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Modularity and Adaptability in Future U.S. Navy Ship Designs

An unpredictably evolving future geopolitical, economic, and naval warfare environment is leading the U.S. Navy to incorporate modularity and adaptability features in its future ship designs. Real options provide an analytical method for establishing which modular and adaptable features (and how much) should be incorporated.

Background

The U.S. Navy is in transition. For roughly 25 years after the end of the Cold War it had not faced a peer or near-peer competitor. Starting in 2001, the U.S military had focused on land conflict involving irregular warfare (Department of Defense, 2007). The result was that from a peak size of 594 ships in 1987, the fleet had dwindled to between 270 and 290 ships in recent years; with force-level goals generally in the low 300s. The current number of ships in the battle force is 280 as of late September 2017 (Naval Vessel Register).

By the late 2013 timeframe, however, a re-emergence of great power competition was apparent (O'Rourke 2017a:2). By 2016, the U.S. Navy had found that "…the global security environment [had] changed significantly, with our potential adversaries developing capabilities that challenge our traditional military strengths and erode our technological advantage" (U.S. Navy, 2016:1).

In response, the U.S. Navy developed a plan to grow to 355 ships. A recent assessment of this plan stated that "the roughly 15% increase in the new 355-ship plan over the previous 308-ship plan can be viewed as a Navy response to, among other things, China's continuing naval modernization effort; resurgent Russian naval activity, particularly in the Mediterranean Sea and the North Atlantic Ocean; and challenges that the Navy has sometimes faced, given the current total number of ships in the Navy, in meeting requests from the various regional U.S. combatant commanders for day-to-day in-region presence of forward-deployed Navy ships" (O'Rourke 2017b:4).

Effective recapitalization of the U.S. Navy in response to the new geopolitical environment depends on designing and building affordable ships that achieve their planned service life. The Congressional Budget Office recently observed that since 1985, "…the average difference between the rate of increase in the Navy's shipbuilding cost index and that in the GDP price index has been about 1.3 percentage points per year" (Labs, 2015). Long-run cost growth in excess of inflation in the general economy increases the economic pressure on ship acquisition programs, reinforcing the need to make optimal choices in terms of force architecture, ship designs, and industrial base configuration.

The high cost of naval ships provides a strong incentive to design them for a long service life. Long life creates a need for periodic technology or mission refresh. For some ship types such as aircraft carriers this is not an issue as they can readily accommodate new systems. Surface combatants, on the other hand, pose a distinct problem in that their mission systems are traditionally tightly integrated into the ship vehicle system. This makes traditional designs difficult to technologically refresh. In the post-World War II era, the inability to economically respond to evolving requirements and technologies has caused dozens of U.S. Navy surface combatants to be decommissioned years before their planned service life. For example, the average service life of the 31-ship Spruance class was 23.6 years; the four nuclear-powered Virginia class cruisers were in service for only 17.7 years (Koenig et al. 2009).

In other cases, time-consuming and costly conversions on surface combatants were needed to keep them operationally viable. Examples include the several-years duration mid-life conversions of the USS *Chicago* (CA 136) and USS *Albany* (CA 123) from heavy cruisers to missile cruisers, necessitated by a drastically changed mission need and shipbuilding industrial base capacity constraints.

Cost and fleet size are not the only drivers, however. Strategic concerns can override. The ability to adapt to ever-changing conditions during peacetime war planning and, especially, during hostilities is a key military capability. Gray (2005) described warfare as "a race between belligerents to correct the consequences of the mistaken beliefs with which they entered combat." The ability to rapidly adapt warships to changing threat environments can mean the difference between victory and defeat.

Of particular interest to the U.S. Navy is preparing for the introduction of high power sensors, electronic warfare systems, and electric weapons such as lasers and electromagnetic rail guns. (Figures 1 and 2) These high power systems, dramatically different from current systems, will be required to counter the technological advances of potential adversaries and the quantities of threat weapons future warships are likely to encounter in battle. The characteristics of these systems are quickly evolving and are likely to change significantly over the anticipated service life of a warship.

