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A Case for Continuous Concept Development in Ship Design

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Abstract

Prevailing in a competition, especially a strategic competition, requires agility greater than your competitor. This agility is needed across the spectrum of operations, including acquisition, but the current acquisition process takes at least ten years to deliver modern, relevant ships to the Fleet. A measurable portion of this time is spent in the early stages with Capability-Based Analyses, Analyses of Alternatives, and conceptual designs. These analyses and concepts are often less relevant at the vessel's delivery because of the added time for preliminary design, concept design, detail design, and construction. As an alternate approach, this paper suggests using a continuous analysis process coupled with Set-Based Design methods, just as Toyota did, to reduce these timelines and have relevant concepts ready to transition to design and construction, potentially cutting the cycle time for ship design in half.

Introduction

Today, the U.S. Navy finds itself in a strategic competition with peer adversaries that desire to upset the existing rules-based international order (Office of the Secretary of the Navy, 2020, 2021). The Navy realizes this requires multi-pronged strategies that encompass everything from technology development to tactical training and that they must execute these strategies with speed and purpose (Kitchener et al., 2021; Office of the Chief of Naval Operations, 2018; Office of the Secretary of the Navy, 2020).

Maintaining this competitive edge poses intriguing challenges. Technology advances at a blistering pace, but all ships are significant capital investments with long service lives, complicating the ability to outfit all ships with the most modern equipment. Further, it is not just our technology that advances, but that of adversaries and competitors—who get a vote in the required capabilities of our fleet. Some of those competitors have capable first-rate navies and seek to challenge existing conventions reaching far beyond their territorial seas (Commander Naval Surface Forces, 2021). Therefore, since technology and requirements change before, during, and after constructing a capital ship, adapting and responding to change faster than competitors is probably better than trying to out-build them.

Additionally, the challenges facing the Navy are multiplicative and non-linear. Maintaining a competitive edge would be difficult enough if the geopolitical landscape changed quickly and the Navy responded to new threats in new locations. It would be difficult enough if technology continued to change at its current rate and we had to maintain or exceed its pace. It would be difficult enough if laws required better environmental stewardship from our designs. It would be difficult enough if the mission requirements for the Navy from Combatant Commanders continued to grow across the spectrum from peacetime, deterrence, and power projection to hostilities, and the Navy had to do its best to fulfill them all. It would be difficult enough with the Budget Control Act, flat investment accounts, and Continuing Resolutions for over a decade. It would be difficult enough to consider that vessels tend to stay in service for 20 years and more and that the requirements and use of surface vessels will change in that time frame. However, the U.S. Navy must address all these with its existing fleet of fewer than 300 ships and the fleet we are investing in today. According to the Fiscal Year 2021 shipbuilding plan, the Navy will add between nine and 20 ships per year to the battle force count (Office of the Chief of Naval Operations, 2020).

Designing and delivering a warship is a complex undertaking. It is appropriate to think of a warship as a system of systems since it manifests as the integration of hull, mechanical, electrical, communications, combat, life support, habitability, navigation, and other systems; each managerially or operationally independent but functionally codependent (Walden et al., 2015). Each of these systems interfaces with the others and is tightly coupled in the design solution. Many combat and communications systems are complex enough to be independent acquisition programs within Joint Capabilities Integration and Development System (JCIDS), Defense Acquisition System (DAS), and Planning, Programming, Budgeting and Execution (PPBE). Ship classes often warrant a bespoke design with efforts exceeding one million hours. Nevertheless, even the ship classes that are not new or unique and borrow many characteristics from an existing ship class take just as long and require as many resources because of the complicated interdependencies of the parts of a ship. The third flight of the Arleigh Burke Class destroyer, the new Constellation Class frigate, and large deck amphibious ships present recent examples of this phenomenon (Dodaro, 2021).

Despite these myriad challenges, the Navy and its acquisition workforce continue the work to deliver necessary platforms and capabilities to the fleet to conduct its enduring roles of sea control, power projection, deterrence, maritime security, and sealift in support of the rules-based international order. In 2017, the Navy conducted a Capabilities-Based Assessment of its Future Surface Combatant Force, including large surface combatants, small surface combatants, and uncrewed vessels. This analysis resulted in an approved Initial Capabilities Document (ICD) in 2018 for the combatant forces. In recognition of the current and future uncertainty germane to investments of large capital ships, the Navy designated flexibility as a top priority for the future fleet. That same year, the Navy conducted a Requirements Evaluation Team (RET) to allocate appropriate requirements from the ICD to the large surface combatant, now known as DDG(X). The Chief of Naval Operations (CNO) approved the initial parameters from that study's results, asking the community to continue challenging the requirements and better understand the cost-capability trades of the design space. He also requested completion in time to award a detail design contract within five years, by 2023 (Office of the Chief of Naval Operations, 2018).

