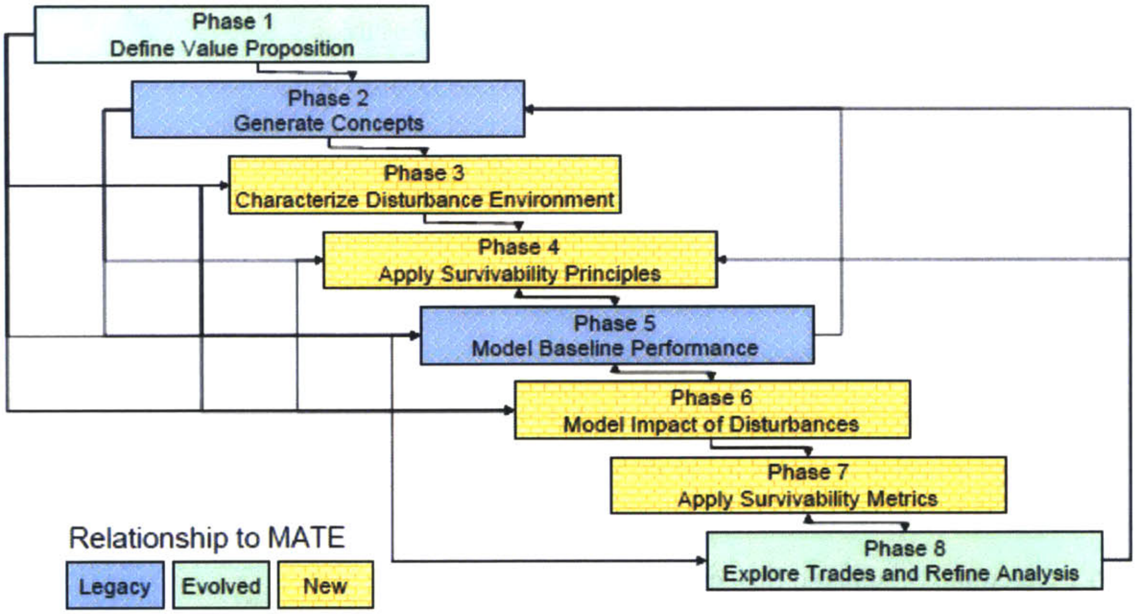

Figure D-1: MATE for Survivability Process Diagram
(Richards 2009)

Phase 1. Elicit Value Proposition

- 1.1 Develop Mission Statement
- 1.2 Identify Decision makers
- 1.3 Elicit Multi-Attribute Value Function
- 1.4 Specify Emergency Value Threshold
- 1.5 Specify Permitted Recovery Time

Phase 2. Generate Concepts

- 2.1 Identify Constraints
- 2.2 Propose Design Variables
- 2.3 Map Design Variables to Attributes
- 2.4 Finalize Baseline Design Vector

Phase 3. Characterize Disturbance Environments

- 3.1 Enumerate Disturbances
- 3.2 Gather Data on Disturbances Magnitude and Occurrence
- 3.3 Develop System-Neutral Models of Disturbance Environment

Phase 4. Apply Survivability Principles

- 4.1 Enumerate Survivable Concepts From Design Variables
- 4.2 Parameterize Survivable Concepts with Design Variables
- 4.3 Assess Ability of Design Variables to Mitigate Disturbances
- 4.4 Filter Survivability Design Variables
- 4.5 Finalize Design Vector

Phase 5. Model Baseline System Performance

- 5.1 Develop Software Architecture
- 5.2 Translate Design Vectors to Attributes
- 5.3 Translate Design Vectors to Lifecycle Cost
- 5.4 Apply Multi-Attribute Utility Function

Phase 6. Model Impact of Disturbances on Performance

- 6.1 Calculate Stochastic Susceptibility
- 6.2 Model Probabilistic Vulnerability
- 6.3 Model Probabilistic Recovery
- 6.4 Generate Distributions of Utility Trajectories

Phase 7. Apply Survivability Metrics

- 7.1 Establish Percentile Reporting Levels
- 7.2 Calculate Time-Weighted Average Utility
- 7.3 Calculate Threshold Availability