Figure 1: USS *Ponce* (ASB(I) 15) conducts an operational demonstration of the Laser Weapon System. (U.S. Navy photo/Released, 141117-N-PO203-072)

Figure 2: Electromagnetic Railgun at terminal range located at Naval Surface Warfare Center Dahlgren Division. (U.S. Navy photo/Released, 170112-N-PO203-142)

Design Strategies for Uncertainty

Figure 3 illustrates a simple matrixed taxonomy of design approaches, against requirements environments.

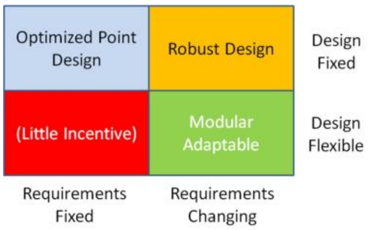

Figure 3: Design strategies

This construct indicates that if the requirements for a ship or system are fixed, then a fixed ship design is appropriate. Using optimization methods, one can arrive at the best design for the requirements. Many naval auxiliaries, such as oilers, have requirements that are essentially static over their service life, as do most merchant ship types (e.g., tankers, bulk carriers, containerships, cruise ships). For such ships, there is little or no perceived value in providing flexibility features. There are instances in which these ships do undergo substantial mid-life alterations. However, those have generally been responses to drastically changing operational requirements that were not envisioned in the early design stage. An example would be the tanker S.S. *Manhattan* which was completely reconfigured as an icebreaking tanker for a voyage through the Northwest passage in 1969, prior to the construction of the Alaska pipeline.

If, during early stage design, a ship's requirements are expected to change significantly during its service life, then the decision framework is different. This is the current environment in naval surface combatant design. The overall design strategy choices can be characterized as:

- Robust design, and
- Modular adaptable design

A robust initial design incorporates the capability to satisfactorily meet evolving requirements, even though they are not fully known at the time of design. The goal is not to optimize the design for a specific set of requirements, but instead to achieve acceptable performance over a broad range of possible sets of requirements.

Modular adaptable designs differ in that they are developed under the premises that the set of requirements possible but unknown at the time of design is so extensive, that a purely robust design would be prohibitively expensive. Instead, the ship is designed to incorporate options such that investments and decisions as to the ship's capability in the future are deferred to the future. These options are expressed in terms of modules and design adaptability. Modular adaptable design therefore incorporates features for changing a ship's capabilities over time to meet the evolving requirements. Successful implementation requires not only the flexibility within the ship, but also the ability to monitor the changing requirements over the ship's service life, and having the modernization processes to translate those changing requirements into evolutionary changes to the ship.

Historically, naval warships have been designed primarily to a fixed set of requirements. The goal of design has been to minimize the cost, either acquisition or total ownership, while meeting the specified requirements. During the ship design process, the potential for future growth has been accommodated principally through the provision of service life allowances for distributed systems, weight and stability. In each design, the amount of service life allowance provided was typically based on design criteria and design practices based on historical growth.

Area and volume have not often included service life allowances. Prior to recent topside designs with reduced radar signatures, extra area and volume could be added later in a ship's life through installation of an additional deckhouse (Gale 1975). The weight and KG service life allowance provided the means for adding the additional deckhouse.

Figure 3 suggests that the historic practice is a combination of the top two quadrants characteristic of a fixed design: optimized point design and robust design. For future surface combatants, a different design strategy is needed to ensure their militarily relevance over their design service life, to prevent wasteful early retirement. In an era of changing requirements, a design strategy based on a combination of robust design and modular adaptable design would result in ships more likely to remain militarily relevant over their design service life.

Designing in modular and adaptable features in response to evolving and unpredictable national security needs, can enable navies to avoid the two unattractive alternatives of (1) early retirement or (2) extremely costly modernization. There is a problem, however: those design features must be paid for. Bertram (2005) sorted the costs into four categories:

1. Higher initial design effort

2. Reduced design freedom (possibly retarding technological progress)

3. Usually higher weight

4. Usually higher space requirement

So, as with so many other issues in ship design, there is a trade space. The problem is to determine how much of what type of modularity and adaptability features to incorporate into a surface combatant design to enable the warship to remain operationally relevant over its design service life.