Under the circumstances, those charged with continuing the requirements and design efforts chose to use set-based methods to accomplish their task. They anticipated a need to utilize this concurrent engineering approach to manage the complexity and knowledge creation of the undertaking efficiently. They recognized they needed a different process with different toolsets to bring together a diverse national team of talent from government and industry. They knew status quo ship design methods would not adequately analyze and value architectural decisions and features that intentionally incorporated adaptability and robustness in balance with other requirements efficiently and affordably.

Their set-based process is an extendable case study with transferrable knowledge points to inform similar activities early in a ship's life cycle. Reducing the time while increasing the rigor of these early stages can play an essential part in delivering necessary capabilities to warfighters at the speed of relevance instead of ship acquisition.

Set-Based Design

The first known introduction of set-based design came from Ward's doctoral dissertation involving the design of a notional power train using catalog parts (Ward, 1989). Since then, the concept of SBD, as an alternate to point-based design (PBD), proliferated in research and practice (Toche et al., 2020). When researchers studied Toyota, they found success that seemed paradoxical: delaying decisions made better cars faster than the competition (Ward et al., 1995). They concluded that Toyota's design and development system contributed to the company's success in important ways distinct from its production system (Sobek II et al., 1999). Those investigators coined the term set-based concurrent engineering, which many people now refer to as SBD.

These principles first transferred to the naval engineering domain with Singer's dissertation (Singer, 2003). Singer introduced the SBD method to the Navy at a Society of Naval Architects and Marine Engineers (SNAME) Ship Design Committee meeting in June 2007 (Singer et al., 2017). This introduction led to a policy memorandum from the Commander of Naval Sea Systems Command outlining high-level goals to establish relevant toolsets and capabilities to conduct SBD for early phases of ship design (Naval Sea Systems Command, 2008). This policy inspired a summary article introducing SBD to the naval engineering community (Singer et al., 2009). These actions sparked several follow-on academic investigations. Frye applied the principles to a submarine design (Frye, 2010). Gray expanded the domain by testing the use of fuzzy logic systems to introduce uncertainty in the design space (Gray, 2011). Hannapel developed a new multi-disciplinary optimization algorithm inspired by SBD principles (Hannapel, 2012). McKenny extended the decision support framework for managing large-scale teams (McKenney, 2013). The principle also inspired practical applications in naval vessels' early-stage design and requirements generation. The Ship-to-Shore Connector program provides the first example of SBD in the U.S. Navy (Mebane et al., 2011). The Amphibious Combat Vehicle for the U.S. Marine Corps (Burrow et al., 2014) and Small Surface Combatant Task Force (Garner et al., 2015), which led to the Constitution-class frigate, followed soon after. This knowledge, and more, created a Technical and Research Bulletin to help guide naval engineers in the practice of SBD (Singer et al., 2017).

In essence, SBD is a design method that uses sets of alternatives to reason about the design space instead of iterating on point solutions. Reasoning using sets allows the designer to account for options, variations, ranges, uncertainty, and other aspects that do not exist in point solutions. The sets exist at every level of abstraction in the design structure at which a designer must consider options, variation, ranges, or uncertainty. Reasoning using a set allows the designer to consider elements of the set that are infeasible and remove those portions from further consideration, avoiding unnecessary analyses. Subsequently, they can consider dominant solutions. Domain boundaries do not limit either consideration because of the intersections inherent in the sets. In other words, if appropriate, one domain may remove a portion of another domain's trade space if the intersection of the two domains dictates that outcome. Similarly, dominance is a system issue and must consider impacts on intersecting sets for conceptual robustness; dominance within a domain is neither necessary nor sufficient for selection in the global design space. The SBD method converges to the final solution by systemically removing inferior alternatives from further consideration.

At its core, SBD reduces design risk by removing elements from the design space vice selecting them. In SBD, the design team eliminates portions of the design evaluated as infeasible or dominated. These decisions withstand scrutiny because infeasibility is highly unlikely to change with time. Therefore, the team can accommodate new information, including requirements changes, in less complicated ways. Further, these types of decisions can be made on partial information; if one domain declares a portion of the design space infeasible, that portion is infeasible for all domains. This aspect means domains can work semi-autonomously to develop and analyze their sets, enabling a dispersed team to progress. SBD minimizes rework and incurs less technical risk in the product by delaying decisions until options are proven feasible. In contrast, PBD selects each element and characteristic at the beginning of the process, when the least amount of design information is known. This method effectively rules out thousands or millions of potentially dominant solutions and with much less justification documented. This method expects rework, iterating around this design point through each domain in succession to reach a converged design. In other words, it expects that one will select the wrong point at the beginning, in contrast to SBD, which endeavors to remove these points at the last responsible moment.

