Using the Principles of Set-Based Design to Realize Ship Design Process Improvement

by

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Abstract

Set-based design (SBD) is a relatively new complex product development method. Its use has been well researched in the automotive and aerospace industries and, although it requires an upfront investment in resources, it has been shown to reduce design cycle time, later stage rework, total ownership cost, and improve design knowledge capture. The current fiscal environment of the U.S. Government has obligated the Department of Defense to challenge each service to “do more, without more” by finding efficiencies. Since 2005, the U.S. Navy has self-identified ship design as a process improvement priority and embarked in design tool and policy changes which resulted in the “Two Pass / Six Gate” process in 2008. Subsequent U.S. Navy ship design and acquisition actions have presented an opportunity to research and analyze the amenability of SBD, and its proposed benefits, with the U.S. Navy’s Two Pass / Six Gate process to realize the efficiencies sought by acquisition executives. The results of this analysis identified that Gates 2 (Analysis of Alternatives) and 3 (Capability Development Document) have the most amenability to the principles and benefits of SBD. An Analysis of Feasibility is provided as an alternative to the current Gate 2 and 3 ship design processes. Executing Gate 2 and 3 ship design activities using the set-based Analysis of Feasibility process produces preferred Cost vs Capability trade-off results while reducing design cycle time and cost. Specific policy recommendations for the Assistant Secretary of the Navy (Research, Development and Acquisition) are provided to decree replacement of the current Analysis of Alternatives with the Analysis of Feasibility.
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<td>2P/6G</td>
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Acknowledgements

Professor Warren Seering and MIT Research Associate Dr. Eric Rebentisch for their mentorship time, assistance, and insightful guidance. Without our pondering conversations, this thesis would not have been possible.

Roxane, we did it.

My family for all their dedication and support, my beautiful wife Jennifer for her never-ending love, and Emma, Livie, and Mila for always bringing a smile to my face!
1.0 Introduction

The United States Navy (USN) is in a cost constrained, contentious, tactical acquisition environment. **From the top,** the Department of Defense Acquisition Executive (DAE) and Undersecretary of Defense Acquisition, Technology and Logistics, (USD ATL), via the Better Buying Power (BBP) series of memorandums, has forced service component acquisition programs to become more efficient: doing more with the same. On April 9th, 2015, Deputy Secretary of Defense Bob Work stated:

"the original goal of Better Buying Power, which was to do more without more, remains our overriding focus" (Work B., 2015)

**From the bottom,** USN war fighters are facing increasing challenges to technological superiority from a variety of adversarial nations, thus generating an even more urgent demand for more technologically advanced and higher capable war fighting products. **In the middle,** acquisition professionals are left to deal with the task of improving the complex processes of USN ship product development. The most recent example is USD ATL’s BBP 3.0. This memo has specifically re-focused the defense acquisition community to stem the steady erosion of the United States (US) military’s technological superiority [a foundation of the nation’s defense strategies] (Kendall, 2015).

In 2005, the USN began an improvement initiative focused on discipline in ship design. One aspect of this improvement initiative has been the use of Set-Based Design (SBD) for USN ship product development. This thesis first sets out to explore SBD in USN ship design and acquisition by seeking to understand the people, processes, and tools used to perform ship design and acquisition today. Secondly, it seeks to realize and outline the efficiencies needed to support the top and bottom from the middle.
1.1 The Problem: Designing an Affordable Fleet

Presently, efficiency gains are required to overcome the ominous next twenty years in the USN shipbuilding portfolio. With the priority procurement programs being large expenditures, like a congressionally mandated aircraft carrier every five years and the upcoming replacement of ballistic missile submarines, the remaining fleet capabilities inevitably face pressure for program survival. In particular, the Navy projects the fleet will experience a shortfall in small surface combatants from fiscal year (FY) 2016 through FY 2027 (O'Rourke, 2016c). The Secretary of the Navy (SECNAV) has commented that he intends to protect shipbuilding to the maximum extent possible, but if additional funding is not available to support the shipbuilding procurement plan throughout the near future, the balance of the shipbuilding plan will be significantly impacted (OPNAV, 2015). That significant impact will most likely be felt in surface ship warfare. Any improvement in surface ship design and acquisition will immediately pay dividends. Although ship design process and tool improvement initiatives have been performed between 2005 and today, there still exists the perpetual challenge to do more without more as reinforced by Secretary Work.

Ship product development is a complex process, and, like most complex processes, ship product development is far from automated. Thus, ship product development requires human designers and engineers to transition the ship from an identified capability gap to a fully operational ship class. Organizations that perform complex product development rely on their design processes to create value (Siyam, Wynn, & Clarkson, 2015). Therefore, the most valuable asset in the USN is its people.

Any impact to an organization’s people resource will have some impact on that organization’s overall capability. While chronicling the last fifty years of USN ship design, Hootman and Tibbets revealed that while trying to find the right balance of design effort, control, and risk taking between government and industry, the USN continued to reduce its most precious design resource: its people (Hootman & Tibbets, 2004). An unbalance became evident starting in 2004.
11 May 2004, Senator Duncan Hunter (R-CA), Chairman of the House Armed Service Committee:

"The lack of discipline in both the requirements development process and the systems design and demonstration process are making new ships unaffordable" (USD, 2005, p. 1).

A leading expert in naval architecture and USN Shipbuilding, Robert Keane, also wrote:

"The basic problem is that the naval ship enterprise lacks the mature capabilities (experienced people, lean processes, integrated tools, mature specs & standards, and enterprise-wide communications) for the consistent design, acquisition and construction of cost-effective, mission capable warships" (Keane, Firemann, Hough, Helgerson, & Whitcomb, 2009, p. 1).

The USN had also identified a process problem. The 2005 National Shipbuilding Research Program (NSRP) Strategic Investment Plan (SIP), stated that ship design was the number one factor contributing to increased ship construction costs, and in 2007, the Commander of Naval Sea Systems Command (NAVSEA) was quoted as saying the USN needs to re-establish its roots in terms of disciplined ship design (Keane, Firemann, Hough, Helgerson, & Whitcomb, 2009) (Sullivan, 2008). Since 2005, the USN has self-identified ship design processes and tools as the main problems leading to unaffordable ships.

1.2 The Solution: Process Improvement

The USN ship design and acquisition processes fall under the written guidance of the Department of Defense (DoD) 5000 series, the Joint Capabilities Integration and Development System (JCIDS) manual, and the annual DoD Planning, Programming, Budgeting, and Execution (PPBE) process. These three pillars of the DoD acquisition process have created a modern socio-technical system of people, processes, and tools that use intertwined systems to develop and produce weapon systems for today’s warfighters. The SECNAV has written SECNAV 5000
series of instructions to guide USN ship design and acquisition compliance with the three aforementioned high level instructions and their subordinate documents. SECNAV 5000.2E is the most comprehensive SECNAV instruction and contains the details of the USN Two Pass/Six Gate (2P/6G) ship design and acquisition process. To make a better USN ship faster and cheaper, an improvement in people, process, and/or tools associated with the SECNAV 5000 series of instructions, and mostly likely SECNAV 5000.2E, needs to occur.

Subsequent to 2005, the USN has explored using a product design approach known as Set-Based Design or Set-Based Concurrent Engineering (SBCE). SBD, as a philosophy, has been utilized by Toyota Motor Corporation (TMC) to achieve acclaimed automobile manufacturing dominance. Ultimately, it aided TMC in producing better cars faster than its competitors. SBD has been shown to reduce product development cycle time and has been touted as a contributing reason for TMC’s dominance in the late 20th century (Ward, Liker, Cristiano, & Sobek, 1995). Further research of SBD use in other manufacturing industries has shown products designed via SBD result in reduced production cost (Raudberget, 2010). Producing better ships faster and cheaper is a process the USN desires to emulate by using SBD. Concurrent with sampling SBD, the USN has produced a suite of design tools to align with this new method of ship product development (Kassel, Cooper, & Mackenna, 2010).

This thesis sets out to explore how this new design method and process tools might be utilized inside the SECNAV 5000 series and within the confines of the DoD/JCIDS/PPBE socio-technological system, in order to realize efficiency gains in USN ship design and acquisition.

1.3 Thesis Outline
This section will provide the reader insight into the framework of this thesis by outlining the sources of information and processes for this work. This section is meant to preview the process by listing both the questions posed to explore SBD use in the USN, and the phases that cover how to answer them.
Information for this thesis was gathered by conducting research of open source literature and unclassified databases. Databases accessed were contained on website servers for the Defense Acquisition Management Information Retrieval (DAMIR), Assistant Secretary of the Navy Research, Development, and Acquisition Information System (RDAIS), and USN Visibility and Management of Operating and Support Costs (VAMOSC) systems. They all required the author to have a valid DoD Common Access Card to validate personnel information. In some cases, program specific documents were classified as Unclassified/For Official Use Only or releasable to only DoD employees or contractors. These documents were only used by the author to identify potential candidates for interviews and are not referenced or cited in this work.

The author also obtained research data through interviews with various stakeholders, decision makers, sponsors, managers, and engineers within the DoD and Department of the Navy (DoN). Twenty-one interviews were conducted in support of this work and are categorized by rank and organization per

Table 1. All interviewees were guaranteed anonymity, but conceded to being cited by organization.

<table>
<thead>
<tr>
<th>Type</th>
<th>Number Interviewed</th>
<th>Rank/Pay Scale</th>
<th>Organization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Executive</td>
<td>2</td>
<td>ADM or SES</td>
<td>ASN, OPNAV</td>
</tr>
<tr>
<td>Upper</td>
<td>7</td>
<td>CAPT or GS-15</td>
<td>ASN, CAPE, NAVSEA 05, OPNAV</td>
</tr>
<tr>
<td>Middle</td>
<td>8</td>
<td>CDR or GS-14/13</td>
<td>NAVSEA 05, NSWC-CD, OPNAV, PEOSHIPS, PEOSUBS, CSRA/DoN contractor</td>
</tr>
<tr>
<td>Lower</td>
<td>4</td>
<td>LCDR or GS-12/below</td>
<td>NSWC-CD, OPNAV, SSGC</td>
</tr>
</tbody>
</table>
Figure 1 shows an organizational map of DoD and DoN ship acquisition with organizations interviewed in bold. Solid lines indicate direct reporting authority, and dashed lines indicate close working relationships which may dictate some form of customer/stakeholder relationship between the two organizations.

Interviewees were asked general questions to extract what the USN values and when in ship design and acquisition. The author then asked more specific questions to understand processes and tools used to perform interviewees respective parts of ship design and acquisition processes. Interviews were conducted by either telephone conversation or by face-to-face meeting. Some interviewees were provided read-ahead written questions to facilitate effective use of interview time, whereas others were conducted in a more ad hoc manner to extract current unbiased opinions.
The Process: Three fundamental questions are proposed to research SBD use in the USN through four phases of work. By answering these three questions, the case will become clearer for using SBD within the unique culture of USN ship design and acquisition.

#1: What are the principles of SBD?

#2: What could be the measured benefits of using SBD in the USN?

#3: Which parts of the USN 2P/6G process are amenable to SBD?

Phase 1: Literary Product Development and Ships

- Research non-USN literature and determine the principles of SBD. These principles will be used to determine if actions taken by USN design teams are set-based and will answer Question #1.
- Research proposed benefits of SBD presented from literature. These benefits will support answering Question #2.

Phase 2: Military Acquisition Processes

- Deconstruct the USN ship design and acquisition process into sub-sections to understand chronological ship design. Determine stakeholder priorities for each sub-section by interview. These priorities will support answering Question #3.

Phase 3: SBD in the USN

- Research USN ship design cases that may have used SBD. Use interviews with authors, design team participants, leaders, and consumers of ship design information to assess how the design was performed, what tools were used, and what the USN learned from the overall design effort.
• Research for evidence of SBD potential benefits being realized by the USN.
  Realizing the benefit of SBD will contribute to the design method being amenable to
  the product development process and support answering Question #3.
• Identify where the USN stands on using SBD.

**Phase 4: Ship Design Process Improvement**

• Use the principles from Phase 1, the structure of the overall process from Phase 2,
  what the USN has learned from Phase 3, and explore which parts of the overall USN
  ship design and acquisition process are most amenable to SBD. Explore if SBD can
  be specifically used to help overcome present stakeholder issues.
2.0 Phase 1: Product Development and Ships

In Phase 1, a review of complex product development processes and design approaches is provided to give the reader background information before presenting the principles of researched design methods and the proposed value of SBD. Prior to discussing design approaches, an overview of product development processes is necessary. Additionally in Phase 1, traditional USN ship design is presented to introduce ships as the “product.”

This chapter/phase will step through [1] the far ends of the product development spectrum, [2] common design elements and two design approaches, in which the principles of SBD will be summarized, [3] a summary and review of the proposed benefits of SBD, and [4] traditional USN ship design. The discussion in this chapter achieves the two goals of Phase 1: Research non-USN literature and determine the principles of SBD, and Research proposed benefits of SBD presented from literature.

2.1 Product Development Concepts

“Price is what you pay. Value is what you get.”

—Warren Buffett

There are many different ways to design a product, but in the end, all products share a common goal: provide value to the customer. How a product is designed, tested, and produced directly determines the cost of the product, and may indirectly determine some of the benefits. Many different product development methods exist to align organizations with marketplaces in order to produce valuable products effectively. Unger and Eppinger discuss product development as a set of activities beginning with the perception of a market opportunity and ending in the production, sale, and delivery of a product (Eppinger & Unger, 2009). What isn’t clarified in Unger and Eppinger’s discussion is how the set of activities is performed.

At the macro-level, there are two main styles of product development: stage-gate and spiral-agile. At the traditional end of the spectrum is stage-gate, or what is sometime also referred to as waterfall, phase gate, toll gate, structured, or life cycle product development. On the opposite
end is spiral product development, and a similar process known as Agile. Stage-gate is typically used to develop manufactured products, while spiral-agile is most often used for software and service product development. The product of a USN warship, with its blend of industrial material, machinery components, and the many technical systems to enable warfighting capability, has aspects of both traditional and modern products.

In this section, both stage-gate and spiral-agile product development processes will be visually presented and summarized, with advantages and disadvantages noted along with the customer value concept of Lean. The general complex PDP segments will be captured for future discussion of potential design processes that may be used to accomplish each segment.

### 2.1.1 Stage-Gate

The stage-gate model is structured to have formal reviews follow phases of work. Figure 2 shows a common depiction of the stage-gate product development process (PDP). After idea generation, intermediate phases may include some form of concept design, assessment, specification analysis, system-level design, detailed design, prototyping and/or testing. At the end of each phase, sufficiency reviews occur to determine project feasibility. If the review is satisfactory, work proceeds to the next phase. If not, iterations occur within the stage, but rarely across stages, to achieve satisfactory results per stage. This method has been commonly used in American industry for the past thirty years (Eppinger & Ulrick, 2004).
Staged product development works well in cases where products have stable requirements, use well-understood technologies, and are driven by quality requirements instead of cost or schedule. The structure of stage-gate favors the early identification of rigid product specifications. This is an advantage of stage-gate. Through repetitive supervisory review, it also supports correcting errors when the cost of changes is low, thus reducing technical risk and poor quality (McConnell, 1996). The repetitive supervisory reviews tend to keep product development teams on track and less likely to pursue a large deviation in product architecture. A disadvantage of stage-gate is limited flexibility to incorporate feedback from customers and later phases of work. If the preliminary assessment or upfront requirements are poorly understood, there is a substantial risk of the product not holding up to final customer acceptance.

2.1.2 Spiral-Agile

At the other end of the product development spectrum is a process that can be described as spiral-agile. The spiral PDP differs from the staged process because of its emphasis on flexibility and comprehensive iteration. It is meant to be adaptive (Institute, 2015). Figure 3 shows the spiral product development model. Unlike the staged process, the spiral includes a series of planned iterations that span several phases of development. Reviews are performed
after traveling around the circle. The same general phases of work are performed as in stage-gate, but the main difference is that reviews occur less frequently and review only a version of the product that can deliver at least partial value to the customer. If a review is unsatisfactory or the deliverable value is inadequate, the spiral is performed again. Repeating a trip around the spiral may also happen to address changing or more specific customer requirements. Once the development team is satisfied with product performance, it is released to the customer. It is assumed that the completed product will require multiple spirals to fully incorporate all customer requirements.

![Spiral-Agile Product Development](image)

**Figure 3: Spiral-Agile Product Development**

(Eppinger & Unger, 2009)

Software firms believe this iterative technique reduces expensive rework in software development, thus lowering development cost and time (McConnell, 1996). The spiral model per Figure 3 shares the same iteration concept as the method known as Agile. Agile, as a product development process, was first documented in 2001 by a collection of software developer professionals in the Agile Manifesto. The term “Agile development” has become widely used by both industry and consultants and suggests a very rapid process of identifying, designing, testing, and validating customer requirements in short sprints and spurts (Varma, 2015). Figure 4 depicts...
an Agile PDP. Agile is a process that focuses development efforts in rapid increments that prioritize meeting a small subset of customer requirements.

![Agile PDP Diagram](image)

**Figure 4: Agile PDP**

*Adapted from (Varma, 2015)*

In an Agile process, the complete product is developed by many quick design iterations on small subsets of customer requirements. Customers can provide feedback to the product manager or company marketing departments, but the circular process of user validation, sprint plan, development, testing, user testing, and release, happens continuously between the product development team and the customer. This process enables the product manager to be very responsive to varying customer requirements and feedback.

Although the spiral-agile process has the advantage of being responsive to customer needs, it does have some disadvantages. First, it is a complex process that requires experienced employees and close management attention. Second, the lack of rigid specifications can potentially lead to delays in developing complex subsystems that have multiple cross-system
interfaces. Last, the spiral process may be most appropriate only for simpler projects which may be accomplished without several iterations (Eppinger & Unger, 2009).

2.1.3 Lean

Another concept that has been touted to improve delivering value to customers is the concept of Lean. The concept of Lean has its roots in the automobile manufacturing lines created by Henry Ford in the 1910’s. He created a flow process using machines and tools to eliminate variation and quickly fabricate Model-T’s in a rapid repeatable process. Where Ford fell short was being able to respond to customer feedback; not everyone wanted the same Model-T. Kiichiro Toyoda, Taiichi Ono, and others at Toyota built upon Ford’s revolutionary assembly line processes and created what is known today as the Toyota Production System (TPS) (Ono, 1988). Toyota’s processes have been widely studied and have even created Lean Institutions, which have produced principles that focus on providing value to the customer. The principles of Lean include the following: identifying customer value, aligning organizational processes to streamline value flow, eliminating wastes, and establishing relationships to pull versus push products through the system (Womack, Jones, & Ross, 1990). By focusing on customer values and eliminating wastes, overall systems become cheaper, faster, and more dominant (Ono, 1988) (Shingo, 1989).

In sum, both the staged-gate and spiral-agile PDPs deliver value to their customers by generating products that meet customer requirements. Additionally, Lean, as a concept, seeks to focus entirely on customer needs and the flow of value to the customer. The stage-gate process may align better with complex products that need to include technological risk in the product design, while supporting transparency in the decision making process. The spiral-agile method may align with products that are more schedule driven, instead of cost or quality driven. Depending on the product being developed, some organizations may choose to perform a blend of stage-gate and spiral-agile based on the classic project management aspects of cost, schedule, quality, and risk for certain segments of the total development method. Overall, literature has shown that the
following generic segments of product development must occur: exploratory design, concept
design, preliminary systems design, detailed design, integration and testing, and production.

2.2 Design Methods
Potential literary design methods to complete each of the product development segments will be
discussed next. The following section will introduce the topic of design, discuss common
elements found in USN ship design, and describe design methods that may target segments of
complex PDPs. After the description of set-based design, its key principles are provided.

2.2.1 Design Elements
To understand a discussion about design, one needs to understand what design really is. At its
core, design is a process that seeks to solve a problem or provide an answer. Jones summarizes
the process:

“Designers are obligated to use current information to predict a future
state that will not come about unless their predictions are correct” (Jones

Unlocking the keys to an effective design method could be akin to predicting the future.
Therefore, much research has been done on design over the past few decades. Recent research
on ship design has revealed that although ship design is already challenging, it isn’t getting
easier:

“Shipbuilding (design) ranks among the most complicated human
endeavors, yet more complex naval vessels are built each year”
(McKenney, Buckley, & Singer, 2012, p. 4).

These two quotes shed light on why ship design is such a challenging endeavor. To begin to
understand the challenging, complex process of ship design, an introduction to the general
elements of design team architecture, complexity, and rework are provided. These elements contribute to the classic program management metrics of cost and schedule that are used to evaluate product development processes and designs in the government Earn Value Management System (EVMS).

2.2.1.1 Product Development Team Composition
The International Council on Systems Engineering (INCOSE) defines systems engineering as integrating all disciplines and specialty groups into a single team, forming a structured development process (INCOSE, 2016). Others explain it as decomposing the product into manageable pieces of work for complex product development as Systems Engineering (Cloutier, Baldwin, & Bone, 2015). These references highlight the necessity for a team effort to accomplish complex product development. The delineation of team suggests that more than one person or group is working together for a common goal. The mix of skill sets among the development team determines the development team’s architecture. In a complex product development process, the development team is typically aligned with a product’s functional architecture (Eppinger & Ulrick, 2004).

Most often, the challenge of engineering complex products is met by breaking down complex products into subsystems, which may be further decomposed into smaller components (Sosa, Gargiulo, & Rowles, 2010). This decomposition determines the architecture of the product, which is defined by how components interface with each other, so that the product can fulfill its functional requirements (Eppinger & Ulrick, 2004) (Ulrich, 1992). Typically, organizations assign development of each component to an activity or group. This activity or group is responsible for a component’s design and for its integration with other components to ensure product functionality (Clark & Fujimoto, 1991). What also results from product architecture are the communication and relationships between functional design activities. These communication relationships create a network, or work-flow, map of how the design process is performed. These design activity relationships can be captured, described, and analyzed in many different ways.
One way to compactly capture functional design activity interactions is by a Design Structure Matrix (DSM). DSM’s have been used since the 1960’s to solve systems of linear equations, but have recently been bridged to Systems Engineering for drawing conclusions about sub-system interactions. DSM methods are becoming more mainstream, especially in the areas of engineering design, engineering management, management/organization science, and systems engineering (Browning, 2016). Figure 5 shows an example of a DSM in which each row corresponds to a Design Activity and each column a Design Variable. The numbered diagonal represents a Design Activity for which row \( n \) produces as output the Design Variable in column \( n \). A dot in a cell indicates that the row Design Activity takes as input the Design Variable corresponding to the column of the dot. This way, dots below the diagonal indicate variables that have been produced by previous design activities. Dots above the diagonal indicate variables that are needed by a design activity, but are not scheduled to be produced until the future.

A few insights can be drawn from analyzing Figure 5. First, Design Variables 1 and 2 do not depend on each other in any way. Therefore, these design activities could be solved in parallel to
reduce cycle time for producing the necessary inputs for Design Activity 3. Second, there is a “cluster” of activities around Design Activities and Variables 3-5 (shown inside a bold square). This suggests that these activities should be solved simultaneously, since Design Activity 3 produces a Design Variable necessary for Design Activities 4 and 5, and Design Activities 4 and 5 produce variables as input for Design Activity 3. This cluster of activities should have well-established communication avenues, possibly be collocated, or performed by one overarching organization to maximize design effectiveness (Browning, 2016).

Complex PDPs require a wide and diverse set of skills. These skills tend to be beyond the grasp of any one individual, and, consequently, groups of engineers and designers must bring together their individual knowledge to collectively solve a problem (Krishnan, Eppinger, & Whitney, 1997). A critical issue in new product development, therefore, becomes the effectiveness with which engineers and designers communicate (Bernstein, 1998). These communications and interactions among design groups and activities align with the architecture of complex products traditionally along functional boundaries. A DSM can then be used to succinctly describe the architecture of a complex product. This product architecture can be considered as the communication or interaction network of sub-system component activities.

Interactions between design groups, via the DSM, can be more formally quantified to support other project management metrics like schedule, productivity, and complexity. Overall, design team architecture is a contributing factor to critical organizational and product specific project management metrics. How design teams communicate is a function of the design team architecture and product architecture. The effectiveness of design team communication is a topic that will be explored further during a discussion of design methods.

**2.2.1.2 Complexity**

For a discussion about complex product development, like ships, the topic of complexity needs attention. Organizations that perform complex product development rely on their design
processes to create value. Therefore, reviewing complexity is relevant in the context of the USN initiative in design process improvement. In this section, definitions of complexity are reviewed and analogies are drawn to link the concept of complexity with design team architecture.