Modularity and Adaptability Technologies

The modularity and adaptability features used or considered by the U.S. Navy include:

- Service Life Allowances
- Planned Access Routes
- Mission Packages
- Standard Interfaces
- Mission Bays
- Weapon Modules
- Aperture Stations
- Off-Board Vehicles
- Flexible Infrastructure
- Modular Hull Ships

Service Life Allowance

Service life allowance (SLA) is the traditional method of providing adaptability to warship design. Typically, SLA was applied to the capacity of a distributed system, weight, and KG. For the electrical system, spare breakers and extra room in wire ways have also provided the means to add additional capability during a ship's service life.

The traditional approach to SLA may no longer be sufficient to enable the in-service introduction of future electric weapons and sensors. Planning will be required to anticipate where in the ship these high power systems would be located. Not only must the electrical generation capacity be sufficient, but the elements of power distribution and power conversion must either be sufficient or upgradeable. Similarly, much of this electrical power will be converted to thermal loads that typically will be removed from the ship via chill water or fresh water cooling. The design of these cooling systems must also anticipate the future, larger loads.

The ability of integrated power systems (IPS) to redirect propulsion power to other high power electrical loads is attractive in mitigating the risk of insufficient power generation capacity. With IPS, the ship's crew can dynamically allocate power to propulsion, sensors, and weapons in response to the tactical situation.

Planned Access Routes

While SLA is important to ensuring new systems can be incorporated into a warship, access routes within a ship are necessary to allow installation or replacement of equipment without extensive removal and reinstallation of interfering equipment. Access routes include features such as passageways, doors, and hatches sufficiently large enough for equipment to pass through, bolted equipment removal patches (BERPs) and welded equipment removal patches (WERPS). If these planned access routes are incorporated into warship designs early on, sufficient space can be allocated to ensure that arrangements are feasible.

Mission Packages

Modularity is a central feature of the U.S. Navy's littoral combat ships (LCS). The U.S. Navy operates two variants of the LCS: a steel mono-hull (figure 4) and an aluminum trimaran (figure 5). The LCS is a high speed, agile, focused mission ship where mission packages tailor the ships to one of three primary missions:

- Anti-submarine Warfare
- Mine Warfare
- Surface warfare (SUW) (primarily against small boats)

An LCS without a mission package is a sea frame. For LCS, mission packages are composed of mission modules, aircraft, and crew detachments to support the mission modules and aircraft. Mission modules in turn are composed of mission systems and support equipment. The mission systems are weapons, sensors, and vehicles. The support equipment consists of support containers, communications systems, and a computing environment. The support containers house much of the mission module equipment and are based on standard ISO containers. Mission packages were designed for rapid installation and removal to enable reconfiguration of the ships to different focused missions. Furthermore, the mission modules adhere to open architecture principles intended to support responsive and economically viable technology upgrades in the future.

Although the U.S. Navy currently does not anticipate changing the focused mission of any particular LCS very often, the option to do so provides significant flexibility in meeting operational needs or rebalancing the force structure.

Figure 4: The future USS *Detroit* (LCS 7) conducts acceptance trials. (U.S. Navy Photo courtesy of Lockheed Martin-Michael Rote/Released, 160714-N-DM751-001)

Figure 5: The littoral combat ship *Independence* (LCS 2) underway during builder's trials. (Photo courtesy Dennis Griggs General Dynamics/Released, 090712-N-0000G-006)

Standard Interfaces

Standard interfaces for distributed systems and networks are key enablers of affordable modernization. These standard interfaces are typically detailed in military standards, industry standards (such as those produced by IEEE), and in interface control documents. Since standards evolve, and new standards displace old ones, active management of the standard interfaces is required over a ship's service life.

Mission Bays

Each of the two LCS variants includes a mission bay to house elements of mission packages. The ISO support containers are secured to the deck of the mission bay and are not intended to be used operationally in a container stack (They may be transported by container ship). Interface standards have been developed to provide distributed system support to these containers. The technology for a mission bay is well established and the specifications are captured in the LCS ship specifications.