In their breakthrough article, Ward et al. (1995) listed the advantages they saw in the seemingly paradoxical SBD approach at Toyota:

1. Enabling reliable, efficient communication.
2. Allowing for greater parallelism in the process, with more effective, early use of sub-teams.
3. Basing the most critical, early decision on data.
4. Promoting institutional learning.
5. Allowing for a search of globally optimal designs.

Therefore, SBD is most appropriate when a design project has: 1) a large number of design variables, 2) tight coupling among those variables, 3) conflicting requirements, 4) flexibility in those requirements allowing for trades, and 5) required learning for a solution (Singer et al., 2017). These characteristics accurately describe the environment of early-stage naval vessel design activities.

Early-Stage Acquisition and Design of Ships

Ship design and acquisition count as major capability acquisitions and follow the two-pass seven-gate process (Office of the Secretary of the Navy, 2019). Each program is tailored into the system at the appropriate gate and milestone according to its maturity. Tailoring a program into a stage in the middle or end of the DAS does not relieve it of the products necessary at previous stages. Each platform still requires the equivalent of a Capability-Based Analysis (CBA), Analysis of Alternatives (AoA), Capabilities Development Document (CDD), and many other statutory and relevant products. Ship acquisition programs constantly tailor the process to remove low-rate initial production and engineering development models (EDM) at the system level: when appropriate, the programs produce EDMs for subsystems.

The acquisition system provides rigor to the process to deliver the right capabilities to the warfighters, but not in a necessarily timely manner. As of 2020, 44 programs that had achieved Initial Operational Capability (IOC) averaged almost 115 months to reach that milestone, and 35 other programs that had yet to complete IOC had an average planned time of more than 130 months (Dodaro, 2021). To put a fine point on this, from the time the DoD makes a Material Development Decision to delivering the first useable article has traditionally taken almost 10 years, on average. Shipbuilding programs exceed this average, as construction times tend to be considerably long (Dodaro, 2021). For instance, the Navy started the program for the USS *Gerald R. Ford* (CVN 78) in June 2000, awarded the construction contract in September 2008, delivered in May 2017 (Dodaro, 2021), with IOC in December of 2021 (*Navy League 2022*, 2022). Even the Arleigh Burke-class destroyers, with decades of learning on the 68 delivered ships and the current backlog of 18, take at least five years from fabrication start to delivery (Dodaro, 2021). Many factors affect these timelines such that substantial improvement to construction timelines may be limited. The phases of the acquisition life cycle before production decisions and detail design awards provide a better opportunity for decreasing the overall timeline.

The ship design team's phases line up with the acquisition process, albeit tailored due to the complexity of the undertaking and the end product. The Concept Design phase aligns with CBAs, AoAs, and pre-Milestone A activities. Concept Design is sometimes broken down into pre-AOA, AoA, and Pre-Preliminary Design. As the name implies, in this phase, designers are creating concepts used in analyses to perform the CBAs and AoAs and develop a draft CDD. They are sometimes as simple as baseball card-like sets of characterizations. They may be as complex as a balanced ship concept design with a hull form, arranged systems, and performance characteristics validated with physics-based models. After Milestone A, the Preliminary Design (PD) phase follows a system engineering process to allocate requirements to systems and establish a baseline for the System Functional Review (SFR). After the SFR, the Contract Design (CD) phase allocates the functions to systems and creates a technical data package for contract award. This phase culminates in the Preliminary Design Review (PDR) before Milestone B. After Milestone B, the Navy awards a Detail Design and Construction (DD&C) contract to a shipbuilder. Detail Design efforts culminate in the Critical Design Review (CDR) with the shipyard, typically a precursor to starting construction.