There are many different definitions for the term “complexity” in systems design. Although they vary, all of the definitions share a similar theme: information. In a recent paper on complexity in ship design, Gasper and Rhodes and Ross and Erikstad (2012) summarize the seminal literature on complexity and present the definition as the information contained within a product. The following analogy portrays Gasper et al.’s complexity definition: a simple thing requires a small amount of information to describe it, and as more things are added onto the original thing, more information is required to describe the new thing. The additional required information is what comprises complexity. Similarly, Magee and De Weck (2004) portray complexity as the amount of relevant information necessary to define a system, including components, interconnections, performance, and scenarios. Building on Magee and De Weck’s description of complexity, Suh makes the leap of discussing product information as a functional requirement (Suh, 2005). Suh further subdivides definitions of complexity based on how functional requirements are achieved. He defines Combinatorial Complexity as resulting from having many dependencies between the design activities, especially those above the diagonal in a DSM (NAVSEA, 2012). The preceding discussions can be distilled into thinking of complexity as: the collection of additional information that is necessary to describe the functional requirements of a product.

With the many definitions of complexity also come the many metrics for complexity. It is beyond the scope of this thesis to search for appropriate complexity metrics to support design style/method evaluation, but the most important concept to glean from complexity is that a “complex” product design requires consecutively overlapping details of information. This traditionally results in many individual design teams sharing design information during the process of complex product design. If a product is architected, decomposed, and design teams are structured into the format of a DSM, a complex product would have more interactions above the diagonal (NAVSEA, 2012). Choosing a design style/method to more appropriately handle
the higher number of inter-dependent design team interactions should be the goal of the complex product design method of choice.

Overall, to design a complex system requires a vast amount of information to be exchanged. The design style/method used for complex product design/development should be able to adequately and robustly handle information exchanges.

2.2.1.3 Rework

The following section will introduce the concept of rework and its relation to project management schedule and cost metrics. In this section, the definition of rework is surmised, examples of rework are given, and the effects of rework are discussed.

Both section 2.2.1.1 and 2.2.1.2 discussed the nature of interactions between individual members or groups of a decomposed design team. What was assumed (or not discussed previously) was the effectiveness of these interactions. One could assume that every time a communication happens, the message is perfectly received. But in reality, this is not the case. Similarly, all humans make errors. Errors of some kind are typically present in design, especially complex design. These errors manifest themselves into “rework”.

Product design managers have all experienced the frustration of seeing development teams revisit decisions based on violated assumptions and the pain of forthcoming reworked plans, analyses, and designs. A few common examples of this frustration are illustrated by the following examples:

- The product management team realizes, to their surprise, that customers do not like the trade-offs made among competing objectives, so key product features must be changed late in the game at significant cost to the organization, or face lower than projected sales (Kennedy, Sobek II, & Kennedy, 2014). This is analogous in DoN
acquisition to the program management office realizing, to their surprise, that the warfighting community does not like the trade-offs made during an Analysis of Alternatives (AoA), so a Key Performance Parameter (KPP) must be changed after the Capability Development Document (CDD) has been validated by the Joint Requirements Oversight Council (JROC), or face potential asset obsolescence once it has been delivered to the fleet.

- In the manufacturing process, the manufacturing engineering team learns that the current equipment is not capable of manufacturing an important product feature, resulting in the tough decision either to redesign the feature, thereby delaying product delivery, or to invest much more than planned in updating manufacturing capability (Kennedy, Sobek II, & Kennedy, 2014). This is analogous in DoN acquisition to the program office designing and constructing a shipboard titanium piping seawater system to reduce the frequency of recurring maintenance, thus reducing life-cycle cost. Yet, realizing the increased costs associated with tools and training of titanium maintenance workers far outweighed the reduction in cost from less occurring maintenance.

Occurrences like the above impact not only cost, but other intangible, organizational aspects too. Damage to an organization’s reputation and internal employee frustration over inefficient processes are difficult to quantify, but are significant (Ford & Sterman, 2003). What is quantifiable, based on previous research, is the cost to correct those identified errors. The cost to correct identified errors can increase from 3 to 1000 times the original development cost, depending on when they are discovered (Kennedy, Sobek II, & Kennedy, 2014) (Keane & Tibbitts, 1996) (Anderson, 2014). This correction cost escalation is shown in Figure 6.
However, the dilemma for product designers and engineers is that less is known about the full impact of decisions made during the early stages of product development. It is not surprising that early decisions get re-examined as more managers learn more during the development and design of a product. How a design team steps through decisions during each segment of the product development process will inevitably determine how a product development team identifies, eliminates, or mitigates rework.

So far, examples of rework have been provided, but a more formal definition is necessary for future design method comparisons. An appropriate definition of rework from Kennedy and Sobek and Kennedy (2014) is: the work that occurs when a prior decision that was assumed to be final has changed because it was later found to be defective. A decision is considered “final” when the team does not have any reason to believe the decision would need to change, and successor work can proceed without risk. It should be noted that rework is different from design iterations for rapid learning or sped-up customer feedback. Iterations should not be considered as rework because decisions made during an iteration are typically not considered “final”. This
definition of rework is satisfactory for general discussion, but falls short when trying to extract how rework specifically factors into project management metrics of cost, schedule, and quality.

A useful way to quantify rework is to capture rework effects by modeling project management with a software model. System Dynamics is one such software tool that has been used by various organizations to quantify project performance and litigate product development contractual disputes (Lyneis & Ford, 2007). It was developed by Pugh-Roberts Associates in the 1970s and is believed to have appeared with varying degrees of complexity in every project management model created by the system dynamics community since then (Lyneis & Ford, 2007). The gist of the rework cycle is that it’s recursive in nature. Rework generates more and more rework, which creates problematic organizational behaviors, which negatively affect schedule duration and cost performance. A generic Systems Dynamics rework cycle is shown in Figure 7.

![Rework Cycle Diagram](image)

Figure 7: Rework Cycle

Adapted from ESD.36 Fall 2013 Lecture 8, Massachusetts Institute of Technology
A project is defined as a certain number of tasks of “original work to do.” The tasks can either be completed correctly or incorrectly. If they are correctly performed at a Work Completion Rate, the tasks become “work done.” If tasks are incorrectly performed at a Rework Generation rate, they become “undiscovered rework,” until it is discovered that they were flawed and need to be redone. “Undiscovered rework” transitions to “rework to do” via Rework Discovery. Once rework is discovered, it is performed correctly or incorrectly contributing to “work done” or “undiscovered rework” respectively. Variables “original work to do”, “undiscovered rework”, “rework to do”, and “work done” can be graphically calculated using rates shown in Figure 7 with the hourglass symbol.

Rates in this rework cycle can be affected by the parameters workforce size, productivity, error fraction, and time to discover rework. For example, the rate at which rework is discovered and reclassified as work to do is affected by the undiscovered rework and the time to discover rework, which can also be affected by the workforce size and productivity. When modeling project management, these parameters represent variables. But, in reality, these parameters are control mechanisms available to an organization (Owens, Leveson, & Hoffman, 2011). For example, an organization can control its workforce size through hiring/firing and can attempt to control productivity through many management actions like training, overtime, and hours of work. What isn’t modeled in this cycle are some observed effects that can erode the control authority like “workforce experience dilution” through the addition of workers to a project, otherwise known as Brook’s Law (Brooks, 1995).

Projects with modeled rework are shown to have the classic second staff peaks to eliminate created rework, duration tails to correctly accommodate all the original rework and rework generated during rework correction, and the 90% syndrome in which it seems like the project will never complete (Ford D., 1999) (Lyneis & Ford, 2007). Projects with modeled rework typically experience the changes described in the two graphs shown in Figure 8 and 9.
Overall, it can be surmised that rework negatively affects the bottom line cost, schedule, and quality metrics of a project. Figures 8 and 9 show the cascading, compounding effect of errors imbedded in work driving up cost, out schedule, and down quality. The way rework is generated, discovered, and corrected is all a function of organizational parameters that revolve around the design style/method/process performed.

The elements of design team structure, complexity, and rework are all inherent to complex product development processes and thus complex product design. The design approach
performed during product development can either enable or hinder the advantages and/or disadvantages of product architecture, complexity, and rework. To investigate how the common design elements interact with the design method, Point Based Design (PBD), Concurrent Engineering (CE), and SBD are reviewed and summarized in the sections following. A simple design example is provided and followed by a discussion of PBD, CE, and Set-Based design to glean the design principles of SBD.

2.2.2 The Simple Example

The following simple example highlights the differences in designing a solution to a common problem for people in any field. The two different design methods offered are categorized to support reflection for the reader in future chapters.

The problem: you need to arrange a meeting with four team members next week. The design space for this problem could be a 2x2 matrix of [1] the number of team members that can meet together and [2] all the dates/times next week. The optimal solution is a date/time that works for the majority. What design process do you use to accomplish the task?

You could first communicate with Person One to arrange a date/time that works for both of you. Once you establish a date/time with Person One, you communicate with Person Two to see if the date/time you set with Person One also works for Person Two. The established date/time either does or doesn’t work for Person Two. If it does, you move on to ask Person Three. If it doesn’t, you establish a new time that works for both you and Person Two and then re-communicate with Person One to see if the new date/time that works for you and Person Two also works for Person One. You repeat the individual communication process until a date/time is identified that is satisfactory for everyone. If there isn’t a date/time that works for everyone, you start the entire process over again. But, while re-performing the process, you only know that one certain time doesn’t work for the most people. This method is a design process in which a single potential
solution is iteratively communicated [passed] between all elements in the design space until the
date/time is identified that works for everyone.

One can imagine that if Person Four cannot meet at the date/time that the organizer has already
established as acceptable for the other three team members, there is considerable rework, or re-
communication, that would be necessary to re-identify a satisfactory date/time for everyone. A
common tactic organizers have used to improve this method might be to co-locate all the team
members to shorten the necessary re-communication loops, or have a meeting to set the meeting
time. Although shortening the re-communication process reduces the time it would take to
achieve the solution, each individual communication loop still needs to happen to achieve the
solution.

In future sections and chapters, this method will be referred to as “The Prospector.” Similar to
how a miner might search for the best place to dig for gold, the meeting organizer probed each
person to find a meeting date/time.

A different approach to scheduling the meeting is to communicate with each person about what
date/times don’t work for them. As you receive replies that contain infeasible dates/times for
individual team members, those infeasible dates/time are automatically removed as potential
solutions from the design trade space. After all infeasible dates/times are received, it is easily
conceivable that the optimal solution will emerge from the gradual trade space reduction. This
method of scheduling a meeting is a process of discovery by elimination. Furthermore, the
organizer knows exactly why each part of the trade space was removed from consideration. In
future sections and chapters, this method will be referred to as “The Panner.” Similar to how a
miner gradually sifts through large rock and silt to progressively toss out non-precious material
until only the desired gold remains, the organizer gradually reduces the potential meeting
date/time by intersecting the desired feasible dates/times provided by each team member.
Which method is better? Naturally, we prefer the effectiveness and efficiency of how the second method arrives at the solution. The following discussion will expound on relating The Prospector to what is known as Point-Based Design and The Panner to what is known as Set-Based Design.

### 2.2.3 Point-Based Design and Concurrent Engineering

The typical US approach to design begins by defining a problem, then generating many alternative solutions (Chapman, Bahill, & Wymore, 1992). After some preliminary analysis, engineers select the alternative that appears the best, then analyze, evaluate, and modify it until a satisfactory solution emerges (Ward, Liker, Cristiano, & Sobek, 1995). If all the initial alternative solutions could be graphed, engineers would know exactly which “point” in the design space they are analyzing, evaluating, and modifying. Thus, “point-based” design. With a point-based design, as the fidelity of the analyses increases, design flaws begin to surface that require quick solutions to bring the design back into the feasible solution space. Often the design cannot be altered enough to achieve a feasible solution, at which point a new design alternative is chosen to re-start the design. The key is that a single solution is synthesized first, then analyzed and changed accordingly (Liker, Sobek, Ward, & Cristiano, 1996).

Think of The Prospector. The organizer proceeded in a point-wise fashion to arrange a meeting time with each person on the team. As the trade space of people and meeting times was explored, the organizer was presenting only a single solution [date/time] to each member of the team. Given the discussion above and the example of The Prospector, a PBD process can be summarized by the following five steps: (Bernstein, 1998) (Liker, Sobek, Ward, & Cristiano, 1996)

1. **Research the problem.** During this step, designers inquire with the customer to clearly set problem requirements.

2. **Once the requirements are known,** engineers and designers use experience to quickly determine a large variety of potential solutions.
3. Engineers then perform preliminary analysis on all alternatives to determine a single, feasible, most opportunistic solution for further analysis.

4. The chosen concept is then analyzed and modified in detail to achieve all product requirements established in Step 1.

5. If the detailed design cannot be modified to meet all requirements, the process starts over at step 1 or 2 until a solution is found.

The emphasis of PBD is on design process speed. An opportunistic solution can be quickly sought, prioritized, and modified in an attempt to reach a satisfactory solution without taking the time to consider other options. The PBD process works well for simple designs. It starts to show weakness when used to solve complex problems that require multiple groups of individual experts brought together to collectively solve a problem.

As designs become more complex, more teams of designers join to complete the design effort. In PBD, an “over-the-fence” approach is used to perform the sequential complex design process, where the “fence” is the divide between different expertise groups. Using an “over-the-fence” process might seem inappropriate, but it can make sense if communication between design groups is challenging and expensive. Additionally, it is often easier to pass a design to a downstream group, instead of dealing with the task of integration in the present. (Wheelwright & Clark, 1992) The “fences” help divide work into manageable pieces that can be completed individually.

Recalling that Figure 6 showed the escalating cost of extracting defects, note that the negative aspect of PBD is performing the process in a sequential only method (Sobek, Ward, & Liker, 1999). The sequential process leads to incorrect work discovered later and challenges in integration. Delay of work is the main issue associated with the process, since major changes
must be made once information is transferred to downstream activities (Ward, Liker, Cristiano, & Sobek, 1995).

In an attempt to improve on the PBD process, The Prospector brought the team together to shorten the communication cycles between the organizer and team members. This act of coalescing the team to improve on design cycle time is synonymous with concurrent engineering. In concurrent engineering, cross functional, or integrated product development teams, are co-located to bring experts together to improve the communication feedback loops during different stages of the design (Gray, 2011) (Keane, McIntire, Fireman, & Maher, 2009). Although feedback is improved to quicken the design learning process and to flush out rework items earlier, the technique of shortening the communication cycle and increasing iterations/feedback doesn’t change the fact that the team is still working on a single (point-based) solution.

2.2.4 Set-Based Design
The Panner organized the meeting with a process that is synonymous with set-based design. The concept of set-based design will be reviewed and summarized to show who researched what and when to arrive at the principles of set-based design. After summarizing the principles of SBD, the “how” of set-based design is provided.

There are many contributors to the fundamental research that has categorized SBD. The work of Ward, Bernstein, Singer, Ghosh & Seering are summarized in this thesis. Although this reads more like a research report, it is fact based, and summarizes relevant core work on SBD “principles.” Many others have used the references cited in this section to define SBD principles that align with their systems or business. The author does the same to provide SBD principles given the summary of previous works.
The theoretical foundation for SBD was instilled by Allen Ward's MIT PhD thesis in 1989. His work presented a computer compiling program that would assist a mechanical engineer during the design of various systems. Figure 10 shows an example of the mechanical components contained in Ward's compiler program for hydraulic piping systems. The program used component interface information to generate a recommended design configuration to the human design agent based on a status of the current environment.

![Diagram of mechanical components](image)

**Figure 10: Mechanical Compiler Hydraulic Parts Library**

(Ward A. C., 1989)

Bridging his research on mechanical systems to the broader context of all product development, Ward proposed two product development fundamentals (Ward A. C., 1989):

1. All products should be designed with all viable options in mind.
2. Options should not be eliminated unless there is a logical reason to do so.

Ward's approach results in a gradual narrowing of the system solution space while investigating different design concepts in parallel. Keeping all feasible options in consideration for as long as
possible was accomplished by considering groups of mechanical components as “sets,” thus leading to the term “Set-Based Design.”

The Office of Naval Research and the Industrial Technology Institute of Ann Arbor, Michigan funded Ward’s research. Following Ward’s presentation of his PhD findings at the 1989 ASME International Design Engineering Technical Conference, Ward and Sobek and Liker performed further research about TMC’s product development process, having been given their proximity and access to Toyota Technical Center in Ann Arbor, MI (Sobek, Ward, & Liker, 1999). They set out to research TMC’s accreditation with Concurrent Engineering and its recognized ability to bring new, high quality products to market rapidly. Prior to their research into Toyota’s non-traditional manufacturing practices, much had been written about the Toyota Production System, its relationship to LEAN manufacturing, and just-in time inventory. In the 1980’s, traditional manufacturing practice held that economy of scale was the best path to better products at lower cost: one minimizes price by maximizing machine speed and capacity while neglecting the impact of space, transportation, and inventory. However, Toyota paradoxically operated with little, to no, inventory and manufactured vehicles at a lower cost with better quality (Womack, Jones, & Ross, 1990).

In 1995, Ward et al. reported a Second Paradox to how TMC executes its business, which included the following generalities: delaying decisions, communicating ambiguously with its suppliers, and pursuing an excessive number of prototypes (1995). This Second Paradox formed the basis for what their research group defined as a culture of SBCE. Their research was conducted by documenting the communications between three groups at TMC: stylists and body engineers, body engineers and manufacturing engineers, and original equipment manufacturers and suppliers. Overall, they were able to explain the paradox between seemingly inefficient sub-steps and the efficient overall process by summarizing the SBCE progress into four steps (Ward, Liker, Cristiano, & Sobek, 1995):

1. The design team considers “sets” of system solutions by defining options of possible sub-system solutions.
2. Possible subsystem design solutions are explored in parallel using analysis, expertise, and experiments.

3. The design team uses the analysis of each subsystem to gradually narrow the sets of system solutions that are possible.

4. Once the design team has found a preferred sub-system solution, the design does not deviate unless absolutely necessary.

Figure 11 was provided as a diagram by a general manager of body engineering. It visually shows how the “sets” of each subsystem are widely defined and then gradually narrowed over time. Conceivably, the preferred subsystem solutions informed constraints on other subsystems, thus gradually reducing the design to an optimal end state.

A process deemed as “Set-Based Concurrent Engineering” can be boiled down to the following general steps (Sobek, Ward, & Liker, 1999):
1. Map the Design Space.
2. Integrate by intersection.
3. Establish feasibility before commitment.

The work of Ward et al. sparked many others to review their respective business areas for opportunities to become more set-based in their culture or product development processes (1995) in order to mimic the market dominance TMC realized in the late 20th century. In 1998, Joshua Bernstein analyzed the aerospace industry for evidence of set-based design. One of his master’s thesis supervisors was Dr. Allen Ward from the University of Michigan. Bernstein’s research defined SBCE with two principles (Bernstein, 1998):

1. Engineers should consider a large number of design alternatives, i.e., sets of designs, which are gradually narrowed to a final design.
2. In a multidisciplinary environment, engineering specialists should independently review a design from their own perspectives, generate sets of possible solutions, and then look for regions of overlap between those sets to develop an integrated final solution.

In 2003, David Singer became a faculty member at the University of Michigan and offered the following interpretation of the principles of SBD through his dissertation. He used fuzzy logic software to assist a human design agent in conceptual ship design (Singer D. J., 2003):

1. Broad sets for design parameters are defined to allow concurrent design to begin.
2. These sets are kept open longer than typical to more fully define tradeoff information.
3. The sets are gradually narrowed until a more global optimum is revealed and refined.

Singer’s work focused on the importance of keeping the human “agent” in the ship design decision loop during conceptual and preliminary ship design. His work highlighted that current ship design methods focus on poor optimization techniques in the marine industry. Singer supervised and collaborated with many individuals regarding the use of Set-Based Design for container vessels and military warships. Singer’s work helped form the bridge between SBD and
the USN. Most recently, Ghosh and Seering reviewed the previous twenty years of preponderance on SBD principles and characteristics. They qualitatively surmised that organizations performing set-based product development display two principles (Ghosh & Seering, 2014):

2. Delaying convergent decision making.

An organization that displays both principles can be labeled as utilizing set-based product development.

Tailoring the principles to a process for larger complex systems like ship design and acquisition, the author offers the following as principles of SBD based on literature:

<table>
<thead>
<tr>
<th>Principle</th>
<th>Establish the design space and sub-divide along areas of expertise: concurrent subsystem evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Principle 2</td>
<td>Gradually and deliberately reduce the design space by integrating preferred sub-spaces: discovery by elimination</td>
</tr>
</tbody>
</table>

How SBD is executed is a unique process. At the beginning of SBD, the conceptual design is organized into separate sub-spaces along the lines of product form or function that align with individual expertise within the design team (Gray, 2011). During this decomposition phase, design teams establish design variables that represent interfaces between sub-spaces. Design teams identify ranges, or sets, for the interfacial design variables based on experts’ opinions of what is possible. With interfaces defined that provide a range of possible sub-systems solutions, sub-space design teams are able to independently and concurrently create their own sub-system designs (Sobek, Ward, & Liker, 1999). During this stage of initial design, enough analysis is
performed on sub-systems to identify priority sub-system solutions. After preliminary analysis, design teams meet and review sub-space design solutions to identify solutions that have overlapping (shared) design variable ranges. The overlapping regions represent a design space that is feasible for all sub-space design teams (Bernstein, 1998). During these meetings, design teams communicate their preferences for the originally established design variables. Given preferences of other sub-space design teams, the design groups then re-convene and rework designs to incorporate trade-offs and benefits for overlapping feasible design regions. The entire process is gradually repeated with higher fidelity analysis. This process results in eliminating, or not further investigating, regions of the overall design space that are sub-optimal to the whole group (Ward, Liker, Cristiano, & Sobek, 1995).

Figure 12 illustrates the process of SBD: During (1) and (2), SBD Principle One is maintained, in that a large design space is determined by establishing boundaries for sub-system design variables and the concurrent development of individual sets of initial design solutions, initial design solutions are compared across interfacial design variables to identify regions of overlap. During (3), (4) and (5), SBD Principle Two is maintained by concurrently reworking overlapping design regions, which gradually eliminates infeasible or un-preferred regions of the overall design space until the optimal solution is obtained.
2.3 The Value of SBD

As touched on in each of the previous sections, product development in general proceeds in such a fashion that knowledge about the product and its design is low at the onset, but increases rapidly during initial development phases. The knowledge creation process and general progress of the design begins to quickly commit life-cycle product costs as development decisions are made about the product. During the initial design phases, when the development team is small, relatively few costs are incurred when making decisions that influence the majority of life-cycle product costs. This imbalance of incurred cost and committed cost is inherent risk that management attempts to control. Figure 13 and Figure 14 show the relationships of product cost and design knowledge.
Figure 13: Product Life Cycle Cost Trend

(Anderson, 2014)
Utilizing SBD principles during the entire product development process seeks to narrow the incurred and committed cost imbalance by enabling design teams to work in parallel along lines of expertise to make more informed decisions about what doesn’t work for product design. By adhering to SBD principles during design, the opportunity for re-work to be discovered later in product development is reduced. In essence, making a more informed decision closes the gap between committed and incurred costs. Figure 15 builds on Figure 13 and Figure 14 to show how SBD could improve the relationships between design knowledge, design cost, and management influence.
The main benefit of SBD is that it forces teams of designers to communicate in an effective and efficient manner along the lines of product architecture and interfaces – performing design using Principles 1 and 2. SBD communication enacts a decision making process that enables effective and logical decisions to be made with confidence. Fundamentally, SBD is a design method that discovers the optimal solution by a gradual elimination of the design trade space. Considering the discussion of The Prospector and Panner design examples, the surmised principles of SBD, and the flexure of committed costs and management influence in Figure 15, the proposed benefits of SBD can be summarized as the follows:

- Reduction of later stage rework when the cost of change is more expensive; therefore, less cost to design, build, and maintain the product

Figure 15: Relationship of Product Cost, Knowledge, and Management Influence

Adapted from (Bernstein, 1998)
• Reduction of design cycle time; therefore, less cost to design the product and more market share gained from entering an opportunity market sooner
• Better design knowledge capture; therefore, less costly to incorporate customer changes during design or to perform future similar product designs
• A better solution is found because of the methodic reduction of the design trade space; therefore, higher customer satisfaction

2.4 Traditional Ship Design
In the previous sections, discussion about design team architecture, complexity, rework, PBD, and SBD, the context of the “product” has been general. Next, USN ship design is introduced to associate the USN as the organization doing product development and warships as the product. A review of traditional USN ship design styles and methods is provided to coincide with the topics of PBD, CE, and SBD.