Generalizing the concept of a mission bay in design guidance has not yet been done. Examples of the issues that this would involve include:

- How large should the mission bay be?
- What is the relative value of different sized mission bays?
- What type of distributed services should be made available to mission modules?
- How should the ship's distributed systems be sized to account for the mission modules?
- How to define the interfaces between the mission module containers and the ship, as a generalized interface not unique to a given ship class? (The interfaces developed for LCS are a good starting point.)

Weapons Modules

Weapons modules were initially developed under the SEAMOD program in the early 1970's and were further matured during the Ship Systems Engineering Standards (SSES) program in the 1980's. SSES created standards for a family of four weapons modules: "AAA", "AA", "A", and "B". Within the U.S. Navy, the 32 cell ("A" Module) and 64 cell ("B" Module) Vertical Launching System (VLS) installed on the DDG 51 class are the best known examples of weapon modules (Figure 6). While VLS is the only U.S. application of the SSES module definitions, Blohm + Voss incorporated the SSES standards for weapons modules into their MEKO small warship product lines. The use of weapons modules enabled Blohm + Voss (now TKMS) to create customized warship designs for domestic and foreign military sales using standard components. Over sixty MEKO vessels in over 15 configurations have been produced.

Figure 6: USS *Barry* (DDG 52) launches a vertical launch anti-submarine rocket missile from its aft launchers (U.S. Navy photo/ Released, 160918-N-UF697-151)

Aperture Stations

The topside arrangements of Radio Frequency (RF) transmit and receive antennas is a challenging task. Ensuring electromagnetic compatibility (EMC) while minimizing electromagnetic interference (EMI) and antenna blockages is difficult even with a fixed set of known RF equipment. Over the service life of a ship however, RF equipment may require replacement or upgrading to remain interoperable with the fleet. Currently, replacement and modification of RF equipment and their associated antennas are not extensively considered or accounted for in shipboard topside design. Upgrading arrays and antennas can be expensive. In particular, phased array radars have traditionally been tightly integrated into the ship superstructure design. When these radars become obsolete, the cost of modernization may drive a decision to decommission the ship prior to its design service life rather than invest in updating the radar. Aperture stations apply modularity concepts to RF antennas and their shipboard integration. The methods to implement aperture stations are not fully developed or institutionalized. The Advanced Enclosed Mast / Sensor (AEM/S) demonstrated on U.S.S. Arthur W. Radford (DD 968) and incorporated into the U.S.S. San Antonio (LPD 17) design (figure 7) uses a frequency selective surface radome to reduce radar cross-section and help with electromagnetic compatibility (EMC) and electromagnetic interference (EMI). (Compneschi and Wilson 2001) Although facilitating upgrading and modernization of antennas was an objective of AEM/S, this capability has not yet been demonstrated. AEM/S technology has also been incorporated in the DDG 1000 (Figure 8).

Figure 7: USS *San Antonio* (LPD 17) – note advanced enclosed masts – transits through the Suez Canal. U.S. Navy photo/Released, 080923-N-1082Z-038)

Figure 8: USS *Zumwalt* (DDG 1000) (U.S. Navy photo/Released, 161025-N-UK306-017)

Off-Board Vehicles

Surface combatants have integrated small boats since the age of sail, and aircraft since the pre-World War II era. In modern times, and especially since helicopter decks have been sized to support the H-60 family of airframes, it has been relatively straightforward for surface combatants to host a variety of rotary aircraft. Likewise, the transition from motor whaleboats to Rigid-Hull Inflatable Boats (RHIB) was largely uneventful. (Figure 9) More recently, the U.S. Navy has started to operate with unmanned vehicles (Figures 10 and 11). Standardized methods to launch and recover these vehicles, replenish them, or control them have not been established and will likely evolve in the coming years.