Phase 8. Explore Trades and Refine Analysis

- 8.1 Conduct Integrated Cost, Utility, and Survivability Trades
- 8.2 Select Design for Further Analysis

E. Small Surface Combatant Trade Study Supplemental Data

1. Pairwise Comparison Calculations

Mission Area Weights

	ASW	AW	EW	MOB	SUW
ASW	1	7	9	1/3	5
AW	1/7	1	3	1/3	1/3
EW	1/9	1/3	1	1/7	1/5
MOB	3	3	7	1	3
SUW	1/5	3	5	1/3	1

Weights	
ASW	0.341
AW	0.062
EW	0.033
MOB	0.437
SUW	0.127

SUW Mission Attributes

	Main Gun	Missile	SUW Helo
Main Gun	1	7	3
Missile	1/7	1	1/5
SUW Helo	1/3	5	1

Weights	
Main Gun	0.618
Missile	0.086
SUW Helo	0.297

Littoral Environment Threat Activity Profile

	Torpedo	AS Missile	Asym. Boat
Torpedo	1	2	4
AS Missile	1/2	1	3
Asym. Boat	1/4	1/3	1

$$P(A) = [0.558 \quad 0.320 \quad 0.122]$$

Open Ocean (Blue Water) Environment Threat Activity Profile

	Torpedo	AS Missile	Asym. Boat
Torpedo	1	1/2	5
AS Missile	2	1	9
Asym. Boat	1/5	1/9	1