Figure 16 presents a ship design example for a surface cargo ship. This ship design spiral has been ship design tradition since originally presented in 1959 by J.H. Evans (Evans J. H., 1959).
This model recognizes the complex nature of the ship design and approaches the design process from the view of conducting iterative passes from one element to the next: weight, volume, stability, resistance, powering, strength, etc. Systematically addressing each element in sequence, and doing so in increasing detail in each pass around the spiral can reach a single balanced design that satisfies all constraints (Frye, 2010). The model incorporates most of the product development process for ships. Iterations around the spiral would first be performed at the concept design level and gradually proceed toward detailed production design. What aren’t captured in Evan’s model are the operations and support phases of ship product development.

This approach to ship product development is synonymous with the term point-based design since each pass through the spiral attempts to resolve conflicts between elements and develop a
design that meets requirements. The result is a base design that is feasible but not typically a global optimum for each segment of the ship product development process. Global optimization methods are available to sample the entire design space to discover favorable solutions, but the complexity and non-linearity of ship design makes this a challenge (McKenney, Buckley, & Singer, 2012). To achieve an optimal solution using a point-based ship spiral design, multiple iterations (or spirals) are performed.

Many problems in ship design arise from traditional design practices, such as, use of the commonly applied point-based design method (Gray, 2011). The problems with a point-based ship design manifest themselves because of the timely, iterative nature of walking around the ship design spiral. As the ship design increases in fidelity and the design progresses in time, it becomes more expensive to “fix” or re-achieve feasibility due to the locking-in of all previous system constraints. The highly iterative nature of point-based design leads to a higher overall design cost and longer design schedule (Mistree, Smith, Bras, Allen, & Muster, 1990).

If the PBD product development method for ships is so problematic, why was/is it used? To answer this question, one needs to step back and look at how the USN fits into the large DoD system during the time period of 1959 to just prior to the 2005, a timeframe dedicated to ship design process improvement. The largest drivers of USN size and strength during this time period were the decommissioning of WWII era ships after the Vietnam Conflict and the build-up/retention of ships during the Cold War (NHHC, 2016b). The DoD, and by proxy, the USN was focused on creating a 600 ship navy to overcome Cold War threats (CBO, 1985). The USN was willing to design ships with a point-based “over-the-fence” method in order to quickly design and produce ships to get them to the fleet. Resolving operations and support issues for ships was achieved by the generally accepted practice of a growing defense budget. This style of product development and production mimicked the US automotive industry during the same era, in which the priority was keeping the production line moving and producing mass volumes of product (Roos, Jones, & Womack, 1990). Figure 17 shows the trend of active USN ships overlaid with the DoN annual budget in billions of Then Year (TY) dollars. The large ramp up
in annual budget in the 1980's coincides with the "over-the-fence" approach of mitigating traditional design practices with increased budget dollars (CBO, 1985).

Figure 17: USN Active Ships and DoN Budget
(NHHC, 2016b) (NHHC, 2016a)

With the conclusion of the Cold War in 1991, the USN began a dramatic decline in ship force structure and therefore re-examined how it conducts its ship design and acquisition processes by directing NAVSEA and DASN to create a process improvement program (Fireman, Nutting, Rivers, & Carlile, 1998). This process improvement program, like The Prospector, adopted Concurrent Engineering and Integrated Product Teams (IPTs) to improve USN ship design and acquisition processes (Keane, McIntire, Fireman, & Maher, 2009). The USS SAN ANTONIO (LPD 17) class of ships was the first to experience many of the process improvement initiatives identified by NAVSEA and DASN in the early 1990's.
The LPD 17 design accomplished many "firsts." The design team for LPD 17 used a design philosophy that prioritized reducing Total Ownership Cost (TOC) by designing for manufacturability and maintainability during detailed design. Keane and McIntire and Fireman and Maher state:

"[LPD 17 was] The first naval surface ship design to employ an Integrated Product and Process Development (IPPD) approach using multidisciplinary, collocated, Integrated Product Teams (IPTs). The authors are not aware of any previous naval ship design that had the NAVSEA Ship Design Manager and the shipyard Technical Director sitting next to each other at the shipyard during the entire Detail Design process" (2009, p. 1).
The first LPD 17 class ship was delivered to the USN in 2005, which results in data being available to evaluate if the LPD 17 design team’s philosophy and many “firsts” achieved reduced TOC. In 1984, the DoD established the Visibility and Management of Operating and Support Costs (VAMOSC) database to be able to track accurate and verifiable O&S costs. In 1992, the DoN centralized management of Navy VAMOSC under the Naval Center for Cost Analysis (NCCA), thus, creating a central database for all USN ship O&S cost data. Using VAMOSC data (VAMOSC, 2013), Figures 19-21 show that, as a class of ships, LPD 17 met its design goal of reduced TOC by achieving lower O&S costs than any previous amphibious ship, but also the lowest dollar per weight ($/LT) cost of any surface combatant in the USN. While observing Figures 19-21, note that the Total Cost Axis for each figure is not to the same scale.

Figure 19: Annual USN Amphibious Ship O&S Cost

(VAMOSC, 2013)
Figure 20: Annual USN Surface Combatant O&S Cost
(VAMOSC, 2013)

Figure 21: Annual USN Aircraft Carrier O&S Cost
(VAMOSC, 2013)
This fact is significant. It shows that the USN took the initiative to invest in studying design process improvement, used its findings, and then realized the expected results. This also shows that a concurrent engineering, IPT, or IPPD approach to ship design and acquisition can be used to design a ship with lower TOC. But Concurrent Engineering still has its disadvantages. It was noted that the LPD 17 design team felt like they were doing ship design better and differently, but there was still room for design process improvement; specifically, the design style was not able to responsively adapt to requirement modifications during LPD 17’s detailed design (OPNAV_e1, 2016).

Initially, the concept of operations envisioned LPD 17 as a ship that could defend itself and others in the Amphibious Readiness Group (ARG) (NAVSEA_m1, 2015). To achieve this aerial self-defense mission, LPD 17 would need a medium combat system, a medium radar, and a bank of Vertical Launch System (VLS) missile tubes. Because LPD 17 would be a missile shooter, it was also necessary to design LPD 17 with reduced radar cross-section mast enclosure and topside paneling (NAVSEA_m1, 2015). As the LPD 17 proceeded into detailed design, its per ship cost began to escalate above established thresholds. Therefore, the USN decided to remove the aerial self-defense mission from LPD 17 and assign a traditional USN Destroyer as an ARG escort (O'Rourke, 2011). Removing the aerial defense mission capability allowed LPD 17 to reduce cost by removing the VLS system, medium radar, and installing a minimal combat system. The design team was able to incorporate the combat system, radar, and VLS removal changes, but was not able to fully explore the secondary effects of the mission de-scoping (OPNAV_e1, 2016). Thus, the final LPD 17 design unnecessarily retained the highly reduced radar cross section topside design. Eventually, the LPD 17 program office realized this unnecessary capability, and they removed it in the 12th and last LPD 17 class ship (O'Rourke, 2016d). Keeping the reduced radar cross section on the first eleven LPD 17 hulls represented an opportunity for further savings that the concurrent engineering, point-based design style, with narrowly focused single design element discussions was not able to realize.
Subsequent to the LPD 17 design and the 1997 Quadrennial Defense Review, the USN found itself with major decisions to make about the entire make-up of its surface combatant fleet (CBO, 1985). With aging Destroyers, Frigates, and Cruisers, the USN needed to decide what mix of large and small surface combatants would be necessary to satisfy future warfighting missions (Work R., 2007). Many different surface ship portfolio options were considered including clean sheet and modified repeat designs for Destroyers, Cruisers, and small littoral ships. In preparing for this period of large surface ship design, the USN again invested in researching new and better ship design methods. Recent research by Dr. Singer and the ship innovation center at University of Michigan inspired the USN to consider SBD as a potential design approach for some aspects of ship product development (NAVSEA_m1, 2015). Further research regarding SBD and the USN will be presented in Phase 3 of this thesis.

2.5 Phase 1 Conclusion

The objectives of Phase 1 of this thesis were to identify principles of SBD and proposed benefits of utilizing SBD for product development. The principles of SBD were summarized in Table 1 and the proposed benefits were listed in Section 2.3. Background concepts regarding product development and design were presented in generic terms. Subsequently, the USN and warships have been introduced as the organization pursuing product development. Significant findings during this phase were the USN’s investment in design process improvement paid off for the LPD 17 class design and the USN has considered using SBD for future large surface combatant design.
3.0 Phase 2: Military Acquisition

Chapter 3 marks the beginning of Phase 2 of this thesis. In this phase, the product development process utilized by the USN is decomposed and analyzed to more critically determine who the stakeholders are in each segment of product development and what are their priorities. The larger DoD acquisition system and common acquisition terminology is introduced, as background information, before presenting the stakeholder priorities and sub-processes that occur inside each segment of the 2P/6G USN warship product development process.

3.1 The DoD Acquisition System

The various organizations of the DoD acquisition environment operate in an integrated manner to perform strategic planning, identification of needs for military capabilities, systems acquisition, and program and budget development. The many experts each serve in numerous capacities and subtly complex roles across this macro-domain, often called the “Big A” acquisition process (Schwartz, 2014).

![Figure 22: The “Big A”](image)

Adapted from (DAU, Defense Acquisition Guidebook, 2016)
Every weapon system in the U.S. arsenal is intended to satisfy a specific military need/capability (JCIDS), must be paid for by the federal budget (PPBE), and is designed and built within an acquisition system (DAS). Those three general functions are represented with a Venn diagram in Figure 22 to depict the nature of checks and balances between each functional group of people and processes. Each segment’s functions are summarized next to provide background context to better understand why design of major defense programs, like ships, is a complex endeavor. The overall goal for the acquisition process is to produce a weapon system on time and on budget that closes an identified capability gap.

### 3.1.1 Defense Acquisition System (DAS)

The DAS provides the management function for all DoD acquisition programs. The most expensive programs, such as shipbuilding, are known as Major Defense Acquisition Programs (MDAPs). MDAPs programs have the most extensive statutory and regulatory reporting requirements. Personnel within the DAS are trained as Acquisition Professionals and certified through the Defense Acquisition University (DAU). DAU is a vast resource of knowledge and training material for the constant entry and exit of military and civilian personnel in the DAS (DAU, 2013). DAS personnel continually perform planning, research, design, development, historical and forecast reporting, innovation, and production management. It is a very dynamic environment, under a rigid structural hierarchy. Acquisition programs, managed from within the DAS, are event-driven but depend on funding, which is calendar-driven (Jones & McCaffery, 2005). The design of ships comes from within the DAS, with requirement validation from JCIDS, and funding from PPBE.

### 3.1.2 Joint Capabilities Integration and Development System (JCIDS)

The JCIDS process operates on an as-needed or where-needed basis, identifying, validating, and prioritizing required capabilities. Only MDAPs that have requirements that cross services (joint) are required to follow JCIDS procedures for capability document reviews (CJSC, 2015). Documents the JROC reviews are the Capabilities Based Assessment (CBA), Initial Capabilities Document (ICD), Analysis of Alternatives (AoA), Capabilities Development Document (CDD),
and Capabilities Production Document (CPD) (CJSC, 2015). Programs that fall under JCIDS purview extensively plan for the somewhat cumbersome progress of staffing a document through the JCIDS review process (PEOSHIPS_m1, 2015). The primary purpose of the JCIDS system is to ensure the operational capabilities required by the warfighter are identified by the DAS with clear performance objectives.

3.1.3 Planning, Programming, Budgeting, and Execution (PPBE)

The PPBE process acts as a means of converting the Defense Planning Guidance into an executable budget that receives Presidential approval, and then congressional authorization and appropriation. Program managers in the DAS support the annual cycle of preparing detailed program budgets that eventually become combined to create a component service Program Objective Memorandum (POM). A POM contains the funding plans to support the next seven years in an executive document known as the Future Years Defense Program (FYDP). The calendar drives the PPBE process and sets the pace for the numerous information exchanges within the Big A (Jones & McCaffery, 2005).

Generically, the functions of the DAS, JCIDS, and PPBE all act in a symbiotic manner to provide some level of transparency and accountability to the government product development and production process. With US taxpayer dollars on the line, the Big A system is designed to have transparent checks and balances. Generally, more oversight and transparency leads to longer product development cycle time. This has been identified in recent GAO criticisms of the DoD acquisition process in which only a marginal amount of benefit has been obtained by the overall review process. Figure 23 summarizes the GAO results of a survey of 24 MDAP program managers which reported more than 50% of required documents were considered to be less than high value. Also, it is significant to note the lengthy time to complete some of the high value requirement documents, like the CDD.
This suggests that there may be room for process improvement in creating these documents, and thus reducing cycle time for overall product development. Noting that one of the proposed benefits of SBD is reduced cycle time, exploring how SBD may be used to reduce the development time of some of the lengthy high value documents will be further explored in Phase 3 and 4 of this thesis.
3.2 General MDAP PDP

Figure 24 shows the generic PDP that decomposes and captures decision points, milestones, and major reviews for a MDAP that is navigating the DAS, JCIDS, and PPBE system.

Major Defense Acquisition Programs (MDAPs) are defined based on Title 10 U.S. Code § 2430, which categorizes programs by acquisition category level (ACAT) based on projected levels of spending. MDAPs are programs that expect to incur more than $480 million in Fiscal Year (FY) 2014 constant dollars or, for procurement, of more than $2.79 billion in FY 2014 constant dollars. MDAPs are labeled as either ACAT ID or ACAT IC programs. All MDAPs have a designated Milestone Decision Authority (MDA) who is the overall executive sponsor. MDAPs that have Joint requirements or JROC interest items are ACAT ID with the DAE as the MDA. MDAPs that do not require JROC oversight are ACAT IC with the CAE as the MDA. As the DAE, USD ATL holds each service acquisition executive accountable for the execution of the DAS within their branch of military service. The USN service (component) acquisition executive CAE is ASN RDA.

The CAE holds program executive officers (PEO) accountable for managing portfolios of similar weapons programs. Program managers (PM) work for PEOs to synchronize information and decision-making for a designated weapons system. During pre-systems acquisition, a PM may not be designated yet. Pre-systems acquisition activities are sponsored [funded] by the
3.2.1 Pre-Systems Acquisition Segments

A MDAP begins with exploratory activities which involve capability gap studies using the National Military Strategy, Defense Programming Guidance, and Defense Intelligence Agency analysis. Capability gap studies may be performed periodically or responsively based on emerging threats. These studies assess the trajectory of adversary threats and the likelihood of planned military solutions to succeed in future concepts of operation. An identified “gap” in capability is where the enemy is predicted to defeat the current military solution AND the defeat is deemed as an unacceptable risk (Schwartz, 2014). Solutions to resolve capability gaps are proposed and assessed as either material or non-material solutions in the form of a Capabilities Based Assessment (CBA). If the service component determines a material solution is preferred, the CBA is validated at the Material Development Decision (MDD) and a sponsored program begins the acquisition life cycle.

After the MDD, the Materiel Solution Analysis (MSA) Phase assesses potential solutions to close identified capability gaps. This analysis is contained in an Initial Capabilities Document (ICD). The MSA phase is critical to program success and achieving materiel readiness because it’s the first opportunity to influence systems supportability and affordability by balancing technology opportunities with operational and sustainment requirements during design (SECNAV, 2011). For MDAPs, the MSA phase ends with an approved MSA decision that has established the materiel solution concept and the Technology Development Strategy (TDS) to mitigate any technology advancement risks.

After the MSA decision, the Technology Maturation & Risk Reduction (TMRR) phase begins. The purpose of the TMRR phase is to reduce technology and life-cycle cost risk and to perform preliminary engineering integration by determining the set of technologies for the full system.
During this phase the Program Manager (PM) will lead a systems engineering trade-off analysis showing how cost and capability vary as a function of the major design parameters. An Analysis of Alternatives (AoA) is conducted to evaluate mission effectiveness and estimate the Life-Cycle Cost (LCC) of alternative solutions that support achieving capabilities per the ICD. The AoA will support generating Key Performance Parameters (KPP) / Key System Attributes (KSA) for the Capability Development Document (CDD). Capability requirements proposed in the CDD should be consistent with program affordability goals. Also, the PM generates the acquisition strategy to execute the remaining technology development and production in future phases. Design, testing, and prototyping are done during TMRR to validate that systems can perform to the level required by KPPs/KSAs from the AoA. The CDD, KPPs/KSAs, and acquisition strategy are all reviewed at the MS B decision point by the MDA.

Overall, planning and design during the early stages of MDAP life represent the foundation of program success. Any weakness in planning or design is likely to result in higher costs over the life cycle of the MDAP. Recall Figure 13 which showed the rapidly increasing rate of committed costs for a product development program. The majority of the material solution design is performed during this pre-systems acquisition stage. After MS B, the material solution has rigid performance requirements which are acknowledged to be feasible based on either modeling and simulation or prototyping of individual sub-systems or complete first-increment deliverables.

3.2.2 Systems Acquisition Segments
The Engineering & Manufacturing and Development (EMD) Phase is where a system is developed and designed before going into production. The EMD phase consists of two major efforts: (1) Integrated System Design and (2) Manufacturing Process Demonstration. The goal of this phase is to complete full system integration and demonstrate an affordable manufacturing process. MS C marks the completion of EMD and the beginning of production and deployment (PD). The PD phase focuses on achieving affordable production by acquiring a small batch of weapon systems to exercise the production process before acquiring the bulk of the planned
weapons system procurement. This phase also implements support and maintenance logistics that will be utilized in the upcoming operations and support (O&S) phase. In this phase, the test and evaluation processes dominate improvement efforts or redesign. As the testing environment more closely approaches that of the users’ needs, the required improvements might be complex and/or subtle. The initial manufacturing process may also reveal issues that were not anticipated (SSGC, 2015).

3.2.3 Sustainment Segments
The O&S phase begins once a MDAP achieves Full Operational Capability (FOC); in other words, once a weapons system has been delivered to the warfighter and the warfighter has the ability to operate and maintain the asset. In this phase, the training and maintenance logistics are just as important as the construction/delivery of the weapons system. Typically, operational commands rely heavily on technical representatives and program office support during the first year of acceptance of a new weapons system. Consequently, annual O&S costs are typically higher for “lead” weapons systems. Also, the majority of the life cycle cost occurs during O&S. Planning and design that occurred as early as material system analysis can have a significant effect on overall O&S costs. Although there is almost no way to accurately predict the operational environment a weapons system will experience during O&S, a weapons system program is held accountable to the designs, estimates, and assumptions performed during earlier life cycle stages that will determine the true cost of the system.

3.2.4 Disposal Segment
A system or piece of equipment is decommissioned when a system has reached the end of its useful life due to age, economic feasibly, new technology, or outdated capabilities. This study does not focus significantly on this period since there is little, to no, design that occurs during disposal.
Overall, MDAP design mainly occurs in pre-systems acquisition and systems acquisition phases. Although some modernization design occurs during O&S, the focus of this thesis is on considering SBD for the USN 2P/6G PDP and not modernization. Therefore, only PDP segments prior to MS B will be evaluated for design process and tool amenability during Phase 3 of this thesis.

3.3 The Triple Constraint and DoD Program Metrics.

PMBOK version 2015 defines project management as “the application of knowledge, skills, tools, and techniques to project activities to meet project requirements. Balancing the competing project constraints, which include, but are not limited to: Scope, Quality, Schedule, Budget, Resources, and Risks” (Institute, 2015). Kernzer is his recent book Project Recovery: Case Studies and Techniques for Overcoming Project Failure discusses project management constraints as evolving from the traditional cost, schedule, and performance to include other secondary constraints which can be folded into the original project management triangle (2014).

Both these recent classifications of project management constraints hint that the classic project management triangle of cost, schedule, and performance might be becoming a different shape. Figure 25 represents the author’s opinion of today’s project management dichotomy which stresses that project managers should manage primary and associated secondary constraints to stay within the stakeholder satisfaction circle.
Figure 25: Today’s Project Manager Triple Constraint

Adapted from (Kerzner, 2014)

DoD program managers are accountable to their respective PEOs; and therefore, need to understand which constraint(s) is/are the priority during the DoD program life cycle. As a MDAP matures through the project life-cycle, cost, schedule, and performance metrics begin to take shape during the pre-systems acquisition phase. The AoA sets initial cost goals and initial KPPs/KSAs (CJSC, 2015). Between MS A and MS B, CDD validation sets objective and threshold performance metrics which cannot be traded-off by the PM without MDA/JROC concurrence (CJSC, 2015). After MS B, a MDAP has established an acquisition program baseline (APB) which rigidly sets the cost, schedule, and performance metrics which are translated into government EVMS for formal project management evaluation. PMs excel by expertly adapting the trade space within the triple constraint to responsively pursue their initial targets as outlined in their APB.

The DoD EVMS system categorizes cost and schedule performance (efficiency) characteristics based on quantifying the cost and time of actual work. In EVMS, the result of actual works is
compared to the original plan to calculate performance. These performance measures are typically visually and mathematically tracked using "S" charts and the EVMS Gold Card equations shown in Figure 26.

![EVMS Chart](image)

**Figure 26: DoD EVMS**

(DAU, 2016)

Data from an APB is captured and updated periodically in the format of a Selected Acquisition Report (SAR). The SAR includes the status of the total program cost, schedule, and performance and is mandated to be submitted annually by the PM using DAMIR (OSD, 2014). Cost and schedule performance on a SAR is documented in a different way than EVMS. Cost and schedule are not mathematically converted into efficiencies, just documented to show numerical
or date differences. The SAR compares the current approved plan (baseline) Acquisition and Operating & Support costs against the original baseline APB. Cost and schedule efficiencies can be easily calculated by anyone using the relationships in Figure 26. Acquisition costs on the SAR are summarized by PAUC. The PAUC factors in all the acquisition costs including all of the RDT&E, Procurement and MILCON costs. Conceptually, the PAUC reflects every cost required to produce the weapons system, including the technology and capital expenditure costs necessary to bring the program into an operational status (e.g., producible, reproducible, reliable, etc.).

\[
\text{Program Acquisition Unit Cost (PAUC)} = \frac{(\text{Total Acquisition Dollars})}{(\text{Total procurement quantity})}
\]

Figure 28 shows an example SAR PAUC cost comparison using the 2015 LPD 17 SAR (cover page shown in Figure 27).

![Figure 27: LPD-lpd 1717 SAR Cover Page](image)

(DAMIR, 2015)
Figure 28: LPD 17 Unit Cost History

(DAMIR, 2015)

Annual O&S costs in the SAR reflect cost from VAMOSC and are simply multiplied by projected years of future service to predict program O&S cost. SARs utilized an antecedent comparison of a similar ship for O&S cost performance comparison. Figure 29 shows an example of O&S cost comparison using the 2015 LPD 17 SAR.
For ship programs, the APB defines the program’s position within the triple constraint. Of the primary constraints shown in Figure 25, ship PMs are least likely to sacrifice performance. Holistically, the acquisition community’s basic purpose is to support the warfighter; thus, Navy PMs are wary of sacrificing capability. Navy PMs strive to be more creative in the cost and schedule areas and involve higher level decision authorities if trading performance appears to be the best course of action.
3.4 How the USN Fits In the DoD Acquisition System

With an understanding of a generic DoD MDAP, the transition needs to be made to the USN organization and warship products. The Secretary of the Navy has authored and issued SECNAV 5000.2E to depict how the USN will operate within the DAS/PPBE/JCIDS triad and describes the 2P/6G process for ship product development. The purpose of the 2P/6G process is to improve insight into ship development and execution of its acquisition. The process seeks to improve senior leadership decision-making through a better understanding of risks and costs throughout a program's entire development cycle (NAVSEA, 2010). Figure 30 depicts the 2P/6G process for a USN MDAP.

Figure 30: USN Two Pass / Six Gate (2P/6G)

(NAVSEA, 2012)
Figure 30 provides a visual depiction of USN ship product development process which identifies the summary deliverable and decision chair for each Gate review board in 2P/6G. But to fully explore how a design method aligns with segments of the 2P/6G process, a more complete understanding of occurring organizational relationships inside 2P/6G is necessary to support obtaining Phase 2 deliverables of stakeholder priorities and cases of SBD use in the USN.