Figure 9: A rigid-hull inflatable boat is hoisted onto the littoral combat ship USS *Coronado* (LCS 4) (U.S. Navy photo/ Released, 170219-N-WV703-239)

Figure 10: Sailors and civilian personnel remotely pilot an unmanned surface vehicle (USV) from ashore several miles away as the USV deploys an AQS-24A sonar (U.S. Navy photo/Released, 160417-N-QG671-003)

Figure 11: A MQ-8B Firescout unmanned aerial vehicle takes off from the flight deck of the littoral combat ship USS *Coronado* (LCS 4). (U.S. Navy photo/ Released, 170822-N-GR361-011)

Flexible Infrastructure

Flexible Infrastructure (FI) consists of several product families which enable rapid reconfiguration of spaces within a ship inexpensively, and without welding. Some elements of FI are currently on aircraft carriers, amphibious warfare ships and command ships. Elements of FI are also being considered for future destroyer, LCS, and amphibious warfare ship construction. FI technology consists of the following:

- Open structure
- Open power
- Open HVAC
- Open data cabling
- Open lighting
- Open outfitting

Open Structure is an enabler for the remaining FI technology. It consists of a foundation track bolted to the deck and fittings/adapters and associated fasteners to attach equipment and other components to the foundation track. The foundation track is based on a modified ISO 7166 slot and hole configuration commonly found on aircraft. This foundation track is a modified version of the "Smart Track" system previously used on U.S.S. *Blue Ridge* (LCC-19). Modifications were made to reduce the cost and labor needed to install the foundation track onboard ship. The FI Open Structure components have successfully completed MIL-S-901 shock tests.

The FI Open Power is based either on a legacy connectorized power panel or on an Integrated Power Management Center (IPMC) described in MIL-PRF-32272A. The remaining FI technologies (Open HVAC, data cabling, and lighting) are based on commercial products. In designing a space using FI technologies, a particular challenge is to determine how much capacity distributed systems should allocate to these spaces. How much current should the feeder cable to an IPMC be rated for? How many IPMCs should be installed in a space?

Modular Hull Ships

Modular hull ship technology provides options for inserting different parallel midbodies. These options can be designed to be exercised only in new construction, or could additionally be designed to be exploited during a major modernization. Modular Hull Ship technology facilitates different acquisition strategies including:

(a) Using a common bow and stern for several classes of ships. An example could be common bows and sterns for a hospital ship, a tender, and a command ship. The application specific systems and spaces would be in the parallel midbody. By using the common bow and stern, design and production efficiencies can be realized by effectively procuring a larger class size.

(b) Using a common bow and stern for different flights of one type of a ship. Concentrate mission systems and other systems that are expected to experience the maximum change over the design life of the class of ships into the parallel midbody. This way the nonrecurring cost of keeping the ships relevant is minimized while keeping the learning curve benefits in preserving the same bow and stern.

(c) Constructing and testing a new parallel midbody for an in-service ship prior to a major modernization availability. Minimize the amount of time the ship is in the shipyard and not available for operational tasking.

While the U.S. Navy has inserted parallel midbodies into ships in all stages of design, construction, and operation, this practice was not usually considered in the initial design of the ship. Examples include the conversion of *Skipjack* (SSN 585) class attack submarines into the *George Washington* (SSBN 598) class of ballistic missile submarines, the modification of the *Jimmy Carter* (SSN 23) (figure 12), and the jumboized *Cimarron* (AO177) class of fleet oilers. In these cases the option to insert the parallel midbody was an option exercised "on" these ships rather than an option that was designed "in" at the time the ship was conceived. Unfortunately, it is not known if time or resources could have been saved had the option to insert parallel midbody been designed-in during the initial ship design. The technology or knowledge needed to design a modular hull ship is well understood and well within the capability of industry to execute. As an extension to the Modular Hull Ship concept, the Dutch Schelde shipyard has developed the Ship Integrated Geometrical Modularity Approach (SIGMA) concept based on standard hull sections. SIGMA allows Schelde to rapidly develop a low risk detail design for a wide range of foreign military sales customers. Ships of three different lengths (91, 98, and 105 meters) with the same beam (13 meters) have been delivered to two customers.

Figure 12: The *Seawolf*-class fast-attack submarine USS *Jimmy Carter* (SSN 23). (U.S. Navy photo/Released, 170414-N-TC277-267)

Determining How Much of What Type of Modularity: Real Options

An option is a contract giving its owner the right, but not the obligation, to buy (call) or sell (put) a security or other financial asset (the underlying asset) at a specified price (the strike price) during a set time horizon or on a specific date (exercise date).