$$P(A) = [0.319 \quad 0.615 \quad 0.066]$$

Other Weights

Weights	
Range	0.25
Speed	0.75
ASW CS	0.75
ASW Helo	0.25

2. Multi-Attribute Utility Function

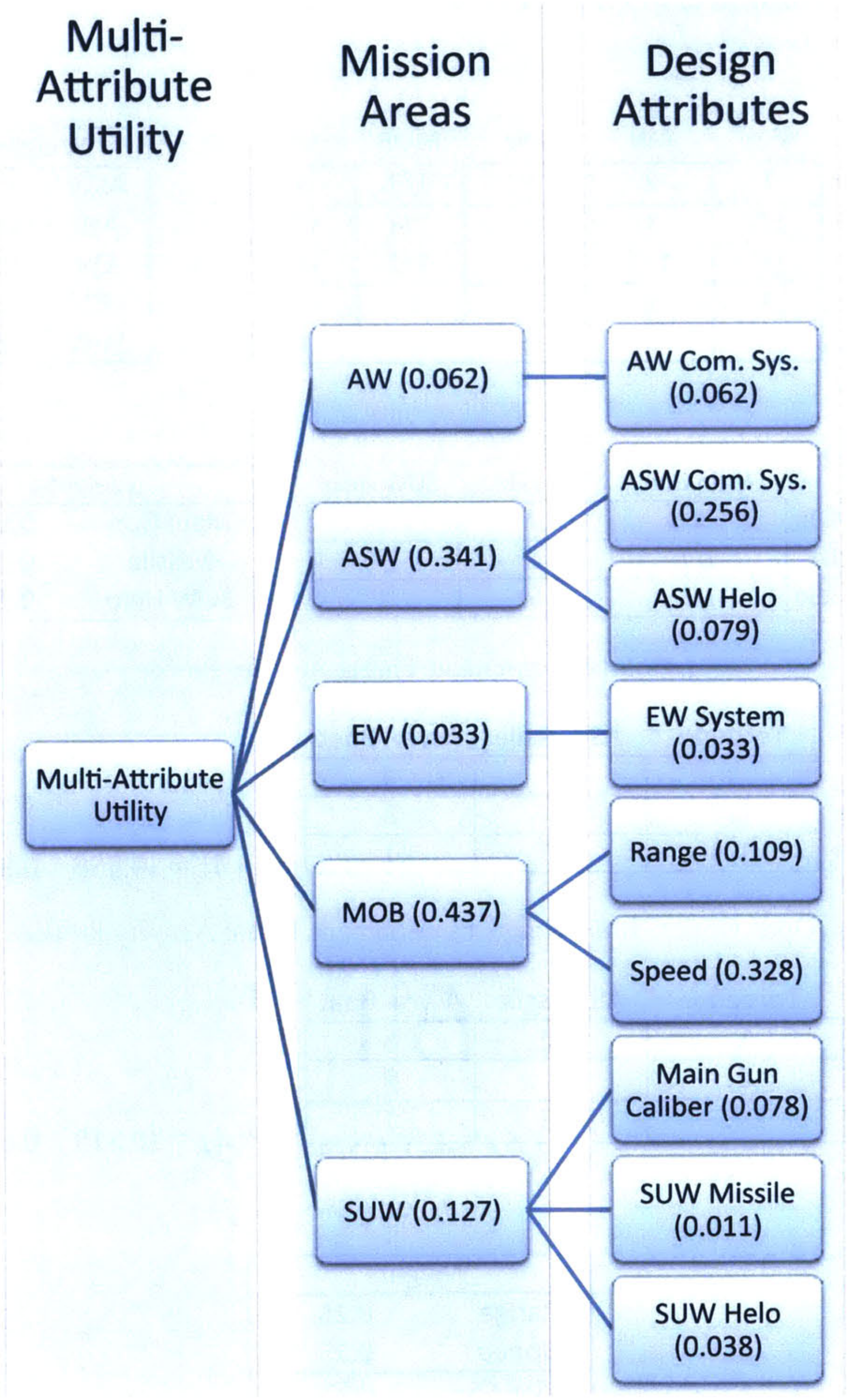

Figure E-1: SSC Trade Study Multi-Attribute Utility Structure