Figure 1 identified the organizational relationships of 2P/6G within the Big A. Solid lines are direct reports via an administrative chain of command, and dashed lines indicate indirect reports via a functional chain of command. For example, ASN RDA, as the USN component acquisition executive, reports indirectly to the defense acquisition executive (USD ATL) but is directly controlled and funded by the Secretary of the Navy. Overall, Figure 1 depicts the DoD ship design and acquisition community organizational relationships in a simple diagram. The following summarizes each organization and its function.

The Secretary of Defense is at the top of the hierarchy and is responsible to the President of the United States for the effectiveness of the Department of Defense. Working under the SECDEF are the Office of Secretary of Defense, the Secretary of the Navy, and the Chairman of the Joint Chiefs of Staff. OSD’s function can be generalized as oversight. SECNAV functions can be summarized as analysis and all acquisitions actions. The Joint Staff, via the Chairman of the Joint Chiefs of Staff (CJCS), support requirements creation and validation during acquisition activities.

Inside the Office of the Secretary of Defense resides USD ATL, various intelligence agencies, and CAPE. USD ATL is the senior civilian acquisition position in the DoD and is the principal advisor to the Secretary of Defense for research, development, production, procurement, logistics, and military construction. USD ATL holds ASN RDA accountable for all USN acquisition actions. Intelligence agencies, such as DIA and DARPA, provide adversary capabilities to program sponsors for requirements development. Following the guidance of the
2009 Weapons System Acquisition Reform Act (WSARA) which forces cost consideration across all of the DOD acquisition functional areas (DAS, JCIDS, and PPBE), the Office of Cost Assessment and Program Evaluation (CAPE) was created to analyze and address the costs of new programs. This mandate creates a central authority that enforces better cost management (affordability). Also, WSARA established that the director of the CAPE (DCAPE) must ensure that each alternative materiel solution presented to the JROC fully considers possible trade-offs among cost, schedule, and performance objectives (Husband & Kaspersen, 2012).

Inside the Secretary of the Navy resides the CNO and staff, ASN Financial Management, and ASN RDA. The CNO is the senior military officer in the USN and is responsible for its operating efficiency. The CNO is a member of the Joint Chiefs of Staff. ASN Financial Management works with the Navy Center for Cost Analysis to produce USN cost positions/estimates for official programs. ASN Financial Management reviews all USN cost estimates before submitting them to CAPE for independent review. ASN RDA supervises all acquisition actions for USN ship programs. DASN SHIPS, PEO SHIPS, and NAVSEA directly report to ASN RDA. The three organizations under ASN RDA mark the transition from oversight to analysis and design.

DASN SHIPS provides advice on ship programs managed by NAVSEA and PEO SHIPS and serves in a similar capacity to independent oversight of internal USN ship design and acquisition activities. PEO SHIPS manages the design and construction of ships. PEO SHIPS relies heavily on NAVSEA 05D to do early stage ship design and the shipbuilding industry to do late-stage ship detailed design. NAVSEA’s primary functions are to engineer, build, and support the USN’s fleet of ships. Internal to NAVSEA is the NAVEA 05 Directorate. NAVSEA 05 is the Chief Engineer of the Navy and provides the technical authority to design, build, modify, and certify USN ships and submarines. Within the NAVSEA 05 Directorate, NAVSEA 05D is in charge of surface ship design and systems engineering and NAVSEA 05C is responsible for cost engineering and industrial analysis. Warfare Centers support NAVSEA by providing people, technology, engineering services and products needed to equip and support the USN ship design.
and acquisition community. Warfare Centers are the Navy's primary Research, Development, Test and Evaluation (RDT&E) assessment activity for ships.

The CJCS is, by U.S. law, the highest-ranking military officer in the United States Armed Forces and is the principal military advisor to the Secretary of Defense. The Joint Staff assists the Chairman by acting as a conduit and collector of information between the Chairman and the combatant commanders. The JROC provides the CJCS a broad, objective, joint group of high ranking military and civilian officials to validate requirements as proposed by the USN acquisition community as previously discussed. As the sounding voice of the Navy, the CNO provides policy specific recommendations on Joint efforts at the National level of discussion. The CNO's staff is comprised of many different departments, but only N8, Deputy CNO for Integration of Capabilities and Resources, and N9, Deputy CNO for Warfare Systems, are heavily involved in USN ship design and acquisition.

N8 coordinates the USN's capability analysis and assessments of ship design requirements. N8 staffs requirement and design documents that need formal USN and JROC approval for ACAT 1D MDAPs. N9 oversees requirements and resource allocation across Expeditionary Warfare (N95), Surface Warfare (N96), Undersea Warfare (N97), and Air Warfare (N98) areas. Before a MDAP is formally created and a program manager is assigned, N9 provides requirement officers and program sponsors to lead the development of the pre-MDAP concept design activities. N96 is the program sponsor for ship design.

Overall, Figure 1 and Figure 30 provide high-level, introductory views of how the USN 2P/6G process fits within the larger DoD acquisition system. But, to understand the sub-processes that make 2P/6G work, a more critical review of each gate and corresponding style of ship design is necessary. Up to this point, a major DoD acquisition program was defined and decomposed into segments of pre-systems acquisition, systems acquisition, operations and support, and disposal. And, it was noted that the majority of design occurs within the first two segments. This section
introduced 2P/6G its organizational interactions. During this introduction, NAVSEA 05 and its associated departments were determined to comprise the foundation of USN engineering and technical authority. To understand the sub-process interactions that are occurring within 2P/6G, a more critical review of ship design from a NAVSEA perspective is warranted.

### 3.5 Navy Ship Design via NAVSEA 05D

Per the SECNAV 5000.2E and through interviews with organizations from Figure 1, most of the tangible activity in USN ship design resides and is supervised by NAVSEA 05D, N9, N8, and DASN/PEO SHIPS. Of those organizations, NAVSEA 05 has the technical authority to certify design products; therefore, NAVSEA 05, and NAVSEA 05D for ships, is tasked with leading and producing ship design products during all stages of the general MDAP development process per Figure 24 and the 2P/6G process from Figure 30. Figure 31 combines Figure 24 and 30 by listing the ship design style per phase of 2P/6G. In some documents and literature, Exploratory and Pre-AoA design were considered Concept design (NAVSEA, 2012) (Garner, et al., 2015)

![Figure 31: Design in 2P/6G](image)

Adapted from (NAVSEA, 2012)

Individuals in NAVSEA 05D align under either Ship Concept Managers (SCM) or Ship Design Managers (SDM). Because ships are complex products, these managers are the designated leaders of integrated design teams. In the early stages of ship design, a formal ship program and PM position may not exist; therefore, the SCM leads and champions ship design activities usually until MS A. Once a ship program is created and a PM is assigned, the SCM role changes
to SDM. An SDM will normally be designated when either of the following events occurs: [1] the ship appears in the Future Year Defense Plan in the current year through three years beyond the current year, or [2] upon receipt of a signed tasking from OPNAV via the Program Office (NAVSEA, 2012). This transition for ships typically occurs after MS A or after the CDD has been developed.

As the ship progresses through various stages of design, the SDM manages a cross functional team of designers who may be a mixture of government personnel or contractors (NAVSEA, 2012). In order to obtain a certified [usable] design product for the ship program or program sponsor, a Technical Warrant Holder (TWH) within NAVSEA 05 must certify the design. By utilizing this cross functional approach where SDMs are leaders and TWH are the certifiers, the engineering integrity of USN design products is improved by isolating the engineering TWH from the program management pressures of cost and schedule. Figure 32 captures the engineering knowledge and IPT structure within NAVSEA 05.
SDMs provide essential technical leadership in guiding the Navy's total ship system engineering team supporting a ship program. SDMs are responsible to the PM for the technical certification and authenticity of ship design products at appropriate stages of the 2P/6G development process. SDMs utilize various different ship design experts, appropriate to the ship design phase, to realize the necessary ship design product to support the PM overall acquisition plans and strategies. SDMs are typically experienced senior ship designers that have expert leadership and communication skills. The ability to lead and work through people is probably the most important qualification of the SDM. The SDM has the following major responsibilities (NAVSEA_u1, 2015):

- Ensure the development of a fully integrated, technically satisfactory ship design that meets the specified performance requirements and cost.
- Serve as the warranted technical authority for the ship assigned. The SDM must ensure other TWHs are engaged as necessary to resolve issues. If technical differences cannot
be resolved, the SDM must document the issue and arbitrate or refer the issue to higher authority for resolution.

- For the ship assigned, serve as the interface between the technical community and the Program Office and OPNAV.
- Establish and communicate the design philosophy for the ship.
- Establish and lead the Design Team and interface with other elements of the program organization.

During discussion and interviews with NAVSEA 05 and OPNAV N8/N9 individuals, it became apparent that the bulk of impactful ship design occurs during Gates 1-4 of 2P/6G. Similar to Figure 15 which showed the trend in design knowledge and committed design costs achieving close to 80% at the end of “design,” design and program management experts familiar with the 2P/6G process shared their experience that once the SDS at Gate 4 is established, almost all of the ship design trade space has been exhausted. Contract Design and Detailed Design activities are performed preceding Gate 5 and are focused on generating design documents to the level of detail necessary for generating a contractual Request for Proposal (Gate 5). Unless there is a significant change in adversary capability, major design revisions during Gate 5 and Gate 6 are typically avoided. This coincides with the conclusion of section 3.2.4 which revealed little impactful design occurs in O&S and Disposal segments of a MDAP PDP.

3.6 Design Intensive Gates of the USN Two Pass / Six Gate Process

Previously, the organizational aspects of USN ship design and its various stages were introduced. Additionally, it was determined that only Gates 1-4 of the 2P/6G process provided significant value for design process analysis. In order to extract the stakeholder priorities of Gate 1-4, each segment will be summarized to more clearly understand the who, what, how, and why of each segment.

In general the objective of 2P/6G is to:
"establish a disciplined and integrated process for requirements and acquisition decision-making within DON. It will endorse or approve key JCIDS and acquisition documents, and facilitate decisions regarding required Navy and Marine Corps capabilities and acquisition of corresponding materiel solutions" (SECNAV, Department of the Navy Implementation and Operation of the Defense Acquisition System and the Joint Capabilities Integration and Development System, SECNAVINST 5000.2E, 2011, p. 52).

The 2P/6G integrated process links the operational and acquisition organizations of the USN. This process enables systems engineering to occur at earlier stages of ship design by bringing together the requirement setters with technical design experts to, in essence, force the discussion of what’s possible, realistic, and feasible for ship design.

The process is a staged-gate process. The work during each “gate” culminates with formatted information presented to a Gate review board. This review board is chaired by one entity but involves many individuals. As with most government decision boards, the entrance, exit, and planned discussion criteria are well known to ship concept and program managers. Expected entrance, exit, and discussion criteria are contained within SECNAV 5000.2E, Annex 1-B - Table E1T3 and are provided in Appendix A for contextual review.

To understand how the entrance criteria and discussion criteria are evaluated during Gates 1-4, interviews were conducted and example ship acquisition documents were reviewed to extract the processes and tools that are utilized by organizations involved in activities during each gate. The following summarizes Gates 1-4 to extract stakeholder priorities for Gates 1-4 for future evaluation of the amenability of a design process to align with stakeholder priorities at each Gate.
3.6.1 Gate 1 (CBA/ICD)

As the tip of the ship design, activities in Gate 1 start by considering the ship at the highest level: capabilities necessary. Required capability determination starts with a USN sponsored CBA in which the future USN Fleet is modeled against projected threats. The result is a CBA which produces an assessment of either a material solution or non-material solution to overcome concerning shortfalls in future USN Fleet performance. The type of ship design performed during a CBA is exploratory design. Exploratory design does not explore the goodness of different types of ship forms or functions against future threats; it only evaluates the performance of the programmed (as budgeted and planned) Fleet. The only design decisions performed during exploratory design revolve around how to model the performance of the future fleet.

Future required Fleet performance is provided by Combatant Commanders identifying mission essential functions for conducting higher strategic guidance. The DoD and USN have predetermined functions Combatant Commanders can submit in the form of Joint Capability Areas (JCAs). During exploratory design, JCAs are refined by OPNAV N8 and NAVSEA 05D SCMs into predetermined tasks from the Universal Joint Task List (UJTL), Universal Naval Task List (UNTL) and the Naval Tactical Task List (NTTL). Designated tasks from the NTTL comprise the Navy Mission Essential Task List (NMETL) which is used during exploratory design to formulate the Design Reference Mission (DRM). The DRM is essentially the functions (capabilities) the ship needs to perform. The ship, as a system of systems, achieves the capabilities necessary to achieve tasks, which satisfy the mission. Figure 33 highlights these relationships.

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1 JCAs are collections of like-DOD capabilities functionally grouped to support capability analysis, strategy development, investment decision making, capability portfolio management, and capabilities-based force development and operational planning at JCIDS Functional Capabilities Boards (FCBs).
DRMs for ships are the inputs used for fleet architecture studies. Fleet architecture studies are large, dynamic in nature, and encompass the system of systems aspects of the USN Fleet. Fleet architecture studies are typically performed by government agencies and their contractors, who have systems modeling tools to create large scale scenarios. Organizations like the Center for Naval Analysis or Applied Physics Laboratory have conducted fleet architecture studies to support Fleet Forces preliminary force structure assessments (Belcher & Shuford, 2012). The outputs of a fleet architecture study are the performance shortfalls of the Fleet against threats. These shortfalls represent capability gaps.

If the capability gaps represent significant operational risk, then recommendations for materiel and/or non-materiel approaches for closing or mitigating the capability gaps are generated (CJCS, 2012). Non-material solutions typically represent an alliance or treaty that leverages use of someone’s capability. If acceptable non-material solutions do not exist, then the default answer is a material solution. The assessment of the Fleet’s performance and the non-material or material solution decision comprise the outputs of the CBA. Further analysis of ship forms (types) to accomplish necessary NMETL functions to overcome, or close, the gap are left for future ship product development phases.
As one of the main deliverables from Gate 1 activities, the CBA serves as the core input to the ICD. The ICD quantifies capability gaps and operational risks based upon the identified capability requirements. The ICD\(^2\) is a significant document that receives much scrutiny and review during the ship development process. Pre-AoA ship design is utilized by NAVSEA 05D to quantify how to assess the capability gap for the ICD. Similar to exploratory design, a NMETL is generated to make a DRM that mitigates gaps identified by the CBA. Existing ship designs with minimal information (complexity) comprise a capability gap material solution.

During Pre-AoA design, a small design team lead by an SCM and a few engineers begin to develop multiple, high-level ship concept, or feasibility, designs to investigate the impact of trading off requirements on ship performance, size, and cost. The emphasis of Pre-AoA design is on more clearly articulating the NMETL as it applies to the ship concept. The outcome of Pre-AoA design and the resulting ICD document is the early stage application of material solution forms to the DRM. These early stage material solutions are then transposed into the preparatory AoA documents: the AoA study guidance and AoA study plan. With a completed CBA, proposed ICD, and generated AoA study guidance and plan, the OPNAV program sponsor is ready for a Gate 1 review board. As a summary of the above discussion, Figure 34 shows the interaction and conduct of activities during Gate 1.

A Gate 1 review board will:

- Grant authority for a DoN-initiated ICD to be submitted for joint review;
- Validate the proposed AoA study guidance and endorse the AoA study plan;
- Authorize a program to proceed to MDD.

Stakeholder Priorities: The Gate 1 review board is chaired by CNO N8. During an interview with an N8 executive, the top level priorities leading to a successful Gate 1 decision board approval centered on understanding two areas: understanding risk and not jumping to conclusions. The top risks for N8 to understand at Gate 1 were intelligence and technology.

Because a CBA is performed internally to the USN with the assistance of the intelligence community; N8’s opinion was, that in the past, the relationship between the USN requirements and acquisition community and the intelligence assessment community may not have been a constant dialogue. Therefore, understanding which threats and assessments formed the
capability gap was a high priority. The assessed threat level determines the extent of USN ship capability. As threat capabilities continue to advance, this has forced the USN to develop new technologies to maintain a tactical advantage. Identifying these potential technologies is captured in the recommendation section of the ICD. In the past, the USN had failed to develop some technologies adequately enough to meet scheduled ship delivery dates; therefore, assets were being delivered to the fleet with legacy system solutions that were more challenging to integrate on a more modern platform. Therefore, N8 prioritized understanding why and what technology the sponsor organization was recommending in the ICD.

In addition to understanding intelligence and technology risk, N8 was cautious not to allow the sponsor to jump to a specific material solution recommendation inside the ICD. N8’s opinion, based on past experience, was that a more general solution in early development allowed more flexibility for the follow-on Gates and development. Even if the sponsor believed they knew what could work, N8 forced a more general material solution recommendation.

3.6.2 Gate 2 (AoA)

There are a lot of activities that occur outside of the USN 2P/6G process that happen prior to a Gate 2 USN review board, especially if the ship program is a Joint (ACAT 1D) program. For a Joint ship program, the ICD is submitted for Joint review immediately after the Gate 1 review board. Regardless of whether the ship program is joint, or not, the USN proposed AoA Study Plan and AoA Study Guide are also submitted to DCAPE for review and concurrence immediately after Gate 1. After the ICD, AoA Study Plan, and AoA Study guidance have all been validated, the ship program proceeds to the MDD. The MDD is the ship program review with executives above the USN. At the MDD, USD ATL reviews and concurs with the ICD and AoA guidance and establishes the plan for future gate reviews. USD ATL’s decision actions are captured in an Acquisition Decision Memorandum (ADM).
Once a ship program has obtained the MDD ADM, the ship sponsor spurs the next sequence of ship design by funding the planned AoA. USN ship AoA’s are typically conducted by the SCM or SDM with a small dedicated staff and follow the AoA Study Guidance by executing the AoA Study Plan. A ship AoA assesses multiple different material configurations (system architecture form) that all achieve the requirements (system architecture functions). This assessment is expected to support a cost effective solution decision. For ships, each designed AoA variant begins to develop a specific topside layout, outboard profile, and major weapon system arrangements. Manning levels are low fidelity; therefore, complete internal arrangements are also low fidelity. Thus, margins are utilized to mitigate design risk (NAVSEA_m1, 2015).

In the past, USN ship AoA’s have been conducted by both private contractors and the USN (OPNAV_m1, 2016). Regardless of who performs the AoA, an AoA Executive Steering Board is established to supervise AoA Working Group in-progress actions and be aware of expected results. Representatives from DCAPE and N8 are part of the AoA Executive Steering Board. The outcome of a ship AoA is an extensive study of the range of potential material solutions [forms] that can achieve the capabilities [functions] identified in the ICD (CAPE, 2016). The AoA Working Group proposes a preferred alternative for AoA Executive Steering Board and ship sponsor approval. The AoA results establish the baseline inputs for the CDD, specifically the KPPs/KSAs.

Once the AoA has been completed and internally reviewed by the Executive Steering Board, the sponsor and SCM/SDM prepare for the Gate 2 review board.

The Gate 2 review board will:

\[\text{KPPs/KSAs represent the most critical design performance parameters for the ship. KPPs/KSAs can be general or specific and can focus on either production or life-cycle attributes. KPPs/KSAs also can have a performance range, vice a point value. When listed as a range, the lower value is defined as Threshold and the higher value is defined as Objective. KPPs are contained in the performance section of a SAR. LPD-17 KPPs are provided as an example in Appendix B.}\]
• Review the TOC estimate for the preferred AoA alternative and assess the operating and support implications of each alternative;
• approve initial KPPs and KSAs (thresholds and objectives) for CDD and CONOPS development;
• Authorize a program to proceed to Gate 3 (SECNAV, Deparment of the Navy Implementation and Operation of the Defense Acquisition System and the Joint Capabilities Integration and Development System, SECNAVINST 5000.2E, 2011).

Stakeholder Priorities: The Gate 2 review board is chaired by the CNO, VCNO, or N8. Overall, the CNO's staff prioritizes a higher number of variants in the initial AoA queue and the resulting Cost vs Capability trade-off information. As the agency who submits the annual USN budget to the SECDEF, the CNO has a notional cost goal in mind for the ship in development; thus, the AoA is the first opportunity to assess the cost of necessary performance. Understanding Cost vs Capability is a priority ingrained into the CNO's staff by the BBP series of memorandums. In 2012, this series of memorandums established affordability\(^4\) to be treated as a KPP like speed, range, or data rate. USD ATL sets affordability targets at MS A and cost constraints at MS B. MS A for ships happens right after Gate 3; therefore, the CNO is relying on the design efforts during Gate 2 to lay the foundation for a defensible Cost vs Capability discussion between DoN and the DoD at MS A.

3.6.3 Gate 3 (CDD)
Activities that occur prior to a Gate 3 review board all push toward creating and refining a USN proposed CDD. In its final state, the CDD\(^5\) provides traceability to predecessor capability

\(^4\) Affordability is defined by USD ATL as conducting a program at a cost constrained by the maximum resources the Department of Defense can allocate for that capability. USD ATL sets an affordability target at MS A via the MS A ADM. At MS B, USD ATL expects a presentation of systems engineering tradeoff analysis to show how cost varies as major design parameters and time to complete are varied.

\(^5\) A CDD contains the following areas: Cover Page, Validation Page, Executive Summary, Operational Context, Threat Summary, Capability Discussion, Program Summary, Development
requirement documents, defines key performance metrics, and outlines projected life cycle costs
(CJCS, 2012). In some cases, the high level ship requirements desired by the warfighter or
OPNAV sponsor have changed during the period of time between the beginning of Gate 2 and
Gate 3 due to either evolving threats or extraneous budgetary pressures; therefore, some
additional effort in Gate 3 is required to re-shape the closest variant considered in the AoA to
current sponsor preferences (Singer, Doerry, & Buckley, 2009). The majority of activities in
Gate 3 are performed by the OPNAV sponsor and NAVSEA 05D. During these phases,
NAVSEA 05D is typically consulting the ship design with the Naval Surface Warfare Center,
Carderock Division (NSWC-CD) for subject matter experts in NSWC-CD’s core competencies:
design and integration technology, environmental systems, hull forms and propulsors, signatures
and silencing systems, and survivability and vulnerability systems. The activities of Gate 3
close-out Pass One of 2P/6G. Overall, Pass One ship design efforts have been funded by the
OPNAV program sponsor, and led by the SCM/SDM through an IPT of technical experts from
both government and contractor agencies.

SDMs and TWHs described ship design after the AoA as re-performing (iterating) the ship
design with just increasing levels of detail. After the AoA, there is often insufficient design
detail or requirements definition to complete generating a CDD or entering into Preliminary
Design (NAVSEA, 2012). Thus Pre-preliminary design is performed to improve quantifiable
ship design characteristics. Since AoA’s only surveyed a finite number of ship design variants,
often on the order of around 7, the preferred ship design concept has often been a blend of two
specific AoA variants. Ship designers and program managers referred to this as the preferred
ship design being a “middle point” between two AoA variants. In order to more accurately
assess the cost of the “middle point,” pre-preliminary design is used to iterate one of the AoA

KPPs/KSAs, Other System attributes, Spectrum Requirements, Intelligence Supportability,
Weapon Safety Assurance, Technology Readiness, Training, Logistics, Material and Facility
Considerations, and Program Affordability

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variants into what the OPNAV ship sponsor and SDM want. This more specific variant is used to generate a more accurate cost or performance estimate.

Pre-preliminary design improves upon previous assumptions used during the AoA for ship design and construction timelines. In general, design maturity has progressed to a state where a feasible solution has been found within the overall program parameters of ship size, cost, and performance (NAVSEA, 2012). This means predicted total ship system capabilities will deliver KPPs/KSA performance levels and there are no technical “show stoppers” at the subsystem level. No problems are anticipated that cannot be corrected in subsequent design phases within the total program constraints. Subsequent phases will evolve the design from a merely feasible solution to a more optimal solution and some changes to major subsystems may still be needed in the next phase but should not require resizing of the ship. The size (displacement) and external dimensions are fixed (or very close to being fixed) and include fallback opportunities for technology or systems that still need to be developed. Major sub-systems have been selected and placed within the ship based on tradeoff studies.

With the selection of ship major systems and sub-systems performed during Pre-PD for the CDD, the plan to complete the massive document, known in the USN as the System Development Specification (SDS), comes together. In Pass Two, the SDS will be used as exact contractual verbiage in a ship production Request for Proposal (RFP) to private industry. Additionally, every ship specification in the SDS must be approved by the cognizant NAVSEA 05 TWH. Thus, it behooves the PM and SDM to begin obtaining the necessary TWH concurrence on written ship specifications as soon as ship designers close portions of the ship design during Pre-PD as the preferred ship variant begins to solidify.