The design phases of a ship's acquisition contribute to the cycle time between an MDD and IOC. Selected Acquisition Reports (SAR) and data from 12 non-nuclear surface programs help relate this. SARs from T-AO, LHA 8, LPD 17, FFG 62, LCS, DDG 1000, and DDG 51 were available. Note that the SARs for LPD 17 and DDG 51 contained data for their Flight upgrades, also, and these were considered classes of their own for purposes of the analysis. Additionally, data regarding the Coast Guard's Icebreaker program and knowledge of DDG(X) filled in the data set. The analysis reveals that the average time for concept design activities is 41 months, PD activities are 16 months, and CD activities are 18 months. Thus, on average, we spend almost five years establishing a baseline and then a year-and-a-half producing the ship specifications and project peculiar documents, timelines that rival those of DD&C. Coupled with this, concept design activities average more than $80 million, PD averages approximately $290 million, and CD averages more than $650 million. Certain ship classes could be considered outliers in this data set, even though it is relatively small, specifically LCS and DDG 1000. When treating those classes as outliers, the concept design average increases to $100 million, while the PD average falls to about $120 million, and the CD average drops to about $150 million. Table 1 summarizes these results, rounded to the nearest month or million dollars.

Table 1: Summary of SAR Analysis

	Concept Design Time (months)	Concept Design Cost ($M)	Preliminary Design Time (months)	Preliminary Design Cost ($M)	Contract Design Time (months)	Contract Design Cost ($M)	Sum (months)	Sum ($M)
Class Average	41	84	16	290	18	650	75	1,024
With Removing "Outliers"	46	100	16	119	16	148	78	367
Class Median	45	67	17	72	18	84		

The table presents the data in aggregate without giving the individual source data. This is appropriate since each program has a unique story, and the Navy tailored its acquisition activities accordingly. Therefore, presenting individual data may distract from the larger picture that regardless of the acquisition story, today's design process paradigm requires considerable time and money. Further, some stories that create long design times or higher costs matter, so the table presents both average and median values. The higher averages in PD and CD tend to align to acquisition stories with EDMs and land-based test sites, practices that still hold value for some future ship classes.

When collating the design phases with the DD&C phase, the average ship delivery happens about 13.5 years after an MDD. Therefore, if one assumes two years of operational test and evaluation, it takes more than 15 years to deliver a capability to the fleet once the material need is identified. This is insufficient considering the pace of change in the world coupled with strategic competition.

Ship acquisition activities before Milestone B have other important characteristics in the aggregate. One is that they take a project-by-project approach. When the Navy completes an MDD, a team organizes to start executing the rest of the process. This project-by-project approach limits the ability for learning, especially Enterprise learning. Further, this project-by-project approach tends to generate knowledge specific to that ship class. There is no incentive for a program to investigate anything outside its requirements. This can lead to behavior where new requirements get piled into new ship classes, driving costs higher and scheduling longer since no previous efforts created transferrable knowledge. Further, the initiation of a program is challenging and inconsistent. Some programs stand up immediately after an MDD; some do not stand up until after CBAs and AoAs. This means engineers and designers conduct these early-stage activities with little and sometimes no acquisition inputs. Some new ship programs are assigned to existing program offices already in production, which stretches the bandwidth of those personnel further since, typically, no personnel are added for this tasking. Therefore, a second-order effect is their loss of focus on the ships in production or fleet introduction. Part of this effect derives from the alternative scope, language, and outcomes from the early-stage efforts that are inherently different than those of detail design, construction, delivery, and transfer.

The project-by-project approach creates other second-order effects, also. One is that Enterprise issues like arctic, flexibility, model-based system engineering, digital engineering, and automation are challenging to fund unless tied to a program and its requirements. Another effect is that although the Navy desires to engage our industry partners early, few contract vehicles are appropriately suited and dedicated to accomplishing this. In general, the project-by-project approach does a poor job of managing and level-loading the naval engineering workforce of the nation. The same is true for the toolsets they use.

The process DDG(X) used over the last four years provides a framework that addresses some of these issues with its SBD methodology. It provided frequent and meaningful engagement regarding cost capability trades with the resource sponsor and was adaptive to changes and queries. It created reusable knowledge for use in processes and future design efforts. The design team proved SBD could scale to a system of systems level, making it appropriate to apply to these other early-stage efforts. The Small Surface Combatant Task Force (SSCTF) also employed SBD to help generate the requirements. However, successful SBD cannot be executed project-by-project; it must be continuous and enduring to reap its rewards fully. One such idea to implement these ideas and avoid some of the current pitfalls of early-stage ship acquisition efforts is Collaborative, Enduring, Concepts and Tools (COLLECT).

Collaborative, Enduring Concepts and Tools (Collect) and the Analytic Engine

COLLECT proposes invigorating the early-stage activities of non-nuclear surface ship programs in a framework called the Analytic Engine. It envisions creating more robust connections between the various early-stage activities like Naval Capabilities Integration Process From The Sea (NCIP-FTS), Future Surface Combatant Force (FSCF) Analysis, and others.