3. Utility Curves

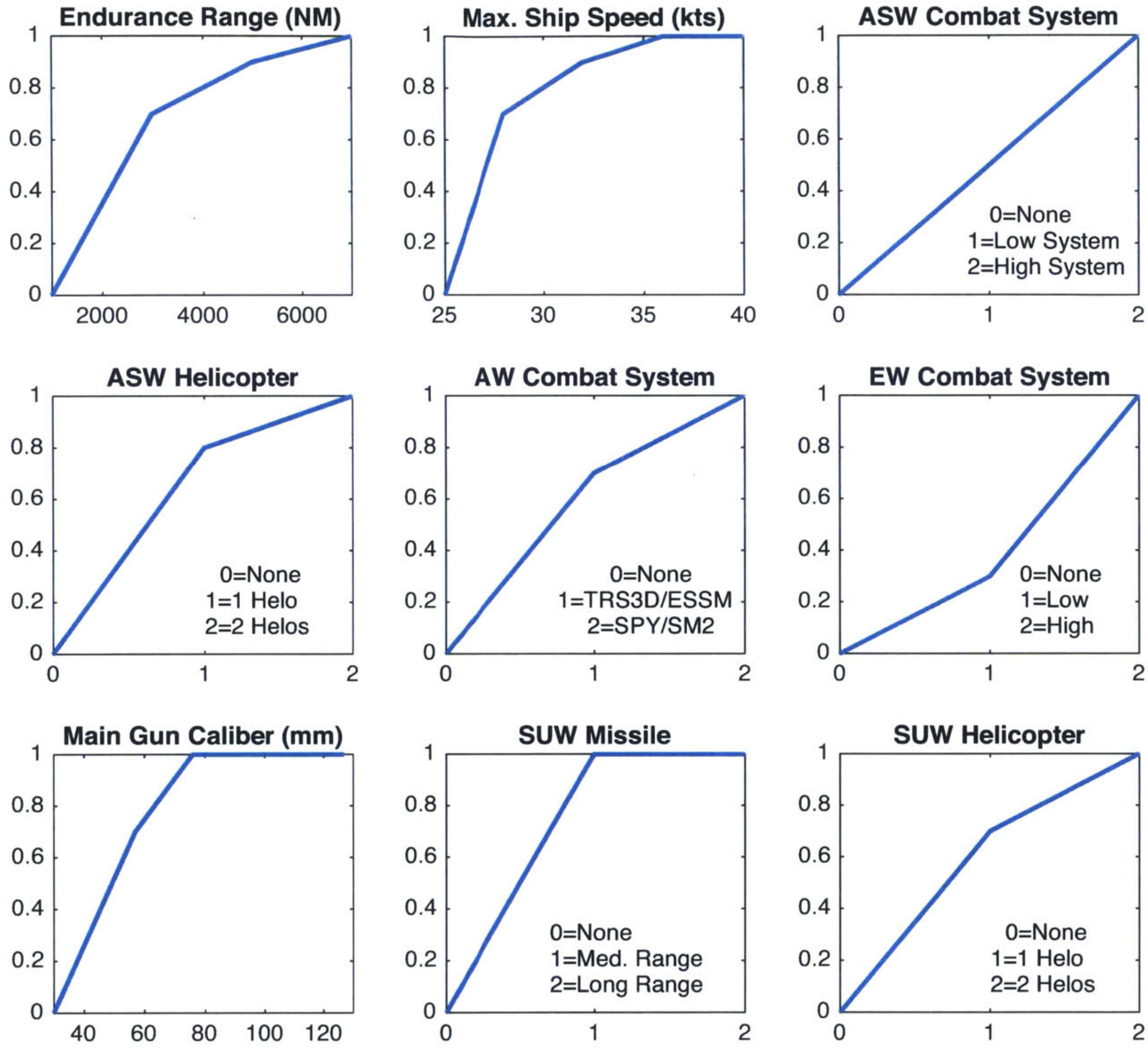

Figure E-2: Multi-Attribute Utility Curves

4. Asset Models

12 ASSET models were created based on 4 design standard arrangements and 3 IPS propulsion plant designs for 30 MW, 50 MW, and 100 MW of installed power.