Overall, ship design activity prior to the Gate 3 review board can be considered a team effort between the OPNAV sponsor, NAVSEA 05D and NSWC-CD ship designers, NAVSEA 05C cost engineers, and the various TWH in NAVSEA 05 to certify ship design performance within
the CDD. The CDD is an extensive document that summarizes most of the ship programs background research, early design efforts, and initial analysis of alternatives. This phase of Gate 3 activity can be summarized as validating that CDD KPPs/KSAs have a reasonable expectation of being achieved within available cost targets. At the end of Gate 3 ship design activities, the ship sponsor and SDM should be able to answer the following questions with a “yes”: Are the system level requirements clear, complete, compatible, achievable, affordable, and testable?

The Gate 3 review board will:

- Approve the CDD prior for MS A and for submittal to the JROC and JCB, if necessary;
- Approve the CONOPS to support life-cycle, total ownership, and the service cost position;
- Validate the SDS development plan.

Immediately following a ship Gate 3 review board, the ship program will prepare for and enter the MS A review board. During the MS A board the PM will present the overall plan to acquire the ship design: the Acquisition Strategy, framing assumptions, program risks and how specific technology development and will reduce risk to acceptable levels, and appropriate cost targets (CJCS, 2012). This major event in the DoD acquisition process shapes many of the efforts during Pass One of 2P/6G and consumes most of the PMs focus during Gate 3 activities.

Stakeholder Priorities: The Gate 3 review board is chaired by the CNO, VCNO, or N8. As the last decision point in Pass One (requirements), the priority for the CNO’s staff is understanding the feasibility of achieving the KPPs/KSAs and associated cost drivers of each KPP/KSA. For a joint ship program, changing a KPP/KSA after validation is a major investment in time and staffing resources; therefore, the CNO’s staff desires to understand specifically areas of the design in which assumptions were made. To fully understand KPP/KSA cost drivers, subsystem integration is required.
3.6.4 Gate 4 (SDS)

Gate 4 activities mark the beginning of Pass Two and the transition from the requirements Pass to the acquisition Pass. Pass Two focuses on detailing ship design integration for contracting procurement.

Exiting Gate 3 has prepared the ship program for the DoD MS A review board by obtaining USN validation of the proposed CDD. While reviewing the CDD at MS A, the MDA considers: the projected threat’s impacts on the ship design and the justification, affordability, and feasibility of the ship design trade space (DoD, 2015). The MDA validates the CDD with a MS A ADM which establishes a PM for the ship program. The PM and SDM use the validated CDD to start the major ship design process known as Preliminary Design (PD).

Preliminary Design emphasizes solidifying ship size, external configuration, and the overall allocation of space to major propulsion, electrical, and mission essential mechanical and combat system elements. This design results in a “budget quality” cost estimate for the APB. The PD process establishes the functional baseline of the ship. Any changes in ship design requirements initiated after PD are normally incorporated as a modification to the existing baseline, instead of a re-optimization (NAVSEA, 2012).

The PD core team consists of the SDM, Design Integration Manager, Project Naval Architect, Project Marine Engineer, general arrangement engineer, structural engineer, weight engineer, System Integration Manager, Combat Systems integrator, and one or two general naval architects. This core team interacts with a large conglomerate of outside agencies that may be a mix of government or private industry ship designers, depending on the acquisition strategy and competitive design plan. Ship PDs span 12 months and on the order of 100 man-years of effort to fully exhaust sub-system integration and fall-back options that may have been pre-existing
based on earlier design assumptions or technology readiness. As the PD process proceeds the SDS\(^6\) should be developed concurrently.

The process of generating the System Requirements and Ship System Design sections of an SDS is analogous to reproducing a 3D ship design drawing with exact text. Appendix C contains the System Requirements and Ship System Design sections of a Ship SDS for further reference. Validating a SDS during PD involves obtaining TWH concurrence with the exact text of each SDS section (NAVSEA\_m2, 2016). Often this process involved “reading meetings” in which sentences of the SDS were flashed on a large screen and TWHs were expected to concur, or provide specific changes, based on previously reviewing the proposed SDS. The specific-ness and exact-ness of the SDS is necessary to support private industry’s cost estimate of the upcoming RFP in Gate 5.

Overall, the culmination of Gate 4 activities occurs with the PD review. As a significant engineering event in the ships design and acquisition life, the completion of PD signifies the vast majority of design has been completed. Completing PD has mitigated all design risks to low and has enabled cost estimates for production and life-cycle. Once a ship design has completed PD, it is considered optimized for the appropriate constraints levied by the DAS on the ship program office. Future design efforts are focused on smoothing the transition between designing the ship virtually and preparing to contract the ship for production, testing, and operation.

The Gate 4 review board will:

- Ensure the SDS reflects the design parameters necessary to provide and satisfy the CDD KPPs, KSAs;

\(^6\) A shell Ship SDS has the following sections: Scope, Operational Requirements, Reference Documents, Naval Design Criteria, System Requirements, Ship System Design, Naval Open Architecture, Qualification Provisions, Producibility, Human System Integration, Ship Supportability, and Risk Areas. (NAVSEA, NAVAIR, RDA, SPAWAR, & USMC, 2008)
• Ensure the system is designed for producibility, operability, interoperability, reliability and maintainability;
• Define DoN critical design criteria in areas that are applicable;

**Stakeholder Priorities:** The Gate 4 decision review board is chaired by ASN RDA and marks the transition from the requirements Pass to the acquisition Pass. An ASN RDA executive discussed the priority of Gate 4 as determining design feasibility after sub-system integration. In the past, the detailed sub-system integration process that occurs to support developing the SDS and PD review has forced Pass One cost and schedule targets to significantly adjust higher and longer. As one of the last reviews prior to MS B and APB establishment, ASN RDA prioritizes sub-system integration design detail to increase confidence in cost and schedule estimates.

### 3.7 Phase 2 Conclusion

In Phase 2 the sociotechnical Big A System was introduced to identify metrics of importance to a MDAP PM and exposed the fact that recent MDAPs had recently experienced a lengthy amount of time to produce and staff highly important documents, like the CDD. Within the Big A, a generic MDAP was decomposed into pre-acquisition system, acquisition system, operations and support, and disposal activities which identified that significant design only occurs within the first two phases. For USN ships as MDAPs, the development process known as 2P/6G was introduced and decomposed to identify the who, what, and how of Gate 1-4 activities. For each Gate, stakeholders and their priorities were identified. Stakeholder priorities are summarized in Table 3.
Table 3: Gate 1 – 4 Stakeholder Priorities

<table>
<thead>
<tr>
<th>Gate</th>
<th>What</th>
<th>Type of Design</th>
<th>Who</th>
<th>Priorities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ICD</td>
<td>Exploratory &amp; Pre-AoA</td>
<td>N8</td>
<td>Understand intelligence &amp; technology risks. Don’t jump to conclusions.</td>
</tr>
<tr>
<td>2</td>
<td>AoA</td>
<td>AoA</td>
<td>CNO</td>
<td>Large span of AoA variants. AoA cost vs. capability trade-off information.</td>
</tr>
<tr>
<td>3</td>
<td>CDD</td>
<td>Pre-PD</td>
<td>CNO</td>
<td>Feasibility assessment of KPP/KSA performance values.</td>
</tr>
<tr>
<td>4</td>
<td>SDS</td>
<td>Preliminary</td>
<td>ASN RDA</td>
<td>Cost and feasibility of sub-system integration.</td>
</tr>
</tbody>
</table>

In comparing the conclusions of Phase 2 and Phase 1, what becomes evident is that the USN design approach during Gates 1 – 4 is strongly point based. Additionally, it appears that during early USN ship design, there is a tendency to establish physical ship specifications early. During Gate 1, stakeholders discussed having to hold-back ship programs from trying to identify a specific material solution too early. During Gate 2 activities, the current AoA process drives the Executive Steering Group to force a selection of a “single” preferred concept. After the AoA, some program managers discussed having to perform re-design efforts on the post-AoA preferred variant to modify it into something that would have been considered in-between two of the original family of AoA variants. To support the CDD during Gate 3, the ship program office prioritized establishing the external parameters of the hull and overall displacement to enable a more focused study on internal sub-system arrangements. During each of the first three gates, there are examples of decision making that emulate the point-based design process as presented in section 2.2.3. Many of these early ship design decisions are made based on parametric ship designs that are considered “feasible” by design review authorities. These feasible designs assume that the major tasks of component integration and subsequent cost estimating will continue to be satisfactory in future detailed design document creation. By executing early ship design in a point-wise fashion, the USN is inherently accepting the risks that accompany a PBD process.
Recalling the value of SBD discussion from Chapter Two, an early point-based decision process forgoes the opportunity to eliminate re-work when the cost of design change is cheap. Because the cost to change design errors rises so rapidly in ship design, the USN is accepting substantial cost risk by choosing to perform a point-based Pass One product development process. It isn’t clear from interviews with stakeholders whether it is clear, or not clear, if stakeholders completely understand their cost risk acceptance decision. The next phase of research will further explore the organizations involved in USN ship product development to more clearly understand how design decisions may be influenced by the nature of government acquisition.

4.0 Phase 3: SBD in the USN

In the previous phases of this thesis, the principles of SBD and proposed benefits have been identified, and the overall USN ship product development process has been decomposed to ascertain stakeholder priorities for each design intensive 2P/6G segment. Phase 3 will explore if the proposed benefits of SBD have been realized in cases where SBD was used. Also, analysis of these cases will determine where the USN stands on SBD. Phase 3 will be performed by analyzing how SBD was executed on each project, what resulted, and what was learned.

SBD, as a cultural philosophy, has been touted to have many implementation hurdles. The founding research on TMC and SBD hazarded organizations from believing that implementing SBD was as easy as just flipping a switch, or just doing design differently (Ward, Liker, Cristiano, & Sobek, 1995) (Sobek, Ward, & Liker, 1999) (Ford & Sobek, 2005). Therefore, little research has been performed on prescribing SBD as a design process (Raudberget, 2010). But, recent USN design efforts have provided an opportunity to explore claimed SBD execution. The following cases claimed SBD use and were identified by either literature or interview: Pre-PD on Ship to Shore Connector (SCC), Pre-AoA design for the Amphibious Combat Vehicle (ACV), and Pre-AoA design by the Small Surface Combatant Task Force (SSCTF). In each case, some of the author’s principles of SBD were identified and some proposed benefits of SBD were achieved.
4.1 Ship to Shore Connector

Figure 35: Ship to Shore Connector
(http://www.textronsystems.com/capabilities/marine/ship-shore-connector)

The SSC program was created to produce a replacement for the Landing Craft Air Cushioned (LCAC) amphibious transport vehicle. LCAC’s were designed in the late 1970s and produced during 1984 through 2000. LCACs are still in service today with the oldest LCACs expected to begin retirement in 2019. When considering options for maintaining LCAC amphibious landing capability, the USN performed Exploratory and Pre-AoA design studies in 2006 that resulted in an approved ICD and AoA in 2006 and 2007, respectively (Mebane, Carlson, Dowd, Singer, & Buckley, 2011).

Like other USN ship AoAs, the preferred AoA variant did provide enough detail to satisfy producing the CDD (Singer, Doerry, & Buckley, 2009). Thus, Pre-PD was performed to support refining the draft CDD. Additionally, NAVSEA ship design leadership decided to pioneer using
SBD on the LCAC replacement in accordance with in-progress design process improvement initiatives as highlighted in Chapter One. These early studies established the LCAC replacement as the SCC program under PMS-377 with a SDM from NAVSEA 05D. USN leadership was aware of the proposed benefits of SBD, but OPNAV and PMS-377 was most interested in SBD’s advantage of critical design decision knowledge capture (McKenney & Singer, 2014) because of the expected high military leadership turnover during typical USN ship design and acquisition (Mebane, Carlson, Dowd, Singer, & Buckley, 2011).

4.1.1 How SBD on SSC Was Executed

Without a formal process described in any USN instruction for SBD, the SCC project team utilized the Decision Object System Engineering (DOSE) method to guide their process for decision making with the support of experienced academics and consultants familiar with SBD. DOSE’s use of knowledge mapping techniques facilitated team decision-making along lines of functional expertise (Buckley & Stammnitz, 2004) (CDI Marine, 2009). With a method to guide overall design execution, the SDM assembled and partitioned the SSC design team per Figure 36 and structured the execution of SSC SBD in three generic phases: [1] Trade space setup and Characterization, [2] Trade space reduction, and [3] Integration and Scoring (Mebane, Carlson, Dowd, Singer, & Buckley, 2011).
**Figure 36: SSC Design Team Structure**  
*(CDI Marine, 2009)*

- **Ship Design Manager (SDM):** The lead system engineer on the project. This individual represents the design team in all matters with outside organizations.
- **Design Integration Manager (DIM):** This individual is responsible for facilitating communication, decision-making, and integration among all the elements.
- **System Engineering Manager (SEM):** These individuals represent the system expert in the specific element field.

**Trade Space Setup and Characterization:**

The inputs used for the design effort were shaped into what the design team referred to as a craft-level Functional Design Document (FDD) which was a compilation of NAVSEA executive guidance, the SSC Analysis of Alternatives (AoA) and the SSC Initial Capabilities Document (ICD), and Landing Craft Air Cushion (LCAC) Service Life Extension Program (SLEP) requirements and lessons learned. Using the performance attributes identified in the FDD, Air
cushion vehicle Design Synthesis Model (ADSM\(^7\)) was used to convert overall craft performance into performance ranges for each Element: Hull, Machinery, Performance, Combat/Command/Control & Communication Networks (C4N), Auxiliaries, and Human System Integration (HSI). These Element performance ranges were converted into Functional Requirements Documents (FRDs) to guide Element trade space characterization and analysis. When characterizing their trade spaces, SEMs were given latitude to explore any potential solution as long as they had concurrence from a TWH that the proposed system solution was acceptable. At the end of Element characterization, the SEM had a Trade Space Summary (TSS), in the form of an MS Excel spreadsheet, which captured TWH comments, approvals, and future trade space reduction decisions.

**Trade Space Reduction:**

After establishing Element solution trade space acceptability, SEMs used design of experiments, or other analysis, to analyze their intra-element set of solutions for key design parameter preference or dominance. Model Based System Engineering techniques compared intra-element solutions against each other by identifying performance measures, modeling and simulation scenarios appropriate for each element based on Subject Matter Expert (SME) opinion. Some SEMs used Response Surface Methodology to compare alternatives, where others used a less rigorous approach because of the lack of design variable continuity over the FRD. This process was completely concurrent for each SEM and was supervised and facilitated by periodic Design Integration Team (DIT\(^8\)) meetings. TSSs captured these reduction decisions. At the end of the trade space reduction phase, each SEM had a set of non-dominated intra-element solutions. These solutions were approved by TWH’s as technically acceptable and concurred upon by the DIT as viable. The next step in the SBD design effort was to combine all Element solutions into craft variants.

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\(^7\) ADSM is an air cushioned craft specific design tool created by TMLS and maintained by the USN for LCAC/SCC design.

\(^8\) The DIT consisted of the DIM, the Deputy DIM, and SBD consultants.
**Integration and Scoring:**

Towards the end of Trade Space Reduction, the DIT identified what they referred to as “negotiating relationships” between Elements, which resulted when the selection of one option in an Element influenced which options could work in the other Elements. Eliminating exclusions based on negotiating relationships resulted in the set of all potentially viable SSC crafts. Next, all potentially viable craft designs were submitted to a Balancing Process in which a design synthesis tool, similar to ADSM, was performed for each candidate craft to ensure design candidates pass a first order test for platform viability. For the SSC project, the balance process screened candidates for important high-level craft attributes: an initial stability check, a test for adequate power to get over the generated bow wave, and a test for adequate power to maintain the required cruise speed. The balancing process eliminated another significant portion of SSC alternatives and produced a set of metrics for each variant that could be used for quantitative comparison. A scoring scheme using an OMOE from multi-attribute utility was created to evaluate the remaining SSC variants between cost, risk, and performance. This resulted in a small group of high scoring variants in which the design team chose two variants, which only differed by hull material selection, to carry into PD. Figure 37 captures the three phases of the SSC design process.
4.1.2 Results of SCC SBD

At the end of design, two preferred, similar variants were identified by the team as the believed global optimums (Singer, Doerry, & Buckley, 2009) (Mebane, Carlson, Dowd, Singer, & Buckley, 2011). Additionally, a vast amount of design knowledge had been captured using the TSSs, specifically the negotiating relationships. The two SSC variants were generated by a process that evaluated functional specific trade spaces concurrently and reduced the trade space by eliminating dominated or infeasible options; thus, satisfying the authors principles for SBD execution. Programmatically, the SSC design was completed on time, within 10% of budget, and used little to no design margins (Doerry N., 2010b). Overall, in 2008, the SBD results for SSC were immediately used for PD, CD and Gates 4/5 of the newly instituted 2P/6G process. Today the SSC program has proceeded past MS B and is supervising construction of the SSC test craft at Textron Marine and Land Systems.
4.1.3 What Was Learned From SSC

Although the overall process used by the SSC team may not have been textbook SBD (McKenney & Singer, 2014), the USN was writing the textbook for using SBD during SSC design efforts (Singer, Doerry, & Buckley, 2009). The biggest lesson learned from the SSC Pre-PD design phase was that SBD principles could be translated into a process for use on USN ships/crafts. The SBD process not only quickly (within 4 months) produced results, but also the formal decision making exclusions and eliminations provided excellent design knowledge capture. For SSC, knowledge capture was obtained by TSSs and the eventual discovery of negotiating relationships between functional Element groups. This design knowledge capture also led to a more fluid design review process during PD, CD, Gate 5, and MS B. The design team was able to immediately answer, or in even some cases prevent, design reviewer and higher level decision maker questions about the recommended edges of the SCC design. Once design reviewers and higher level decision makers understood the trade space elimination process, they became satisfied that an ideal solution had been reached. Thus, there was no need to further question why the design team arrived at their recommended solution. In the end, future fluidity of design review is what the USN hopes to achieve by capturing lessons learned from the SSC.

Design fluidity, in the SSC case, could be translated into better cost and schedule performance. By preventing the extra questions from reviewers during the PD, CD, and Gate 5 review phases, the SSC design team ultimately prevented undertaking additional studies to answer posed questions. In the past, these extra questions were considered to be significant due to either the seniority level that asked the question or because the question was generated in front of a large diverse group. After performing the study to answer the extra question, the conclusion often ended up being low value. Thus, re-work.

4.2 Amphibious Combat Vehicle

Chronologically, another opportunity arose for a rapid ship/craft design learning event shortly after the SSC team finished their critical design review. In 2011, the United States Marine Corp (USMC) cancelled the 40-year old Amphibious Assault Vehicle (AAV) replacement program,
the Expeditionary Fighting Vehicle (EFV), due to poor reliability and excessive cost (O'Rourke, 2016a). The USMC immediately began re-planning for the development of a more affordable and sustainable amphibious combat vehicle (ACV). This resulted in an ICD to align capabilities and future CONOPs and an AoA that re-enforced the need for a self-deploying survivable craft. But, neither the ICD nor AoA explored the operational benefits of a high water speed (HWS) craft (Burrow, et al., 2013). With extra scrutiny on the ACV program from the previous EFV cancellation, senior USMC leaders expressed concern with proceeding with a low water speed craft without evaluating the HWS requirement, citing operational flexibility and the potential tactical advantage HWS might have (Burrow, et al., 2013). To satisfy the “what about... what's not shown on the slide” question from USMC leadership, the Assistant Commandant of the Marine Corps and ASN RDA developed an ACV directorate team to evaluate the cost and capability trade-offs of a HWS ACV.

The ACV design team was focused on expeditiously answering the “what about... " question while simultaneously using previous EFV information and capturing ACV design knowledge. The proposed reduced cycle time and knowledge capture benefits of SBD aligned with the ACV directorate’s priorities. Therefore, the ACV design team desired to explore incorporating aspects of SBD, where possible, in the ACV design approach. In the end, the results of the ACV design produced a detailed cost-benefit assessment of the HWS requirement. Additionally, USN and USMC leadership became more aware of configuration diversity terminology and how early stage design decision information may be presented using a SBD approach.

4.2.1 ACV Design Definitions and Philosophy

The following list represents terminology and design philosophy summarized from ACV design literature (Burrow, et al., 2013) (Doerry, et al., 2014):

- Capability Concept – a complete set of requirements.
- Configuration— a set of potential solutions
• Feasibility—evaluation of a configuration based on current fidelity of modeling and analysis.

• Viability—evaluation of a configuration based on future, more detailed analysis and testing.

• If a configuration is NOT feasible, then it will also likely be NOT viable.

• If a configuration is feasible, it may or may not be viable in the future.

• Early in SBD— the solution space is comprised of many potential configurations.

• Later in SBD— configuration feasibility implies viability; therefore, configurations may be eliminated based on Pareto Optimality.

• Concept Exploration concentrates on the tradable requirements. It assesses the combinations of tradable requirement values for feasibility, effectiveness/utility, and affordability.

### 4.2.2 How ACV Design Was Executed

To assess the feasibility and cost of the HWS ACV, the ACV directorate established a design team, formulated an analysis plan, and executed a series of four focused design studies. Where possible, concurrent design efforts were performed and design knowledge was shared between core teams to improve the validity and value of sequential ACV design studies.

First, the ACV directorate established the team structure per Figure 38 and formulated the general analysis plan as shown in Figure 39. In addition to the ACV team structure, the ACV directorate identified four analysis groups that could concurrently perform segments of the analysis plan: Requirements Analysis, Effectiveness Analysis, Trade Space Analysis, and Affordability Analysis.
Figure 38: ACV Design Team Structure and Analysis Groups

(Burrow, et al., 2013)

Figure 39: ACV Analysis Plan

(Burrow, et al., 2013)

Before beginning the first Baseline study, the operational requirements and specifications from the ICD, AoA, and CONOPs were translated and formatted into ACV requirements using
DOORS and other specific ACV design tools. With clear performance requirements, the ACV team generated a library of ACV components that could comprise an ACV variant based on the AAV work breakdown structure. The library initially incorporated only proven low-risk technologies, but was expanded to high risk/high reward components based on the Innovation Team’s research (Burrow, et al., 2013). Component size, weight, and cost information was the basis for the Market Research Database (MRDB) which utilized the synthesis tool Framework for Assessing Cost and Technology (FACT) for evaluating ACV performance. With a library of components, a set of requirements, operational scenarios, and a performance synthesis model, the ACV design team was able to generate a large design trade space of potential configurations to satisfy capability concepts.

To evaluate the large trade space, individual studies were performed to first validate the design team’s models and then to target specific design attributes. The Baseline Study was performed to validate the process models and design tools. The follow-on studies further explored technical viability and specific operational performance of HWS vs LWS ACVs. The four studies used multi-attribute utility theory to produce configuration Performance vs Cost graphs.

### 4.2.3 Results of ACV Design

Figure 40 shows the results of the HWS study which highlights the feasible configurations which can carry payload (positive mass margin) in blue. Each blue dot represents a capability concept which is made up of a number of different MRDB component configurations. These results were translated back into a recommendation regarding which set of HWS ACV requirements was most feasible to attain based on other schedule and affordability analysis.
The ACV design team claimed their use of diversity in design decisions was set-based; but, the use of the author's SBD principles on ACV was sparse. The only aspect of the authors SBD principles that occurred during the ACV design was the knowledge sharing that occurred between the functional groups. This partial use of SBD has been identified by some researchers as aligning with effective trade space exploration (Schmid, 2015) (Ghosh & Seering, 2014) and is a better description of the overall design approach used by the ACV design team. As the requirements group identified new or changing requirements from the USMC, they would update DOORS. A DOORS update changed the parameters of FACT, which then ultimately resulted in opening or eliminating some of the ACV configuration trade space. Additionally, as the Affordability Analysis team identified supply chain or logistic issues that resulted in the preference of one component over the other, the MRDB would be updated. Changed parameters in the MRDB resulted in configuration utility changes, which could impact final recommendation results. This knowledge sharing represented separate groups of concurrently
evaluating sub-systems (Principle 1). Outside of the authors SBD principles, the ACV directorate introduced the topic of cost diversity in which the overarching SBD premise of the optimal solution residing within the feasible set was reinforced.