The engine also seeks to invigorate the national engineering workforce and bolster concept design work to inform the other analyses in collaboration with our national partners. The national engineering workforce includes vendors, shipyards, industry partners, contract support, warfare centers, the S&T enterprise, academia, and other appropriate performers and stakeholders. It will take lessons learned from the concept design work on DDG(X) and extend them to the surface enterprise. In doing so, COLLECT can continually provide viable concepts to other studies like NCIP And FSCF. These concepts will have known cost-capability trades and be ready for program transitions between phases.

The analytic engine is the collection of all these activities (NCIP, FSCF, COLLECT, and others) acting in concert to create defendable requirements and resourcing decisions. The engine operates continuously; it is enduring. Each execution year, the engine will run analysis cycles and develop knowledge instead of waiting for the next MDD. The studies intend to continuously validate the CBA and resultant ICDs, updating them appropriately based on new information from appropriate sources. The continuous concept design work can also feed continuous AoA studies on an annual cycle in line with PPBE. The continuous concept design work requires continuous development of tools to support that work.

Notably, the proposal centralizes these activities within an organization. This organization is notionally a program office that is staffed with acquisition professionals to establish contracts, execute funding, institute systems engineering rigor with configuration control, and consider sustainment and testing early in these concept phases. Centralizing the early design activities in one organization allows for better institutional learning. It provides a logical proponent for the Enterprise issues like arctic capabilities, automation, and digital engineering. It also develops a workforce trained in the early stages to complement and interact with those better trained for Milestone B and subsequent activities. Transitions from the early-stage program office to the later-stage program offices would be tailored by the programs between Milestone A and Milestone B.

Connecting the Proposal with the Problem

The fundamental problem statement presented here is the time and cost of warship acquisition in an era of Strategic Competition. On average, the cycle time of a ship class from MDD to IOC is more than 15 years, which allows too much time for technology development, obsolescence, and adversary advancement and adaptation. Further, the cost of the platform development averages over $1 billion, and even when removing outliers that affect the average exceeds $360 million in research money to get a program to detail design and construction. Partitioning the timeline to view the pre-Milestone B problem reveals 78 months, with most of that spent pre-Milestone A. This means each program, on average, spends over $55 million per year on pre-Milestone B activities.

The analytic engine and COLLECT attempt to tackle both metrics. First, continuously executing CBAs, AoAs, and concept development naturally decreases the time those take. Ideally, when the engine is at its “Full Operational Capability,” these efforts replace the project-by-project CBAs and AoAs, effectively having outcomes “on the shelf” and validated with appropriate stakeholders. Thus, by continuously conducting these efforts and continuously generating the concept designs that feed them, the timelines for pre-Milestone A can theoretically shrink to zero. But whether the process reaches its theoretical limit or not, the practice will train a workforce prepared to execute those activities more efficiently, especially with the learning gained from continuously executing them. Thus, 12 months is a reasonable estimate for the timeline under these circumstances. These efficiencies carry forward into PD and CD since the knowledge created in a set-based method for the concepts carries forward into those phases. Further, tool and workforce development can organically bolster these phases with ship specification updates and other baseline transition work. Therefore, the PD and CD phases should also shorten because of the analytic engine and COLLECT efforts. A 33% reduction in those phases seems reasonable and cleanly estimates each phase pre-

Milestone B as about 12 months. This could create a scenario in which an idea could be ready for detail design within 36 months, on average, instead of 78, cutting this time more than half. With shipyard involvement in these phases, including establishing digital threads, there are potential schedule savings in detail design, but those effects are much more difficult to predict.

Second, the analytic engine and COLLECT address the cost metric. It is pre-decisional to release actual numbers, but they are less than the average cost the Navy incurs today—per ship class—for these efforts, representing a fiscal return on investment in the long run. This steady funding creates steady work for the ecosystem of naval engineering, though, which is an added return on investment, one that is less easy to quantify.

Further, the efforts address the other stated issues with pre-Milestone A activities. An organization dedicated to these activities allows for institutional learning. That organization can also assume responsibilities for engaging the entire ecosystem of naval engineers, from shipyards and combat system vendors to the science and technology enterprise and academia. Using SBD for the concepts makes them more robust to change and can also make them more flexible to it.

Summary

Set-based design, as executed at a system of systems scale on DDG(X), provides a framework for continuous concept development of naval vessels. The concept of set-based design for an enterprise requires its continuous employment. This paper proposes that construct and offers potential benefits achieved from its implementation. The Navy can also extend the framework beyond concept design work to CBA and AoA work to continuously create reusable knowledge in those activities. Collectively, this construct can reduce the cycle time of the development of our ships, helping to ensure they stay relevant and better accommodate the rapidly changing world in an era of Strategic Competition.

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