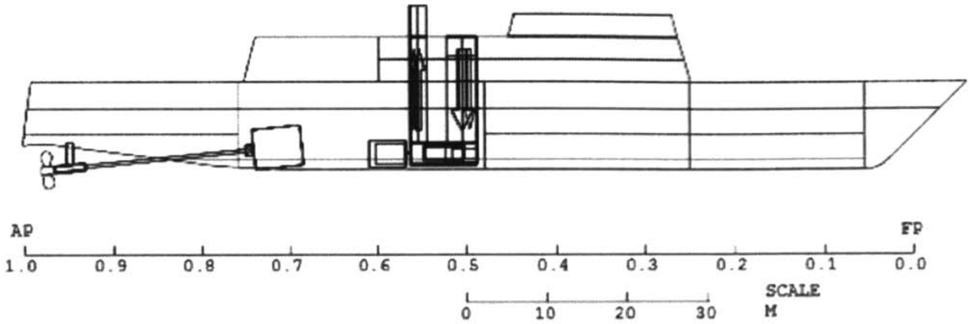

Figure E-3: ASSET Model for Commercial Design Standard

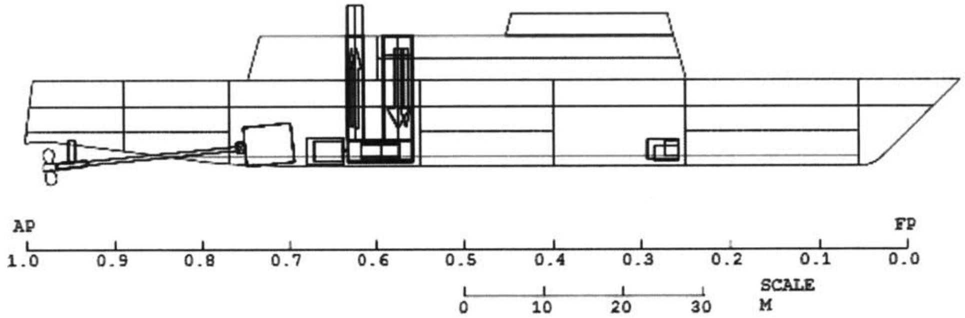

Figure E-4: ASSET Model for Mixed-Low Design Standard

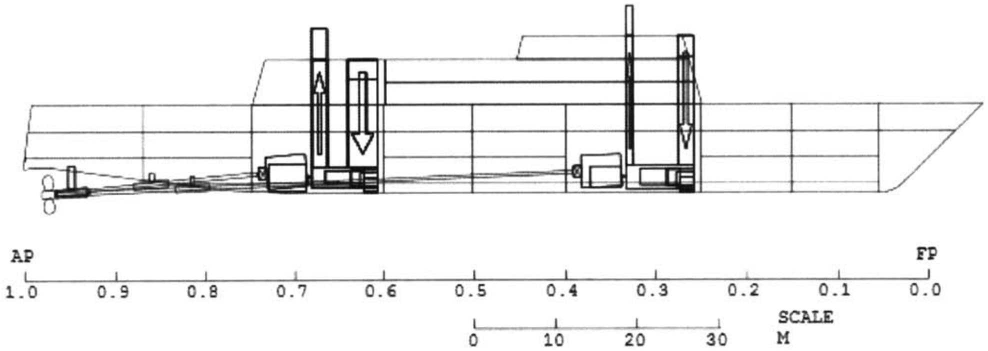

Figure E-5: ASSET Model for Mixed-High Design Standard

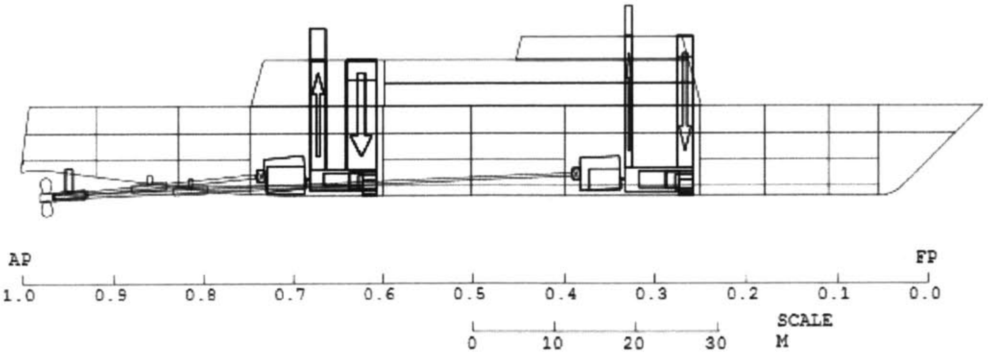

Figure E-6: ASSET Model for Combatant Design Standard

5. Survivability Data

Susceptibility	Design Variable	P(DT)	P(KE)
Torpedo	**Speed**		
	26-28	0	0.2
	28-32	0	0.3
	32-36	0	0.5
	36-40	0	0.6
	ASW Combat System		
	Small System	0.5	0.6
	Large System	0.7	0.75
	EW System		
	None	0	0
	Small: Passive/Chaff	0.25	0
	Large: Passive&Active/Nulka	0.25	0
	Helicopter		
	None	0	0
	1 Helicopter	0.3	0.4
	2 Helicopters	0.6	0.6
Anti-Ship Missile	**AAW System**		
	Small: IMS,TRS-3D, ESSM	0.75	0.8
	Large: Mini-Aegis, SPY, SM2	0.85	0.9
	EW System		
	None	0	0
	Small: Passive/Chaff	0.7	0.6
	Large: Passive&Active/Nulka	0.7	0.9
SUW Attack	**Speed**		
	26-28	0	0.2
	28-32	0	0.3
	32-36	0	0.45
	36-40	0	0.7
	Main Gun (w. Fire control radar)		
	1 Small: 57mm	0.75	0.7
	1 Large: 76mm	0.8	0.85
	Secondary Guns		
	None	0	0
	1-30mm	0	0.7
	2-30mm	0	0.8
	Missile		
	None	0	0
	8x Harpoon	0	0.8
	Helicopter		
	None	0	0
	1 Helicopter	0.4	0.4
	2 Helicopters	0.8	0.8
	EW System		
	None	0	0
	Small: Passive/Chaff	0.8	0
	Large: Passive&Active/Nulka	0.8	0