When generating the utility graph of performance vs cost, the ACV team used representative cost for a capability concept based on a subset of the feasible configurations for that capability concept. Using this approach, a diversity metric that corresponded to the number of design variants contained within each capability concept helped visually identify which concepts contained more or fewer variants. Figure 41 shows the diversity of the feasible solutions from Figure 40 with red being less diverse and green being more diverse. Thus, the ACV design team claimed a more informed, therefore better, risk based cost decision was made utilizing an attribute of SBD.

**Figure 41: Cost Diversity Results for Positive Mass Margin HWS Results**

(Burrow, et al., 2013)
4.2.4 What Was Learned From ACV Design

Overall, the ACV design assessed HWS ACV feasibility and cost. The design team felt they achieved this goal by performing design in a way that produced presentable, understandable information to decision makers. They felt the presentation of design information supported a high degree of confidence in cost and risk decisions. Interviews with ASN RDA and literature confirmed what the ACV team believed, that leadership was very satisfied with the ACV design team results (ASN-RDA, 2016). In the end, the ACV team was able to address leadership “what if” questions succinctly and with the technical rigor to enable high confidence decisions. Additionally, the ACV concept design introduced and familiarized USN leadership with a design information presentation style founded on solution feasibility, viability, and diversity discovered through a SBD approach.

4.3 Small Surface Combatant Task Force

On February 24, 2014, Secretary of Defense Chuck Hagel restructured the LCS program by directing the USN to provide alternate proposals to procure a more capable and lethal small surface combatant for the last 20 of 52 planned LCSs (O'Rourke, 2014). Originally, the LCS program was announced in 2001 as a variant of the Future Destroyer concept of operations amid the large decisions facing the USN after the 1997 Quadrennial Defense Review (Work R., 2007) (O'Rourke, 2016b). Today, the LCS is a small surface combatant that is equipped with modular “plug-and-fight” mission packages. The basic version of the LCS, without any mission package, is referred to as the LCS sea frame. LCSs have been procured since FY2010 as either a mono-hull or trimaran variant from two shipbuilders—Lockheed and Austal USA.
In the spring and summer of 2014, the USN responded to SECDEF’s LCS restructure direction by assembling a group of surface warfare, ship design, and industry experts: the Small Surface Combatant Task Force (SSCTF). The SSCTF received direction from ASN RDA and the CNO to (Garner, et al., 2015):

- Establish the requirements for a small surface combatant
- Assess the requirements delta against the existing LCS (both sea frames)
- Translate the requirements delta into concept designs considering: existing ship, a modified existing ship, and new ship design options with schedule, cost, sensor systems, and lethality measures of performance.
Similar to the ACV concept design, one of the priorities for USN leadership was quickly coming to a well-informed decision to re-direct a program proceeding in the wrong direction. Fresh from the ACV concept design experience, a core group of NAVSEA 05D SDMs were available to advise the SSCTF on use of SBD in concept design. Their insights enabled the SSCTF to tailor their design approach to take advantage of the knowledge sharing and concurrent work principles of SBD. The overall approach the SSCTF used to achieve their tasking was a similar process to Gates 1-4 of 2P/6G in which: [1] capabilities were defined, [2] capabilities were translated into configurations of different ship systems to achieve required capability performance levels, and [3] synthesized ships were evaluated using utility theory for performance vs cost (Garner, et al., 2015). During this effort, the SSCTF utilized the author's SBD principles during synthesis and evaluation.

### 4.3.1 SSCTF Design Execution

**Develop Capability Concepts:**

Capability Concept—a set of missions (and associated performance levels) for the small surface combatant (Garner, et al., 2015).

The SSCTF established the range of capability concepts for the small surface combatant by utilizing previous LCS designs and the experience of the senior USN surface warfare officers and civilians. A process similar to a CBA was performed to identify which future warfighting functions the small surface combatant would have and to what extent it would need to function to overcome future threats. This analysis resulted in a collection of missions segregated into Primary Missions (PMs) and Enabling Capabilities (ECs). For each mission, four levels of performance were quantified. A Capability Concept was the combined performance of all of PMs and ECs. Each capability concept had to achieve at least Level One in all PMs, but did not have a minimum requirement for ECs. This collection of missions and capabilities was represented in a bullseye chart to visualize the extent of concept performance. Figure 43 shows the entire bullseye chart capability concept trade space with one capability concept as an example.
Just using the four PMs and four levels of performance, 192 different capability concepts were possible. Adding ECs generated a vast capability trade space. The trade space of actual small surface combatant configurations is exponentially larger due to the different components that may be used to achieve each mission level of performance. The creation of the Capability Concept bullseye chart marked the end of first phase of SSCTF design.

Design Ship Sub-Systems to Achieve Capabilities:

Although this reads like the second segment of SSCTF design was performed in a series with Capability Concept development, in reality, SDMs from NAVSEA 05D began identifying potential sub-systems and weapons system configurations from the beginning of SSCTF design. SDMs worked closely with USN warfare centers and combat system experts to create a library of components and sub-system configurations that would be necessary for achieving capability Levels One – Four of the bullseye chart. Initially SDMs made assumptions for specific space
and weight criteria for sub-system components and refined their assumptions as TWHs validated or updated weapon sub-system component design. Overall, the process to design ship sub-systems was a continuous process throughout the SSCTF design.

**Synthesize the Ship and evaluate Performance:**

To produce cost and performance measures for utility analysis, the ship design synthesis tools Advanced Surface Ship and Submarine Evaluation Tool (ASSET), Rapid Ship Design Environment (RSDE), and Leading Edge Architecture for Prototyping Systems (LEAPS) were intensively utilized by the SSCTF (NSWC-CD_11, 2015). These early stage ship design tools have been created by the USN to specifically facilitate rapid trade space exploration and analysis (Keane R., 2012). Three different generic small surface combatants were independently synthesized during this stage of design: the existing LCS, a modified LCS, and new designs submitted by industry.

During this stage of design, what challenged synthesis design teams the most was combat system physical characteristics of space, weight, power and cooling (SWAP-C). Without identifying all component physical characteristics, naval ship design cannot be accurately completed (NAVSEA, 2012). Thus, predicted performance will not match reality. To overcome the delinquency in combat sub-system design, assumptions were made for combat system physical performance characteristics by SDMs during design of Hull, Mechanical and Electrical (HM&E) systems. ASSET, RSDE, and LEAPS easily facilitated making these SWAP-C assumptions.

The results of a synthesized ASSET design produced quantifiable metrics which could be converted into a representative cost and performance metrics for each proposed design. With the wide variety of potential components that could comprise a sub-system, and the wide variant of Capability Concept performance levels, all synthesized variants were submitted to a Feasibility Element Calculator and Overall Feasibility Assessment Criteria, per Table 4, for the following feasibility elements (Garner, et al., 2015):

- SUW Performance
- ASW Performance
- AW Performance
- Sustained Speed
- Endurance Speed
- Arrangeable Area
- Displacement
- Length to Beam Ratio
- Stack up Length
- Seakeeping

The results of the Feasibility Assessment were converted into a Risk Assessment and then analyzed against ship performance metrics. An example of the modified-LCS Acquisition Cost vs Displacement is shown in Table 5.

Table 4: Feasibility Element Calculator and Overall Feasibility Assessment Criteria
Adapted from (Garner, et al., 2015)

<table>
<thead>
<tr>
<th>Feasibility Element Calculator</th>
<th>Overall Feasibility Assessment Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category</td>
<td>Performance</td>
</tr>
</tbody>
</table>
| Feasibility Excessive         | Greatly Exceeded       | Feasible | All elements "Feasible"
| Feasible                      | Confident              | Not Feasible | Any element "Not Feasible" or ≥5 elements are "High Risk for Feasibility" |
| High Risk for Feasibility     | Low Confidence         | High Risk for Feasibility | 1-5 elements are "High Risk for Feasibility" and remaining elements are "Feasible" or "Feasible Excessive"
| Not Feasible                  | Unable                 | Feasible Excessive | ≥1 element is "Feasible Excessive" and the remaining elements are "Feasible" |
4.3.2 How SBD Was Used During SSCTF

One of the author's SBD principles used by the SSCTF design team was concurrent design of the HM&E and Combat Systems during synthesis. When designing and converging full ship designs, HM&E experts assumed the SWAP-C metrics for the combat system. HM&E designers utilized a large (low-risk) range for combat system SWAP-C architecture to more likely enable future ship convergence feasibility and therefore viability. Establishing these "placeholders" for combat system architecture allowed the combat warfare system experts to independently design their systems. As combat system design solutions matured, the matured combat system SWAP-C metrics were intersected with the HM&E assumptions to refine the solution space. Performing the HM&E and combat system work in parallel and then intersecting design efforts matches the author's first and second principles of SBD. The SSCTF claimed to follow the literary SBD principle of canvassing a large trade space, but as discussed in Chapter Two, just because a large trade space is generated at the onset of design doesn't make a design approach set-based.

4.3.4 What Was Learned From SSCTF Design

Three major points were learned from the SSCTF design effort. First, early stage ship SBD can be achieved by partitioning along HM&E and Combat Systems functional boundaries. The

### Table 5: Risk Assessment vs Performance for Modified-LCS

(Garner, et al., 2015)

<table>
<thead>
<tr>
<th>Risk Assessment</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feasibility Assessment</td>
<td>Color</td>
</tr>
<tr>
<td>Feasible</td>
<td>Green</td>
</tr>
<tr>
<td>High Risk for Feasibility</td>
<td>Yellow</td>
</tr>
<tr>
<td>Not Feasible</td>
<td>Red</td>
</tr>
</tbody>
</table>
interfacial variables that exist between these two groups are physics-based variables which are easily quantified within existing design tools. Furthermore, ASSET, RSDE, and LEAPS provide effective, rapid generation and comparison of ship designs independent of concurrently working in the HM&E or Combat System functional group. These tools easily intersect interfacial variables between the HM&E and Combat System functional groups. Second, USN leadership preferred the visual risk assessment and data presentation that accompanied the ASSET, RSDE, and LEAPS design products. Similar to the ACV design, USN leadership discussed their perceived confidence in decision making based on the in-depth and easily decipherable data presented by SSCTF designers. Third, the USN ship design community has established a core group of designers that can responsively react to emergent ship design tasking and produce well received results in a rapid fashion. Overall, as the most recent SBD ship excursion, the SSCTF has helped validate the tools, processes, and metrics associated with a set-based surface ship design.

4.4 Summary of USN Cases of SBD

In each of the three identified cases of USN SBD use, the design process was analyzed, but did not specifically explore acquisition programmatic metrics for design performance. In this section, the four proposed benefits of SBD identified in section 2.3 will be re-reviewed by reasoning if available programmatic information for SSC, ACV, or SSCTF is available to support the claimed proposed benefit. The proposed benefits of SBD are (with discussion):

- **Reduction of later stage rework when the cost of change is more expensive; therefore, less cost to design, build, and maintain the product.** This benefit was not specifically discussed by literature or interviews for the in-process design cases for SSC, ACV, or SSCTF; but, may be more macroscopically analyzed by considering the follow-on effects of each program. Each of the USN SBD cases occurred early\(^9\) during the ship product development life-cycle; therefore, the overall acquisition cost performance of the ship program should be improved based on the SBD principle of reducing later more costly re-

\(^9\) Even though the SSCTF design event occurred during mid-life of the LCS, it was evaluating ship design concepts from the beginning of the ship product development life-cycle.
work. This can be confirmed by reviewing the adherence of a ship program's actual acquisition cost to its original APB cost in a SAR. The ACV and modified-LCS have not proceeded past their MS B APB decision; therefore, only the SSC can be assessed for this proposed benefit. Cost performance is captured in Table 6 and confirms this benefit as being realized for SCC. Not only does SSC have the highest acquisition cost performance, achieving greater than 1.0 means that overall actual acquisition costs have decreased as compared to the original APB estimates. As the only program that has performed some type of SBD, this parallel can't be understated.

![PAUC Cost Performance Diagram](image)

**Figure 44: Per Unit Acquisition Cost Performance**

*(DAMIR, 2015)*

- *Reduction of design cycle time; therefore, less cost to design the product and more market share gained from entering an opportunity market sooner.* For each of the USN design cases studied, design cycle time reduction was a goal of each design team. All three design teams reported producing results within a time-span previously not achievable. USN leadership confirmed the previously not achievable claim for each case. Therefore, this proposed benefit was realized by USN’s use of SBD.
- Better design knowledge capture; therefore, less costly to incorporate customer changes during design or to perform future similar product designs. Knowledge capture was also a goal of each design case studied. In the SSC design, this attribute was realized by generating TSSs and the identification of negotiating relationships. The design team specifically stated that future modernization or recapitalization efforts for SSC would go smoother with the information gathered during SSC design. The likelihood of knowledge capture improving future design or cost performance for the ACV and SSCTF still remain to be seen. In ACV and SSCTF designs, the SBD discovery by elimination principle was not specifically adhered to throughout each design. Therefore, only time will tell if the USN will fully realize this proposed SBD benefit.

This proposed benefit also hints at SBD being a more flexible design approach due to the ability to easily and definitely re-open parts of the design space that were previously excluded by a elimination/design space reduction decision. Although changing stakeholder or customer requirements was not highlighted by literature or reported as significant during interviews for each USN SBD case, this topic was discussed during a general interview with NSWC. NSWC reported conducting an internal study in which two different teams independently used SBD and PBD to design a surface combatant. The results of their study showed that the PBD team needed significantly more rework to accommodate requirements changes and the mid-life upgrade modernization (Rhodes & Ross, 2016). Therefore, this proposed benefit has been demonstrated in a structured ship design academic setting.

- A better solution is found because of the methodic reduction of the design trade space; therefore, higher customer satisfaction. To evaluate this benefit, the “customer” needs to be defined. For the three ship design cases, the customer could be acquisition leadership, or the USN sailor who will eventually operate the warship product. Additionally, it is difficult to gauge the degree of satisfaction in both the acquisition leadership and USN sailor cases. As best determined from interviews with executives involved with the three cases studied, leadership was satisfied with the results of each design. They reported being able to better understand information presented during design update or final briefs.
based on the visual representation that accompanied the Monte Carlo simulations for ACV and SSCTF and the key variable reduction graph from SSC. Data presented in this manner was able to drive home the SBD principle point about designing through discovery by elimination.

4.4 Where the USN Stands on SBD

The USN, as a ship design organization, has begun to insert discipline back into ship design by focusing on processes, people, and tools. NAVSEA 05D has been responsive in updating design process instructions and the USN ship design enterprise has continued to invest in both its people and design tools. These changes are in response to the drastic comments made by USN ship design leadership from 2005 – 2007 and have begun to codify SBD use in ship design.

Similar to all government organizations, the USN captures its processes in the form of written instructions. Specific to USN ship design, NAVSEA 05D has authored the Ship Design Manager’s and Ship Integration Manager’s Manual to guide SDMs and SIMs in their duties and responsibilities as a TWH in ship and submarine design. This instruction has been cited throughout this thesis. As an overarching guidance instruction, it summarizes strategies and lessons learned from previous ship designs. It walks the SDM manager through each stage of USN warship design and highlights what needs to be done and options for how to do it. The manual was last updated in 2012, and therefore, contains lessons learned from the SSC design. The manual discusses Bernstein’s principles of SBD and only offers that the SDM consider SBD during Pre-PD. It does not prescribe how to execute SBD. Overall, the fact that SBD is discussed and offered as a potential design approach in the USN design manual shows that the USN is responsively incorporating the successes of SSC into its larger ship design processes.

In addition to incorporating SBD into its written process instructions, the USN ship design community is growing its knowledge base in SBD through hiring practices and design tool
investment. USN warfare centers are actively recruiting academics in ship design to continue their research in a more robust ship design environment. Additionally, the USN ship design community has invested in ship design tool improvement, which has specifically enabled a more set-based design approach for early ship design (Keane R., 2012) (Kassel, Cooper, & Mackenna, 2010). Specifically, the High Performance Computing Modernization Program (HPCMP), initiated in 1992, has resulted in enabling government owned and managed supercomputing capability to support the CREATE-Ships Project library. This library of physics based ship design tools works through the LEAPs database to incorporate higher fidelity, concurrent, modeling into early stage ship design. Using RSDE and ASSET through LEAPs were the cornerstones of enabling the SBD effort on SSCTF and the academic NSWC ship design study (NSWC-CD_m1, 2015) (McKenna, 2012). By hiring experienced ship design academics, many of whom have contributed literary citations to this thesis, and by investing in higher fidelity design tools, the USN is increasing its capability to exploit SBD on ships.

4.5 Phase 3 Conclusion

Overall Phase 3 has identified and studied cases of USN SBD use, analyzed each case for adherence to the author’s SBD principles, and identified that at least some of the principles were adhered to in each case. In each case, what resulted and what was learned was presented. A major takeaway is that USN leadership has become more familiar and accustomed to the style and depth of early stage design information resulting from a set-based design approach. The proposed benefits of SBD were re-reviewed and shown to have been realized in some capacity for each benefit. Last, a summary of where the USN stands on SBD revealed that SBD is acknowledged in ship design process instructions and SBD ship design tools continue to be developed in the USN.
5.0 Phase 4: Ship Design Process Improvement

Phase 4 will draw upon conclusions from previous phases and discuss where the USN might use SBD and what programmatic effects it might have. At this point, the principles of SBD are understood (Phase 1), the USN’s ship product development process is understood (Phase 2), and cases of specific SBD use by the Navy have been reviewed to garner facts and lessons learned (Phase 3). These first three phases have delivered an understanding of the process, people, and tools the USN has used to perform ship design and achieved the first point of this thesis. Phase 4 will deliver the second point by outlining efficiency opportunities available to the USN through SBD. First, amenability of SBD to each design intensive gate will be discussed. Then, the concept of an Analysis of Feasibility will be introduced as a SBD ship process improvement recommendation.

5.1 Amenability of SBD to Gates 1 – 4

Chapter Three identified stakeholders and their priorities for Gates 1 – 4. In this section, each Gate will be re-reviewed for amenability to SBD. The methods for achieving the priorities of each stakeholder will be assessed by checking for alignment with the author’s principles of SBD from Chapter Two. This section will show that Gates 2 – 4 show some amenability to SBD.

5.1.1 Gate 1 (ICD)

At the tip of the ship product development spear, N8, as the stakeholder, prioritized understanding intelligence/technology risks and not forming early material conclusions. Design performed during Gate 1 is only modeling the programmed future USN in a war-game scenario against predicted adversarial threats. This modeling process produces the CBA and is accomplished by government analysis organizations that have the large scale computing capacity to handle Fleet Architecture Studies. Any failures in USN Fleet performance during the war-game scenario can be thought of as a necessary future capability.
Because relatively little real ship design is occurring during the construction of a CBA, the principles of SBD have little merit on improving the results of the CBA. One possible improvement could be to split up USN Fleet modeling and simulation among more specific groups of experts. Individual experts might have more exact models of particular USN Fleet assets. But, eventually all models and simulations would need to be recombined to deliver the overall assessment result. If the performance accuracy gains of more specific modeling outweigh the cost of communicating and paying for the individual modeling, then the USN should partition the Fleet Assessment. If not, the USN should keep the Fleet CBA within one organization. One exception to this case could be if the CBA was focused on only a specific mission or specific type of ship. In this case, a smaller scale architecture study may be sufficient. But, there are no single mission ships in the current or future USN fleet. Overall, because the CBA focuses on using existing ship designs and plans, the principles of SBD do not align with the conduct of a CBA.

Additionally in Gate 1 is the creation of the ICD. Pre-AoA design is led by NAVSEA 05D and performed by USN warfare centers, private contractors, and NAVSEA 05D to resolve how to achieve the NMETL. But, the intention of the ICD is not to provide a material solution recommendation past the highest level of ship type: carrier, submarine, amphibious ship, large combatant, small combatant, transport craft, etc. The design intentionally is not complex. Because of the inherent focus on simple designs for Pre-AoA design, a simple design approach is best. Chapter Two identified the ways in which SBD was best suited for complex product design. Thus, SBD is also not amenable to the conduct of an ICD.

Loose parallels to SBD for Gate 1 activities could be made by saying that considering the ship platforms amphibious vs. carrier vs. large/small combatant is similar to the processes that managers at TMC used to constrict the ranges of their body styles and therefore communicate more effectively with their customers. But in the USN’s case, communication between the USN and DoD about ship type is most-often predetermined. Overall, the author’s principles of SBD do not align with desired outcomes of the CBA and ICD, and therefore, Gate 1.
5.1.2 Gate 2 (AoA)

During Gate 2 activities, the ship program proceeds through MDD and into the AoA. During the AoA, true early stage design occurs. During this stage, ship design tools are expected to canvas an extensive range of material solutions to evaluate the effectiveness of achieving the capabilities identified in the ICD. The CNO and DCAPE prioritize the depth and breadth of AoA ship variants and their resulting Cost vs Capability trade-off information.

When performing a trade-off study, the crux of the study depends on the balance of computation time, variants considered, and level of design detail (Felix, 2004) (Doerry N., 2010a). If a design method presents an opportunity for parallel design effort, then theoretically more design information could be included within the study. The SBD principle of concurrent sub-subsystem evaluation aligns with this trade study improvement technique. Therefore, the author’s SBD principles align with stakeholder priorities for Gate 2.

5.1.3 Gate 3 (CDD)

After performing the AoA in Gate 2, a ship program conducts design activities to refine the CDD in Gate 3. Depending on the AoA results, Pre-PD may occur to mold a variant into a condition that can achieve KPPs/KSAs. The ship design environment used during Gate 3 is a mixture of ASSET and associated evaluation tools via the LEAPS architecture. The CNO is the gate keeper for Gate 3 and prioritizes understanding the cost drivers for each KPP/KSA. Overall, the CNO wants a firm commitment from the program office that the proposed ship design will be able to achieve the CDD KPPs/KSAs within cost and schedule targets. Also, the CNO and the SCM/SDM use activities during Gate 3 to prepare for the upcoming MS A review board.

The essence of ship design work that occurs between Gates 2 and 3 was described during interviews as re-performing the ship design with increasing levels of detail. Traditionally, this
has meant re-performing ship design spirals to flush out general arrangements and sub-system selections to enable an accurate weight-based cost estimate.

But, what the CNO really wants to understand are the “drivers” of KPP/KSA cost. To understand drivers, the ship designer needs to understand “relationships” between systems that cause weight. SBD, as a general method, works by identifying and communicating through “negotiating relationships” as demonstrated on the SSC. Understanding these negotiating relationships between sub-systems will enable a better understanding of what is “driving” the weights in a cost estimate. Therefore, SBD is a potentially better method of providing what stakeholders really want from Gate 3. Therefore, SBD is amenable to Gate 3.

5.1.4 Gate 4 (SDS)

Gate 4 activities represent the transition between the requirements Pass and the acquisition Pass. Activities in Gate 4 all steer toward making the ship design ready to be formally communicated to industry for production. PD occurs during Gate 4 activities and the functional baseline is created. ASN RDA is the gatekeeper for the Gate 4 review board and interviews revealed that the ship design’s overall feasibility after sub-system integration is the bottom line priority.

Interviews also revealed that most of PD activity during Gate 4 revolves around obtaining TWH concurrence for sections of the SDS. PD was described as an iterative process of specifically documenting the 3-D design into written text for the upcoming RFP. During PD, the design is typically already partitioned into specific design areas that align with TWH cognizance. Open design trade spaces are scarce and may only reside in areas which may represent a cost savings to the producer but relatively constant performance to the USN.

Because the ship design is already partitioned and close to complete, utilizing SBD may be amenable in areas with open design space. But, it is likely indistinguishable in value added over
point-based or traditional ship design. Whatever overarching design method has been in place during Gate 3 activities is likely to be the best during Gate 4. Therefore SBD may be amenable with activities during Gate 4, but it depends on how the design progresses from Gate 2 to Gate 3.

Overall, a re-review of stakeholders priorities, activities that occur between Gates 1 – 4, and the author’s principles of SBD showed that Gates 2 and 3 are amenable to SBD, Gate 1 is not amenable, and Gate 4 may be amenable.

5.2 Using SBD for Ship Design Process Improvement
This section will build upon the previous findings that Gates 2 – 4 are, or may be, amenable to SBD. The current state of Gates 2 – 3 will be more formally assessed and a recommendation for ship design process improvement will be provided for these two Gates.

5.2.1 Gate 2 SBD Process Improvement: The Analysis of Feasibility
During interviews, discussions, and literature research, the AoA seemed to be the first large decision point and possibly the most influential in directing the course of a ship design. For ship design programs, the AoA occurs right at the time of highest design influence slope per Figure 13. Almost every ship program researched had a foundational AoA that, at the very least, collected and described the basic need for the ship. Given the importance of this ship design event, it was surprising to discover that past USN ship AoA’s have not been as productive as one would expect. Given the amenability of SBD to Gate 2 stakeholder priorities and the historical poor performance of USN ship AoA’s, the current ship AoA process was diagrammed to assess opportunities for SBD process improvement.

This resulted in the realization that current ship design tools support a different way to approach performing a ship AoA. This new method leverages RSDE’s capability to communicate interfacial design variables to achieve the author’s principles of SBD. This new method, termed
the Analysis of Feasibility (AoF), improves the current state by producing data that better aligns with DoD 5000.02 AoA guidance, eliminating the “middle point” pitfalls of past AoAs, and providing results in response surfaces instead of bar charts. Additionally, the AoF enables follow-on Pre-PD design to continue in a set-based fashion. Most importantly, the AoF produces results in a fashion preferred by stakeholders to enable higher confidence decisions. Last, the AoF contributes to lower overall PAUC by preventing future re-work and shortening overall ship design cycle time.

In the past, USN AoA’s have been performed by NAVSEA 05D or private ship design consultants with varying results, but similar styles. Some past AoA’s produced satisfactory results, while some produced preferred variants which required extensive re-work to pass MS B. Specifically, the ship AoA’s for the proposed replacement Cruiser, Large Deck Amphibious ship LHA(R), and Marine Maritime Prepositioning Force (MMPF) ship all produced results that did not support timely follow-on acquisition efforts (Doerry & Fireman, 2009). Also, research showed, and interviews confirmed, that ship AoA’s all seemed to follow a point-based initial alternative selection pattern. Initial alternatives typically were a mix of the following concepts: legacy ship, a slightly larger (less dense) legacy ship, a slightly smaller (more dense) legacy ship, the next ship class up, a blend of the legacy ship and next ship class up, similar foreign ships, and ship designs from industry. The design environment used for AoA’s is the ship synthesis tool ASSET with weight based cost estimates performed using ASSET output SWBS groups. Ship performance evaluations are conducted using ship analysis tools through the LEAPS architecture. Cost and capability for each AoA variant is typically reported in a bar chart. Figure 45 is a depiction of a generic current state USN ship AoA.
General AoA design team structure only supports designing, simulating for performance, and cost-estimating one variant at a time. The tabular structure cost and performance in Figure 45 is the typical bottom-line information presented to stakeholders for preferred AoA variant selection. In the past, the selected AoA variant has needed re-work in future design phases to align the variant’s capabilities and performance with what the ship’s sponsor can afford.

The relative crude display of cost and capability and the post-AoA re-work “middle point” syndrome present opportunities for AoA process improvement. A process, similar to what was used by the SSCTF, can be implemented using existing ship design tools and a set-based
approach to improve Gate 2 activities. This new process is termed the Analysis of Feasibility (AoF).

The SSCTF used two functional teams split between Combat Systems and HM&E to accomplish capability concept designs. The same AoF design team division could be used by a NAVSEA SCM, who is familiar with SBD, to generate a large span of variants to inform a ship AoF trade-off study.

Ship AoA’s use the DRM from the ICD to determine required ship performance. For ships, the DRM determines the type and variety of Combat Systems, but not the sea frame that carries it. A simple analogy is to think of the Navy ship as a truck which carries the sensors and weapon systems to perform the DRM. The truck supplies the weapon systems with energy and physical support. Splitting a design team along the weapons system and truck functional boundaries would establish energy and physical support as interfacial variables; and thus, partition the design space into separate groups of experts (Author SBD Principle 1). By splitting into two functional teams, Ship and Combat System designers can independently and concurrently design their systems to meet the required performance of the DRM. Once designs are complete, the two teams meet/communicate to share what range of energy and support each team needs from the other (Author SBD Principle 2). For example, determining how the truck is built determines how heavy or high the weapons system could be placed before the truck tips over or breaks. Likewise, the DRM would determine the size and type of weapons system needed.

In the USN ship design environment, ASSET has the capability to design the ship [truck] and place the weapons system. But, ASSET only produces results for one unique, individual ship and weapons system configuration at a time. Using ASSET with RSDE allows a range of ship design parameters and a range of weapon system locations and sizes to be analyzed concurrently. Figure 46 shows a visual description of how a range of combat system configurations could be varied while simultaneously varying ship parameters.
Figure 46: New AoF Variant Creation Process

Varying the ship and combat system parameters per Figure 46 could result in a span of variants comprised in Table 6.

Table 6: Example of AoF Configurations

<table>
<thead>
<tr>
<th></th>
<th>Combat System 1</th>
<th>Combat System 2</th>
<th>Combat System 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hull</td>
<td>B_{Lower} - B_{Upper}</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>D_{Lower} - D_{Upper}</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T_{Lower} - T_{Upper}</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C_p - C_p</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Propulsion</td>
<td>Type 1</td>
<td>Type 2</td>
<td>Type 3</td>
</tr>
<tr>
<td>Energy</td>
<td>Type 1</td>
<td>Type 2</td>
<td>Type 3</td>
</tr>
<tr>
<td>Auxiliaries</td>
<td>Type 1</td>
<td>Type 2</td>
<td></td>
</tr>
<tr>
<td>Crew</td>
<td>Option 1</td>
<td>Option 2</td>
<td>Option 3</td>
</tr>
</tbody>
</table>
Ship hull parameters Beam (B), Draft (T), Depth (D), and Prismatic Coefficient (Cp) are not the only parameters available to be varied in ASSET with RSDE and were chosen just to highlight the example. Similarly, various different propulsion, power generation, and auxiliary cooling configurations are typically considered when performing early stage ship design when all available options should be included in the design trade space. Each set of ship parameters can be evaluated over the range of possible Combat Systems by simply utilizing RSDE to run multiple ASSET evaluations.

The blank space in the middle of Table 6 represents all the possible combinations of Ship parameters and Combat Systems. RSDE would facilitate performing ASSET synthesis on every possible variant using various sampling methods for ranges of ship parameters or physical locations of Combat Systems. As the Ship or Combat System design group identifies ranges of parameters that are infeasible or not physically possible, those variants would be excluded from the feasible (blank) trade space.

Overall, conducting an AoF in the above set-based manner produces a large number of variants that would fill in the middle points of a current state AoA. This larger data set should produce better capability and cost trade-off assessment for decision makers using statistical tools like JMP. JMP can easily produce graphs and view charts that quickly show regions of the performance variables and how they change with variations in Ship or Combat System parameters. Figure 47 shows an example from a NSWC-CD internal design study of how ship capability trade-offs can be presented using JMP. And, most importantly, data presented in this manner is preferred by stakeholders over the classic cost and capability bar-charts. The concurrent evaluation of the trade space by the Ship and Combat System design experts should result in a faster design cycle time. Also, the knowledge obtained by identifying the ranges of infeasibility for various Ship parameters and Combat System configurations is invaluable. This design knowledge is captured by the formal meeting/communicating process inherent to SBD and supports eliminating future more-costly re-work. Overall, using a set-based AoF approach in Gate 2 should support a lower ship program PAUC and faster acquisition.
5.2.2 Gate 3 SBD Process Improvement: Continue the AoF Analysis

Given the amenability of SBD to the stakeholder priorities of Gate 3, the AoF method was considered as an opportunity to improve Gate 3 ship design activities. With the priority of assessing the feasibility of KPPs/KSAs, the large trade space and design knowledge gained from Gate 2 AoF activities presented an excellent opportunity to support continued design feasibility assessments.

After a successful Gate 2 review board, the focus of the ship design team turns towards generating the CDD. Which ultimately means conducting enough design to assess if the performance levels required in the KPPs/KSAs can be achieved within cost and schedule targets. In the past, AoA’s have produced preferred variants that do not represent the right combination of affordable capability; thus, ship program sponsors have had to fund re-design efforts on AoA
resultant variants. These redesign efforts present an improvement opportunity for Gate 3.
Continuing the AoF design method can reduce or prevent the re-design effort experienced in past Pre-PD and PD designs.

The AoF design method reduces or prevents AoA variant re-design by keeping the design trade space open across the Gate 2 review board. In the past, AoAs were contained design events that only produced a written report to make a decision. AoA ASSET ship models were retained by NAVSEA 05D, but rarely re-used because exact AoA variants tended to not exactly align with what the ship program manager desired for the CDD.

To continue the AoF in Gate 3, the SDM should start by re-evaluating the design team functional partition to identify sub-regions of expertise for further concurrent evaluation. For example, in the Gate 2 AoF, the propulsion was only at the “type” level. A specific Propulsion design team could be created during Gate 3 with identified interfacial design variables of space, thrust, and weight with the Ship design team. This would support evaluating “options” of different propulsion methods. Once a span of propulsion options has been studied, the propulsion team would communicate the exact space, thrust, and weight of their preferred propulsion choice to the Ship team. This would most likely eliminate some of the propulsion options from consideration and thus refine the performance of the overall ship. The ship design tools ASSET and RSDE could be used to perform this type of sub-group study. Figure 48 highlights the Propulsion design team example communicating across the identified interfacial variables.
Overall, continuing the AoF approach in Gate 3 provides the SDM with the opportunity to flexibly adjust the design team in areas of the design that may need more specific evaluation to provide a feasible assessment of required KPP/KSA performance. Also, it limits the iterations of re-design performed in the past by keeping the real design trade space open and using SBD to reduce or eliminate dominated sub-system options. Thus, the AoF represents a better way to proceed through Gate 3 activities.

5.3 Phase 4 Conclusion

In Phase 4, amenability of SBD to the stakeholder priorities of Gates 1–4 was performed to identify possible opportunities for improvement. Gates 2 and 3 were identified as the most likely candidates for SBD process improvement. The Analysis of Feasibility, using SBD principles and existing, modern ship design tools, was introduced as a way to improve overall ship program PAUC and design cycle time by segmenting the to-be-designed ship initially into Ship and Combat System functional design teams. The AoF method was shown to be flexible enough to keep the ship design space open across the Gate 2/3 boundary. In sum, the AoF method uses existing ship design tools and SBD principles to deliver Gate 2 and 3 stakeholder priorities in a preferred fashion.
6.0 Thesis Conclusion

This thesis set out to achieve two points [1] explore SBD in USN ship design and acquisition by seeking to understand the people, processes, and tools used to perform ship design and acquisition today, and [2] identify opportunities and outline efficiencies to improve 2P/6G performance. The process to accomplish these two points was proposed as researching and answering three questions through four phases of work. The result of this research culminated in identifying and describing process improvement initiatives in Gates 2 and 3 of the Navy 2P/6G process. Each question and answer re-summarized for totality.

#1: What are the principles of SBD? During phase 1, the principles of SBD were found to be [1] establish the design space and sub-divide along areas of expertise: concurrent subsystem evaluation, and [2] gradually and deliberately reduce the design space by integrating preferred sub-spaces: discovery by elimination. These two principles captured the fundamentals of SBD through a simple example illustrated by The Prospector and Panner. The unique process of SBD was described to illustrate how interfacial variables and communication become the key aspects of executing a SBD process.

#2: What could be the measured benefits of using SBD in the USN? Four proposed benefits of SBD were found and easily translated into potential benefits for the USN: [1] lower PAUC, [2] reduced design cycle time from MDD to MS B, [3] lower Life Cycle Cost, and [4] lower future ship recapitalization cost. The SSC, ACV, and SSCTF cases of SBD in the USN were critiqued and identified at least some of the principles were adhered to in each case, some of the proposed benefits of SBD were realized in each case, and that USN leadership has become more familiar and accustomed to the early stage design information resulting from a SBD approach.

#3: Which parts of the USN 2P/6G process are amenable to SBD? Discussion and presentation of DoD and DoN design and acquisition processes resulted in identifying Gates 1 – 4 as ship design intensive gates with the stakeholder priorities assessed for each gate per Table 3. Processes in Gates 2 and 3 were identified as most likely to be improved by SBD.
Building on the answers to the three research questions, the following recommendations for ASN RDA, as the process authority for 2P/6G and the USN CAE, are proposed to improve the USN ship design and acquisition process:

- **Official re-designate the Analysis of Alternatives as the Analysis of Feasibility.** Although this change is only administrative in nature, it fits with the general process of trying to change the culture of an organization. During interviews with the USN ship design community, it became apparent that an Analysis of Alternatives suggested the results should lead to a conclusion in which the one single ship design configuration should be selected. Although recent efforts by the USN and CAPE have attempted to broad and counter-act this point-based design culture, changing the designation of the process to the Analysis of Feasibility should further support the cultural shift in ship design behavior towards a more set-based philosophy.

- **Direct NAVSEA 05D to create a temporary TWH position for design process to champion SBD until all SDMs/SIMs have gained familiarity with the process.** In each of the cases of SBD use in the USN, there were paid design consultants to shepherd the SBD process. To transition away from continuing to pay for this service, the USN ship design community should capitalize on the in-house SBD process knowledge created from the SSC, ACV, and SSCTF events and create a temporary design process TWH group. This would be similar to temporary design tool TWH position creation in 2009 (McKenney, Buckley, & Singer, 2012) (Doerry N., 2010b). The Design Process TWH would advise the SDM during Gate 1 – 4 design activities and replace the previously contracted design process experts. The temporary TWH position would only be created until all SDMs/SIMs in NAVSEA 05D/L/H/U/V obtain a to-be-determined level of satisfactory performance with SBD. Figure 49 shows how the new Design Process TWH would interact within the current NAVSEA 05 engineering construct.
Figure 49: New NAVSEA Design Process TWH Functional Interaction

- Direct AoA study plan to consider SBD as the overall design approach. If the results of Exploratory and Pre-AoA design point towards a material solution, CAPE produces AoA Study Guidance during the end of Gate 1 activities. A USN ship program office creates an AoA Study Plan in response to the AoA Study Guidance. This Study Plan is concurred upon by USN stakeholders at the Gate 1 review board. In order to force the Analysis of Feasibility, or a more set-based, early ship design process, N8 can direct ship program offices to consider SBD during the staffing/review period of the AoA Study Plan.

Overall, the unique process of set-based design has been shown to be a mitigating opportunity for ship design cost and schedule risk. SBD’s ability to force communication across interfacial variables between groups of experts leads to elimination of infeasible and dominated solutions in a gradual narrowing of the possible ship design trade space. This forced communication process greatly reduces the opportunity for later stage re-work, thereby reducing cost and schedule risk. Additionally, SBD reduces risk in future ship design. The structured SBD decision making
process captures critical design knowledge across inter-design negotiating relationships. It is those relationships that often take time to be re-discovered during modernization or recapitalization efforts in future ship design.

In conclusion, this thesis was written to ultimately identify and enact process improvement to “do more, without more,” as emphasized by top defense acquisition leadership. The proposed process improvement initiatives captured in this work are within the capability of the current USN ship design and acquisition work force. Future work entails the processes of changing written policy and guidance at an institutional level. Specific policy recommendations for ASN RDA, as author of the SECNAV 5000.2E, are provided. Furthermore, the USN should continue its investment in ship design and process tools that align with the two principles of SBD as presented by the author. The proposed benefits of SBD, as applied to USN ship design, are too great to be ignored. In the face of the near to mid-term ship acquisition budgetary challenge, aligning the amenable aspects of the 2P/6G USN ship design process with SBD is one of the most promising opportunities to realize ship design and acquisition improvement.
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## Appendix A: Entrance and Exit Criteria for Gates 1 - 4

SECNAV 5000.2E, Annex 1-B - Table E1T3, DON Requirements and Acquisition Gates, Membership, Entrance Criteria, Goals and Exit Criteria, and Briefing Content for Gates 1 – 4 (SECNAV, 2011, pp. 61-64):

<table>
<thead>
<tr>
<th>Gate 1 (ICD)</th>
<th>Membership</th>
<th>Entrance Criteria</th>
<th>Goals/Exit Criteria</th>
<th>Briefing Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purpose: Validate ICD &amp; AoA Study Guidance, authorize proceeding to materiel development decision (MDD).</td>
<td>Chair: CHO (N9)/DC, CD&amp;I</td>
<td>1. Completed Service review of ICD. 2. Identification of mutually shared needs with foreign countries. 3. Completed Service review of AoA Study Guidance.</td>
<td>1. Approval for ICD entry into joint review, or endorsement of ICD entry to CNO/CNO for signature. 2. Validation of AoA Study Guidance, assumptions, &amp; timeline and authorization for submittal to Director Cost Assessment and Program Evaluation (CAPE) (ACAT II).</td>
<td>1. ICD description. 2. AoA proposed Study Guidance. 3. Doctrine, organization, training, materiel, leadership &amp; education, personnel, &amp; facilities (DOTMLPF) change recommendations (DCRs) inputs. 4. Programmatic (projected costs, schedule, interdependencies). 5. Program health.</td>
</tr>
<tr>
<td>Briefing: RO, prospective PM, and AoA director (Dir)</td>
<td>Principal: N1/DC, M4/A, N2/N4/HC Intel, N3/NS/DC, FPAO, N4/DC, I&amp;L, DON CIO, DirC4/CIO, DC, PAR, ASH(RDA), N000, PM/A/ASN, WE Lead 6/0 or USEF/FORCOM/HARFOR, SYSCOM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>As required: PEO/DISRSP, CHR, DC Avn</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Advisory: DASN(RDAE) CHENG, DASII, N90, N01, N02, N11D, N091, USEF/FORCOM(N9), N06D, N06E, N07E, DASN(Budget), DASN(C&amp;I), SYSCOM cost director, resource sponsor, DISNIPO, OPA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Entrance Criteria - is a requirement to convene a Gate Review
Exit Criteria - is a requirement to complete a Gate Review
Annex 1-B - Table E1T3 DON Requirements and Acquisition Gates, Membership, Entrance Criteria, Goals and Exit Criteria, and Briefing Content (cont’d)

<table>
<thead>
<tr>
<th>Gate 2 (AoA)</th>
<th>Membership</th>
<th>Entrance Criteria</th>
<th>Goals/Exit Criteria</th>
<th>Briefing Content</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Purpose:</strong> Validate AoA results, assess affordability, approval to develop CDD and CONOPS, recommend approval of technology development strategy (TDS) to HDA, concurrence to proceed to gate 3 or milestone (MS) A.</td>
<td><strong>Chair:</strong> CNO/CMC, or designee <strong>Principal:</strong> VCNO/ACMC, NM/OC, P&amp;R/OC, CDDI, NA/OC, M&amp;A, N2/H6/HC Intel, N3/H5/DC, Prop, N4/OC, IIL, DON CIO, Dc4/CIO, ASN(RDA), ASN(FM6C), NOM, PDASN, WE Lead &amp;/or USFLTRCOM/MARFOR, SYSCOM</td>
<td>1. Approved JCD 2. Completed service review of AoA Report. 3. MS A documentation sufficiently mature for senior service leadership review. 4. Preferred alternative identified. 5. Completed initial technical review (ITR) &amp; alternative system review (ASR). 6. NSS by the milestone decision authority.</td>
<td>1. Evaluation/validation of AoA findings. 2. Approve initial capabilities thresholds and objectives (KPPs/KSA's). 3. Approval to develop CDD &amp; CONOPS with guidance &amp; assumptions documented in decision memorandum. 4. Satisfactory review of program health. 5. Concurrence to proceed to the next event (i.e., to gate 3).</td>
<td>1. Summarize AoA report including assumptions, findings, &amp; implications of TOC for the selected alternative(s). 2. Warfighter review of AoA results. 3. Analysis of the relative cost risk of each proposed alternative. 4. Assessment of DON/US Navy DoD DoA. 5. MS A service cost position (SCP), assumptions, and cost risk for the selected alternative; 3-curves by appropriation. 6. Cost arrayed per MCCA policy (i.e., MIL HDBK 881 and OSD CAPE protocols). 7. Initial sustainment strategy. 8. Proposed CDD/CONOPS guidance. 9. Present ITR &amp; ASR results including TDS, TES, SEP, &amp; technology maturation efforts. 10. Environmental issues/impacts. 11. TD RFP content (less non-disclosure sections) /Assessment of industrial base. 12. Programmatic (schedule, interdependencies). 13. Program risks. 14. Program health.</td>
</tr>
<tr>
<td><strong>As required:</strong> CIR, DC Avn <strong>Advisory:</strong> DASN(RDT&amp;E) CHSENG, DASNs, N80, N81, N82, N91D, USFLT RCOM(NR), GMCM(CL, P&amp;A), OGC, DASN(Budget), DASN(C&amp;A), SYSCOM cost director, Resource Sponsor, PED/DirSSP, DirNPPO, OPA</td>
<td>Entrance Criteria - is a requirement to convene a Gate Review Exit Criteria - is a requirement to complete a Gate Review</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gate</td>
<td>Membership</td>
<td>Entrance Criteria</td>
<td>Goals/Exit Criteria</td>
<td>Briefing Content</td>
</tr>
<tr>
<td>------</td>
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<td>-------------------</td>
<td>--------------------</td>
<td>------------------</td>
</tr>
<tr>
<td>3 (CDD/CONOPS)</td>
<td>[Membership details]</td>
<td>[Entrance Criteria details]</td>
<td>[Goals/Exit Criteria details]</td>
<td>[Briefing Content details]</td>
</tr>
</tbody>
</table>

**Entrance Criteria** - is a requirement to convene a Gate Review

**Exit Criteria** - is a requirement to complete a Gate Review
Annex 1-B - Table E1T3 DON Requirements and Acquisition Gates, Membership, Entrance Criteria, Goals and Exit Criteria, and Briefing Content (cont’d)

<table>
<thead>
<tr>
<th>Gate 4 (SDS)</th>
<th>Entrance Criteria</th>
<th>Goals/Exit Criteria</th>
<th>Briefing Content</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chair:</strong></td>
<td>1. Approved CDD, approved CDD update, as required.</td>
<td>1. Approved SDS</td>
<td>1. Review capability &amp; threat.</td>
</tr>
<tr>
<td><strong>Membership:</strong></td>
<td>2. Approved CONOPS</td>
<td>2. Validate SDS traceability to CDD</td>
<td>2. Analysis (FEA).</td>
</tr>
<tr>
<td><strong>Entrance Criteria:</strong></td>
<td>3. SDS has been signed by PM, SYSCOM, CSENG, and resource sponsor.</td>
<td>3. Acknowledgement of Configuration Steering Board (CSB) recommended capability changes.</td>
<td>3. Cost driver by phase &amp; by KPP/KSA to include specific cost reduction strategies.</td>
</tr>
<tr>
<td><strong>Exit Criteria:</strong></td>
<td>4. Completed cost review board.</td>
<td>Approval to proceed to R3B/HGOC, or CMO/CNC, for assessment &amp; Service approval.</td>
<td>4. Draft acquisition strategy.</td>
</tr>
<tr>
<td><strong>Goals/Exit Criteria:</strong></td>
<td>5. Service review of program cost containment and cost reduction strategies.</td>
<td>5. Sufficiently structured to operate within DON’s business enterprise.</td>
<td>5. Draft lifecycle sustainment strategy.</td>
</tr>
<tr>
<td><strong>Briefing Content:</strong></td>
<td>6. Updated SCP, assumptions, &amp; cost risk &amp; curves by appropriation.</td>
<td>6. Satisfactory review of program health.</td>
<td>10. Modular, common, &amp; open systems plan.</td>
</tr>
<tr>
<td><strong>Gate 4 Chair:</strong></td>
<td>7. Cost drivers by phase &amp; by KPP/KSA to include specific cost reduction strategies.</td>
<td>7. Approval to proceed to the next event.</td>
<td>11. Job task analysis (JTA), preliminary Navy training system plan (HTSP), &amp; front end analysis (FEA).</td>
</tr>
<tr>
<td><strong>Briefing Content:</strong></td>
<td>11. Environmental issues/impacts.</td>
<td>11. Job task analysis (JTA), preliminary Navy training system plan (HTSP), &amp; front end analysis (FEA).</td>
<td>15. Demonstration that financial, logistics, &amp; procurement functions have agreement on the appropriate &amp; compliance level of acquisition detail.</td>
</tr>
<tr>
<td><strong>Entrance Criteria:</strong></td>
<td>14. Review the overall I&amp;A program &amp; results of key test events.</td>
<td>18. Review the overall I&amp;A program &amp; results of key test events.</td>
<td>19. Programmatical changes, (schedule, interdependencies).</td>
</tr>
<tr>
<td><strong>Goals/Exit Criteria:</strong></td>
<td>15. Program risks.</td>
<td>20. Program health.</td>
<td>20. Program health.</td>
</tr>
</tbody>
</table>

Entrance Criteria - is a requirement to convene a Gate Review
Exit Criteria - is a requirement to complete a Gate Review
Appendix B  Key Performance Parameters for LPD 17

![Table of Key Performance Parameters for LPD 17]

Figure 50: KPPs for LPD 17

(DAMIR, 2015)
Appendix C System Requirements and Ship System Design

The following are the verbatim sections from the NAVSEA Ship Design Specification guidebook to provide an understanding of the level of detail. (NAVSEA, NAVAIR, RDA, SPAWAR, & USMC, 2008)

5. System Requirements - This section shall be divided into the following paragraphs to specify the system requirements, that is, those characteristics of the system that are conditions for its acceptance. Each requirement shall be assigned a project-unique identifier to support testing and traceability and shall be stated in such a way that an objective test can be defined for it. Each requirement shall be annotated with associated qualification method(s) (see section 7) and, for subsystems, traceability to system requirements (see section 6.7), if not provided in those sections. The degree of detail to be provided shall be guided by the following rule: Include those characteristics of the system that are conditions for system acceptance; defer to design descriptions those characteristics that the acquirer is willing to leave up to the developer. If there are no requirements in a given paragraph, the paragraph shall so state. If a given requirement fits into more than one paragraph, it may be stated once and referenced from the other paragraphs.