Table E-1: Design Variable Survivability Performance Parameters

6. SSC Detailed Arrangements by Design Standard

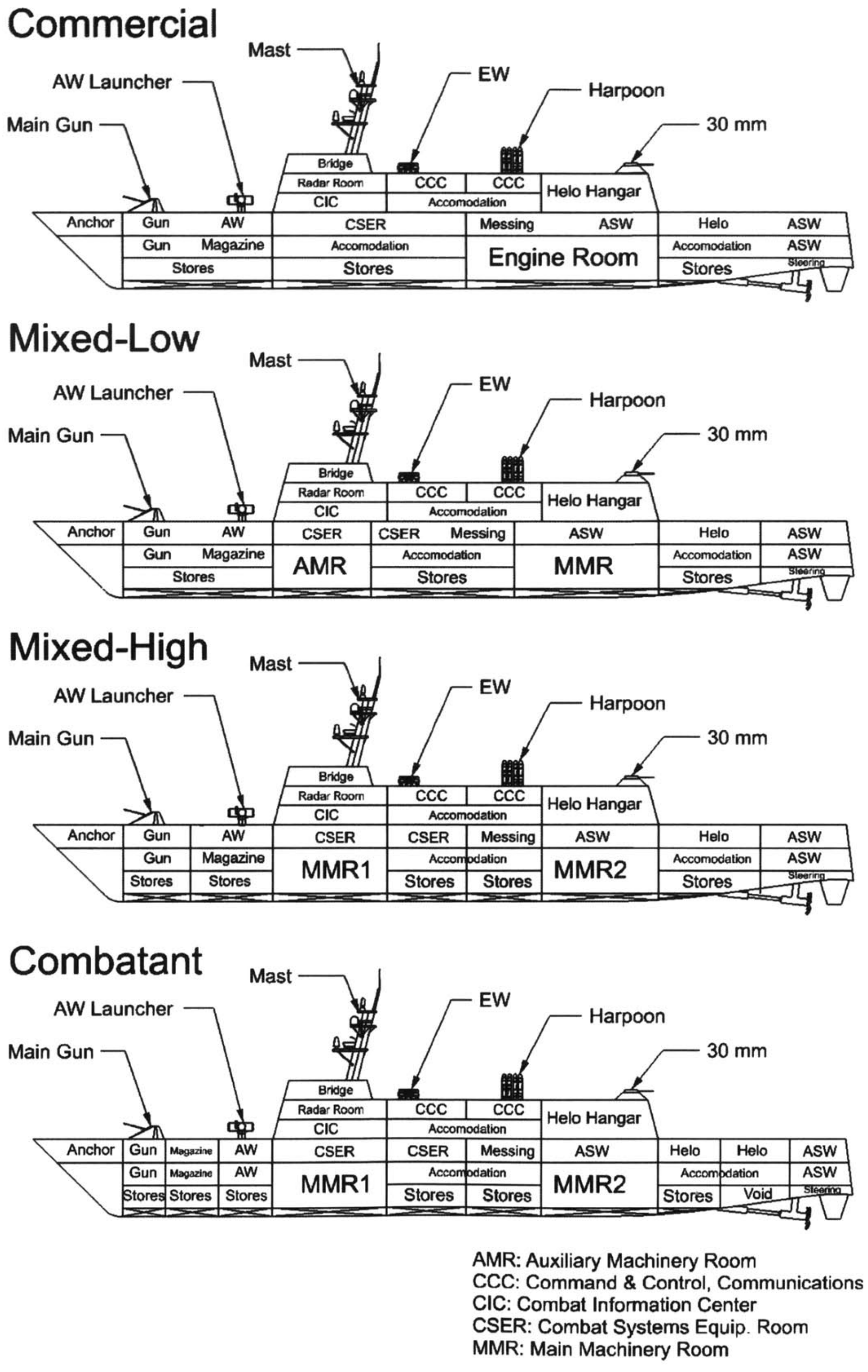

Figure E-7: SSC Detailed Arrangements by Design Standard Specifications