5.1. System capability requirements - This paragraph shall be divided into subparagraphs to itemize the requirements associated with each capability of the system. A "capability" is defined as a group of related requirements. The word "capability" may be replaced with "function," "subject," "object," or other term useful for presenting the requirements.

5.1.1. Anti-Air Warfare - This section should include hard-kill and soft-kill performance requirements against Anti-Ship Cruise Missile Threats, Manned and Unmanned Aircraft, Land Attack Cruise Missiles and High Divers in various environmental and jamming conditions. The requirements should include planning, sensing, control and engagement capabilities. The performance requirements should cover detection ranges, number and types of tracks, reaction time, coverage, firepower, simultaneous engagements, probability of kill, system availability etc.

5.1.2. Ballistic Missile Defense - This section should include hard-kill and soft-kill performance requirements against Short Range Ballistic Missile, Medium Range Ballistic Missiles, Intermediate Range Ballistic Missiles and Inter-Continental Ballistic Missiles in various environmental and jamming conditions. The requirements should include planning, sensing, control and engagement capabilities. The performance requirements should cover detection ranges, number and types of tracks, reaction time, coverage, firepower, simultaneous engagements, probability of kill, system availability etc.

5.1.3. Surface Warfare - This section should include hard-kill and soft-kill performance requirements against Small Boats (manned and unmanned), patrol boats and Naval Ships in various environmental and jamming conditions. The requirements should include planning, sensing, control and engagement capabilities. The performance requirements should cover detection ranges, number and types of tracks, reaction time, coverage, firepower, simultaneous engagements, probability of kill, system availability etc.

5.1.4. Undersea Warfare - This section should include hard-kill and soft-kill performance requirements against submarines, unmanned underwater vehicles, and
mines in various environmental and jamming conditions. The requirements should include planning, sensing, control and engagement capabilities. The performance requirements should cover detection ranges, number and types of tracks, reaction time, coverage, firepower, simultaneous engagements, probability of kill, system availability etc.

5.1.5. Strike Warfare - This section should include hard-kill and soft-kill performance requirements against Land Based targets (mobile and fixed) in various environmental and jamming conditions. The requirements should include planning, sensing, control and engagement capabilities. The performance requirements should cover detection ranges, number and types of tracks, reaction time, coverage, firepower, simultaneous engagements, probability of kill, system availability etc.

5.1.6. Naval Surface Fire Support - This section should include gun and missile performance requirements against land targets (mobile and fixed) in support of USMC call for fire in various environmental and jamming conditions. The requirements should include planning, sensing, control and engagement capabilities. The performance requirements should cover detection ranges, number and types of tracks, reaction time, coverage, firepower, simultaneous engagements, probability of kill, system availability etc.

5.1.7. Command, Control and Communications – This section should include the systems performance regarding planning, command and control and communications for force level command functions.

5.1.8. Electronic and Information Warfare – This section should include performance requirements associated with achieving information superiority by affecting adversary information, information-based processes, information systems, and computer-based networks while defending one’s own information, information-based processes, information systems and computer-based networks.

5.1.9. Anti-Terrorism and Force Protection

5.1.10. Amphibious Warfare – This section should include performance requirements regarding attacks launched from the sea by naval forces and landing forces embarked in ships and craft designed to achieve shore presence in a littoral zone.

5.1.11. Naval Special Warfare – This section should include performance requirements associated with naval special warfare operations include special mobile operations, unconventional warfare, coastal and river interdiction, beach and coastal reconnaissance, and certain intelligence operations.

5.1.12. Mobility – This section should include performance requirements associated with mobility of the ship including maximum, cruise, and sustained speed; endurance to include maximum range, range at speed characteristics and fuel capacities; operating envelope for submarines and other submersibles; maneuverability including turn radius and stopping distance.

5.1.13. Seakeeping – This section should include performance requirements associated with performance of the ship in a seaway to include extreme ship motions and Dynamic Load factors, stability and reserve buoyancy, intact and damaged stability, limiting displacement, stability margins, buoyancy and weights

5.1.14. Environmental – This section should include performance requirements associated with expected operational environmental conditions to include minimum/maximum temperatures, submersion requirements, stack gas effects, blast
over pressurization, flight deck operations impact on operational environment and equipments, Electromagnetic Environment Effect (E^3)

5.1.15. Total Ship Survivability – This section should include performance requirements associated with the survivability of the platform. It should include performance requirements associated with detectability; infrared signature; radar cross section/signature; magnetic signature; EMCON signature; Acoustic signature; visual signature; ship protection; shock to include hull response, combat system equipment fragility, and shock resistance of equipments; Force Protection; protection against CBR Weapon effects; nuclear fallout and radiation protection; biological and chemical warfare protection; protection against transient radiation effects on Electronics (TREE); carbon/graphite fiber protection; and damage control (identification of vital spaces, damage control deck, fire zones, major damage control systems)

5.2. System external interface requirements - This paragraph shall specify the requirements, if any, for the system’s external interfaces. This paragraph may reference one or more Interface Requirements Specifications (IRPs) or other documents containing these requirements.

5.3. System internal interface requirements. This paragraph shall specify the requirements, if any, imposed on interfaces internal to the system. If all internal interfaces are left to the design or to requirement specifications for system components, this fact shall be so stated. If such requirements are to be imposed, paragraph 5.3 provides a list of topics to be considered.

5.4. Safety requirements. This paragraph shall specify the system requirements, if any, concerned with preventing or minimizing unintended hazards to personnel, property, and the physical environment. This paragraph shall include the system requirements, if any, for nuclear components, including, as applicable, requirements for component design and compliance with nuclear safety rules.

5.5. Security and privacy requirements. This paragraph shall specify the system requirements, if any, concerned with maintaining security and privacy. The requirements shall include, as applicable, the security/privacy environment in which the system must operate, the type and degree of security or privacy to be provided, the security/privacy risks the system must withstand, required safeguards to reduce those risks, the security/privacy policy that must be met, the security/privacy accountability the system must provide, and the criteria that must be met for security/privacy certification/accreditation.

5.6. System environment requirements. This paragraph shall specify the requirements, if any, regarding the environment in which the system must operate. Examples include the environmental conditions that the system must withstand during transportation, storage, and operation, such as conditions in the natural environment (wind, rain, temperature, geographic location), the induced environment (motion, shock, noise, electromagnetic radiation), and environments due to enemy action (explosions, radiation).

5.7. Computer resource requirements. This paragraph shall be divided into the following subparagraphs. Depending upon the nature of the system, the computer resources covered in these subparagraphs may constitute the environment of the system (as for a software system) or components of the system (as for a hardware-software system).
5.7.1. Computer hardware requirements. This paragraph shall specify the requirements, if any, regarding computer hardware that must be used by, or incorporated into, the system. The requirements shall include, as applicable, required characteristics of processors, memory, input/output devices, auxiliary storage, communications/network equipment, and other required equipment.

5.7.2. Computer hardware resource utilization requirements. This paragraph shall specify the requirements, if any, on the system’s computer hardware resource utilization, such as maximum allowable use of processor capacity, memory capacity, input/output device capacity, auxiliary storage device capacity, and communications/network equipment capacity. The requirements (stated, for example, as percentages of the capacity of each computer hardware resource) shall include the conditions, if any, under which the resource utilization is to be measured.

5.7.3. Computer software requirements. This paragraph shall specify the requirements, if any, regarding computer software that must be used by, or incorporated into, the system. Examples include operating systems, database management systems, communications/network software, utility software, input and equipment simulators, test software, and manufacturing software. The correct nomenclature, version, and documentation references of each such software item shall be provided.

5.7.4. Computer communications requirements. This paragraph shall specify the additional requirements, if any, concerning the computer communications that must be used by, or incorporated into, the system. Examples include geographic locations to be linked; configuration and network topology; transmission techniques; data transfer rates; gateways; required system use times; type and volume of data to be transmitted/received; time boundaries for transmission/reception/response; peak volumes of data; and diagnostic features.

5.8. System quality factors. This paragraph shall specify the requirements, if any, pertaining to system quality factors. Examples include quantitative requirements concerning system functionality (the ability to perform all required functions), reliability (the ability to perform with correct, consistent results -- such as mean time between failure for equipment), maintainability (the ability to be easily serviced, repaired, or corrected), availability (the ability to be easily accessed and operated when needed), flexibility (the ability to be easily adapted to changing requirements), testability (the ability to be easily and thoroughly tested), usability (the ability to be easily learned and used), and other attributes.

5.9. Design and construction constraints. This paragraph shall specify the requirements, if any, that constrain the design and construction of the system. This paragraph shall include the physical requirements imposed on the system. These requirements may be specified by reference to appropriate commercial or military standards and specifications.
Examples include requirements concerning:

- Use of a particular system architecture or requirements on the architecture, such as required subsystems; use of standard, military, or existing components; or use of Government/acquirer-furnished property (equipment, information, or software)
- Use of particular design or construction standards; use of particular data standards; use of a particular programming language; workmanship requirements and production techniques
- Physical characteristics of the system (such as displacement limits, dimensional limits, etc.);
- Materials that can and cannot be used; requirements on the handling of toxic materials; limits on the electromagnetic radiation that the system is permitted to generate

5.10. Personnel-related requirements. This paragraph shall specify the system requirements, if any, included to accommodate the number, skill levels, duty cycles, training needs, or other information about the personnel who will use or support the system. Examples include requirements for the number of work stations to be provided and for built-in help and training features. Also included shall be the human factors engineering requirements, if any, imposed on the system. These requirements shall include, as applicable, considerations for the capabilities and limitations of humans, foreseeable human errors under both normal and extreme conditions, and specific areas where the effects of human error would be particularly serious. Examples include requirements for adjustable-height work stations, color and duration of error messages, physical placement of critical indicators or buttons, and use of auditory signals.

5.11. Training-related requirements. This paragraph shall specify the system requirements, if any, pertaining to training. Examples include training devices and training materials to be included in the system.

5.12. Logistics-related requirements. This paragraph shall specify the system requirements, if any, concerned with logistics considerations. These considerations may include: system maintenance, software support, system transportation modes, supply-system requirements, impact on existing facilities, and impact on existing equipment.

5.13. Other requirements. This paragraph shall specify additional system requirements, if any, not covered in the previous paragraphs. Examples include requirements for system documentation, such as specifications, drawings, technical manuals, test plans and procedures, and installation instruction data, if not covered in other contractual documents.

5.14. Precedence and criticality of requirements. This paragraph shall specify, if applicable, the order of precedence, criticality, or assigned weights indicating the relative importance of the requirements in this specification. Examples include identifying those requirements deemed critical to safety, to security, or to privacy for purposes of singling them out for special treatment. If all requirements have equal weight, this paragraph shall so state.

6. Ship System Design
The follow paragraphs should address:

- Identify the component of the system (element hardware configuration items, software configuration items, etc).
- Show the static (such as "consists of") relationship(s) of the components. Multiple relationships may be presented (using multiple diagrams), depending on the selected design methodology.
- State the purpose of each component and identify the system requirements and system-wide design decisions allocated to it.
- Identify each component's develop status/type, if known (such as new development, existing component to be reused as it, existing design or component to be reengineered, component to be developed for reuse, component planned for Build N, etc.) For existing design components, the description shall be provided identifying information, such as name, version, documentation references, location, etc.
- For each computer system or other aggregate of computer hardware resources identified for use in the system, describe its computer hardware resources (such as processors, memory, input/output devices, auxiliary storage, and communications/network equipment). Each description shall, as applicable, identify the configuration items that will use the resource, describe the allocation of the resource utilization to each configuration item (CSCI) that will use the resource (for example, 20% of the resource's capacity allocated to CSCI 1, 30% to CSCI 2), describe the conditions under which the utilization will be measured, and describe the characteristics of the resource:
  - Computer processors
  - Memory
  - Input/output devices
  - Auxiliary storage
  - Communications/network equipment
  - Growth and diagnostics capabilities

6.1. System Components – High Level diagram and description of the segments, elements, and components of the ship system. A Distributed System Block Diagrams showing system interfaces should be included.

6.2. Major System /Equipment Selections

6.2.1. development status of system / equipment

6.2.2. GFE or CFE?

6.3. Combat Load

6.3.1. Aircraft - describe the number and type of aircraft, any flight critical systems, payload requirements, any special maintenance or stowage requirements driving design requirements, identify deck movement envelopes and fueling requirements, identify launch and recovery systems

6.3.2. Boats / Marine craft - describe the number and type of craft, any critical support systems, payload requirements, any special maintenance or stowage requirements driving design requirements, identify craft movement envelopes and fueling requirements, identify launch and recovery systems

6.3.3. Vehicles and Vehicle Square - describe the number and type of vehicles, any critical support systems, payload requirements, any special maintenance or stowage requirements driving design requirements, identify vehicle movement envelopes and fueling requirements, identify launch and recovery systems.
6.3.4. Embarked Detachments / Staff / Troops – describe the number of detachments, the number of accommodations required for each detachment, special equipment storage needs of each detachment

6.3.5. Cargo Cube – describe the environmental conditions required for cargo, volume, weight, accessibility requirements (testing/monitoring), transport mechanisms, and any special handling requirements

6.3.6. Special Forces vehicles / craft / launch platforms – describe the number and type of craft, any critical support systems, payload requirements, any special maintenance or stowage requirements driving design requirements, identify craft movement envelopes and fueling requirements, identify launch and recovery systems

6.4. Warfare Systems

6.4.1. System Components – High-level diagram and description of the segments, elements, and components of the warfare system. A diagram should be included.

6.4.2. Computing Infrastructure Segment

6.4.2.1. Processors
6.4.2.2. Networks
6.4.2.3. Displays
6.4.2.4. Common Services
6.4.2.5. Operating Systems
6.4.2.6. Middleware

6.4.3. Sense Segment

6.4.3.1. Air Search Radar
6.4.3.2. Surface Search Radar
6.4.3.3. Towed Array
6.4.3.4. Fire Control Radar
6.4.3.5. Ballistic Missile Defense Radar
6.4.3.6. Air and Missile Defense Radar
6.4.3.7. Bow Array
6.4.3.8. Sonobouys
6.4.3.9. ES Systems
6.4.3.10. EO/IR Systems
6.4.3.11. Identification Systems (IFF, NCTR, etc)
6.4.3.12. Off-board Sensors (UAV, etc)
6.4.3.13. Sensor Management Element

6.4.4. Command and Control Segment

6.4.4.1. Combat Control Element

6.4.4.1.1. Track Management
6.4.4.1.2. Identification
6.4.4.1.3. Tactical Planning
6.4.4.1.4. Threat Evaluation
6.4.4.1.5. Weapon Assignment
6.4.4.1.6. Off-board Vehicle Control
6.4.4.1.7. Resource Management
6.4.4.1.8. Readiness Assessment
6.4.4.1.9. Communications
6.4.5. Operational C2 Elements
   6.4.5.1. GCCS-M
   6.4.5.2. DCGS
   6.4.5.3. Communications

6.4.6. Engage Segment
   6.4.6.1. Weapons Management Element
   6.4.6.2. Strike Missiles
   6.4.6.3. AAW Missiles
   6.4.6.4. BMD Missiles
   6.4.6.5. Torpedoes
   6.4.6.6. Rockets
   6.4.6.7. Launchers
   6.4.6.8. Guns
   6.4.6.9. Electronic Attack
   6.4.6.10. Decoys
   6.4.6.11. Illuminators
   6.4.6.12. Helicopters
   6.4.6.13. Off-board Weapons (UAVs, TACAIR, etc)

6.4.7. Support Segment
   6.4.7.1. Weapon System Power
   6.4.7.2. Weapon System Cooling
   6.4.7.3. Training Elements
   6.4.7.4. Logistics Elements
   6.4.7.5. Maintenance Elements

6.5. Hull
   6.5.1. Hull characteristics
      6.5.1.1. Dimensional characteristics (length, beam, height above waterline, draft, etc)
      6.5.1.2. Hull lines and hydrostatic properties
      6.5.1.3. Hydrodynamic performance
      6.5.1.4. Hull appendages
      6.5.1.5. Artist rendition / drawing of ship if available

6.5.1.6. Capacities
      6.5.1.6.1. Personnel
         6.5.1.6.1.1. Crew accommodations
         6.5.1.6.1.2. Detachment accommodations
      6.5.1.6.2. Cargo / Payload
         6.5.1.6.2.1. Volume
         6.5.1.6.2.2. Weight
         6.5.1.6.2.3. Environmental considerations
      6.5.1.6.3. Fuel
         6.5.1.6.3.1. Types of fuel (i.e. DFM, JP5, etc)
         6.5.1.6.3.2. Own ship use / detachment use
         6.5.1.6.3.3. Replenishment capability
      6.5.1.6.4. Water
         6.5.1.6.4.1. Potable
         6.5.1.6.4.2. Non potable
6.5.1.6.4.3. Cooling
6.5.1.6.5. Stores
   6.5.1.6.5.1. Type / weight / volume
   6.5.1.6.5.2. Environmental considerations

6.5.2. Hull Structure
6.5.3. General Arrangement of Structure
6.5.4. Longitudinal Strength
6.5.5. Lateral Loads
6.5.6. Material and Stresses
6.5.7. Structural Rigidity
6.5.8. Special Structure
6.5.9. Habitability Summary and Environmental Requirements (HVAC, Noise, Vibration)
   6.5.9.1. Crew size
   6.5.9.2. Habitability Summary
   6.5.9.3. Living, Berthing, Sanitary and Lounge Facilities
   6.5.9.4. Work Area Sanitary Facilities
   6.5.9.5. Commissary and Messing Spaces
   6.5.9.6. Laundry and Dry Cleaning Spaces
   6.5.9.7. Service Spaces
   6.5.9.8. Medical and Dental Facilities
   6.5.9.9. Offices

6.6. Integrated Power System
   6.6.1. Total Power requirements
   6.6.2. Power generation equipments
   6.6.3. Power generation capacity
   6.6.4. Power Distribution / transmission systems
   6.6.5. Support systems
   6.6.6. Vital / Non-Vital loads
   6.6.7. Plant lineup for various operational conditions
      6.6.7.1. Fuel efficiency calculations for expected plant alignments
6.6.8. Control Systems

6.7. If not an Integrated Power System Power Generation or Propulsion Plant Capabilities (if not IPS), General
   6.7.1. Propulsion System type
      6.7.1.1. Diesel / gas turbine / nuclear /
   6.7.2. Propulsion Units
   6.7.3. Transmission and Propulsor Systems
   6.7.4. Propulsion Support Systems (except fuel and lube oil)
      6.7.4.1. Combustion Air System
      6.7.4.2. Propulsion Control System
      6.7.4.3. Auxiliary Systems Control
      6.7.4.4. Ballast Control System
      6.7.4.5. Fuel Service System
      6.7.4.6. Propulsion Lubricating Oil System
      6.7.4.7. Reduction Gear Lube Oil System
6.8. Electric Distribution, General
6.8.1. Electric Power Generation
6.8.2. Ship Service Power Generation
6.8.3. Batteries and Service Facilities
6.8.4. Electric Plant Control
6.8.5. Power Conversion Equipment
6.8.6. Power Distribution System
6.8.7. Lighting System
6.8.8. Vital / Non Vital Loads

6.9. Navigation Systems
6.9.1. Non-Electrical/Non-Electronic Navigation Aids
6.9.2. Electrical Navigation Aids
6.9.3. Electronic Navigation Systems, Radio
6.9.4. Electronic Navigation Systems, Acoustic
6.9.5. Electrical Navigation Systems
6.9.6. Inertial Navigation Systems

6.10. Interior Communications
6.10.1. announcing systems
6.10.2. communication systems
6.10.3. entertainment systems
6.10.4. training systems
6.10.5. alarm, safety and warning systems

6.11. Auxiliary Systems, General
6.11.1. Climate Control
   6.11.1.1. Heating Systems
   6.11.1.2. Ventilation Systems
   6.11.1.3. Air Conditioning Systems
   6.11.1.4. Refrigeration Systems
6.11.2. Seawater Systems
   6.11.2.1. Firemain and Flushing
   6.11.2.2. Sprinkler Systems
   6.11.2.3. Washdown Systems
   6.11.2.4. Auxiliary Seawater System
   6.11.2.5. Drainage Systems
   6.11.2.6. Ballasting and Deballasting System
6.11.3. Freshwater System
   6.11.3.1. Distilling Plant
   6.11.3.2. Freshwater Cooling
   6.11.3.3. Potable and Distilled Water
   6.11.3.4. Aircraft Washdown
6.11.4. Auxiliary Saltwater Freshwater Cooling
6.11.5. Fuels and Lubricants, Handling and Storage
   6.11.5.1. Ships Fuel Service, Fill, Transfer and Stripping Systems
   6.11.5.2. Liquid Cargo
6.11.6. Air, Gas, and Miscellaneous Fluid Systems
   6.11.6.1. Compressed Air Systems
6.11.6.2. High Pressure Air System
6.11.6.3. Low Pressure Air System
6.11.6.4. Compressed Gases (Gaseous Oxygen, Nitrous, Oxide, Helium, and Nitrogen Systems)
6.11.6.5. Deballasting Air System
6.11.7. Fire Extinguishing Systems
   6.11.7.1. types of systems - Carbon Dioxide, dry chemical, AFFF, Potassium
            Carbonate, Halon, Salt water etc.
6.11.8. Ship Control Systems – main and redundant
   6.11.8.1. Steering System
   6.11.8.2. Remote / local operation
      6.11.8.2.1. Rudder Slewng Speed
      6.11.8.2.2. Emergency Steering Unit
6.11.9. Replenishment Systems
   6.11.9.1. Replenishment-at-sea System
   6.11.9.2. Ship’s Stores, and Provisions Handling System
   6.11.9.3. Cargo Handling System
6.11.10. Mechanical Handling Systems
   6.11.10.1. Anchor Handling and Stowage System
   6.11.10.2. Mooring and Towing Systems
   6.11.10.3. Boats, Boat Handling and Stowage
   6.11.10.4. Cranes and Hoists
   6.11.10.5. Elevators / Elevator Doors
6.11.11. Aircraft Handling Servicing and Stowage
6.11.12. Aircraft Stowage & Servicing
6.11.13. Aircraft Launching Systems
6.11.15. Aircraft Elevators

6.12. Outfit and Furnishings
6.12.1. Outfit and Furnishings, General
6.12.2. Ship Fittings
6.12.3. Preservatives and Coverings
6.12.4. Living Spaces
   6.12.4.1. Berthing, General
   6.12.4.2. Officer Berthing and Messing Spaces
   6.12.4.3. Non Commissioned Officer Berthing and Messing Spaces
   6.12.4.4. Enlisted Personnel Berthing and Messing Spaces
   6.12.4.5. Sanitary Space and Fixtures
   6.12.4.6. Leisure and Community Spaces
   6.12.4.7. Service Space
   6.12.4.8. Commissary Spaces
   6.12.4.9. Detachment Berthing Spaces
   6.12.4.10. Medical Spaces
   6.12.4.11. Dental Spaces
   6.12.4.12. Utility Spaces
   6.12.4.13. Laundry Spaces
6.12.4.15. Working Spaces
6.12.4.16. Offices
6.12.4.17. Damage Control Stations
6.12.4.18. Workshops
6.12.4.19. Workshop Functional Capabilities