Consider a stock whose current price is $40 per share. A call option is purchased for $3 with a strike price of $45, expiring in two months. Two months later, the stock is worth $55. The option is exercised, the stock is purchased for $45, sold for $55, and the profit is $7 less the transaction cost of purchasing the option at the outset. On the other hand, if the stock was worth, say, $40 (unchanged) at the end of the two month life of the $45 call option, the option expires worthless. The purchaser of the option is out the $3 cost of the option plus the transaction cost of the purchase. If the value of the stock were to be fixed permanently at $40, then there would be no option contracts written as they would be pointless (and worthless). Option value depends on future uncertainty.

Although this example was purely financial, the analogy to ship and force structure design is clear. The idea of real options analysis in naval force structure formulation and naval ship design is based on future requirements uncertainty, and recognition that the opportunity to make certain kinds of future decisions on ship design characteristics has value which changes over time, that value must be paid for, and it expires within some future time horizon. Conventional business case analysis methods do not take account of this embedded option-type value. Decision makers implicitly understand that such value exists even if they cannot describe it quantitatively. So decisions are made based on intuition and judgment.

In real options analysis terms, the initial design of a ship includes the purchase of options in the design (such as modularity features). The configuration of the ship over time reflects the cumulative effect of options in the design that have been exercised, as well as options on the design; i.e. modifications for which features have not been explicitly provided (Koenig 2009, Page 2011). The modernization process defines the work necessary to identify and evaluate the changing strategic and economic environment and decide how and when to exercise modularity and flexibility options to modify ship configurations. The payoff of the option is represented by the evaluation of the configuration over time in terms of unacceptable, acceptable, and superior operational performance. Unacceptable operational performance is considered a capability gap.

As detailed by Mun (2006), a standard real options analysis presumes the following requirements hold:

a) A financial model must exist

b) Uncertainties must exist

c) Uncertainties must affect decisions when leadership is actively managing the project and these uncertainties must affect the results of the financial model

d) Management must have strategic flexibility or options to make mid-course corrections when actively managing the projects

e) Management must be smart enough and credible enough to execute the options when it becomes optimal to do so

For the Navy, the financial model (a) needs to account for affordability. Affordability is not exclusively a matter of cost; a reduction in cost does not necessarily cause an increase in affordability. Affordability is the willingness to spend budget authority on a system. How much the government is willing to spend to modernize and upgrade a ship depends on a complex interaction between many factors including the nature and immediacy of the geopolitical threat, prospective employment at defense contractor production facilities versus other local economic opportunities, the prior record of reliability in program cost estimates, a number of other technical and managerial factors, and finally the fiscal environment.

Affordability considerations place a constraint on requirement (d). Management has limited flexibility, and the degree of flexibility in a given year is uncertain. Hence, while a capability gap may present itself to the modernization process, the gap may not be able to be effectively filled because the fiscal environment (limited budget authority) may place the upgrade priority below the cut-line (hence not affordable). In another fiscal environment, the funds would be available to fill the same gap (hence affordable).

This implies that the lowest total ownership cost (independent of affordability) may not be the best answer ... the ability to rapidly adapt when funds are available may have greater value. The significance of a capability gap also depends on the defense environment; a capability gap in peacetime is less pressing than the same gap during a major conflict.

Real Options Analysis of alternate ship designs

Figure 13 illustrates one possible way of analyzing alternate ship designs using real options. This framework explores the interaction of three sets of variables:

- Uncertainty space
- Configuration vector
- Design vector

The uncertainty space includes elements such as a future adversary's capability in a warfare area, future technology breakthroughs, or the conflict environment (preparing for major combat operations, major combat currently ongoing, regional conflict, or peacetime). The uncertainty space evolves stochastically over time and is evaluated at discrete time steps (typically annually). The stochastic nature of the uncertainty space means that multiple different uncertainty space trajectories through time can be created. The configuration vector describes the ship configuration, tactics, force architecture, and the status of R&D projects as a function of time. The modernization process and the initial design of the ship are assumed constant and comprise a design vector. The configuration vector evolves from the initial design as the modernization process reacts to each uncertainty space trajectory. The relationships among the initial design vector, the configuration vector and the uncertainty space are depicted in figure 14. In this figure, the different colors signify different systems that are incorporated into the ship configuration in response to the different uncertainty spaces.

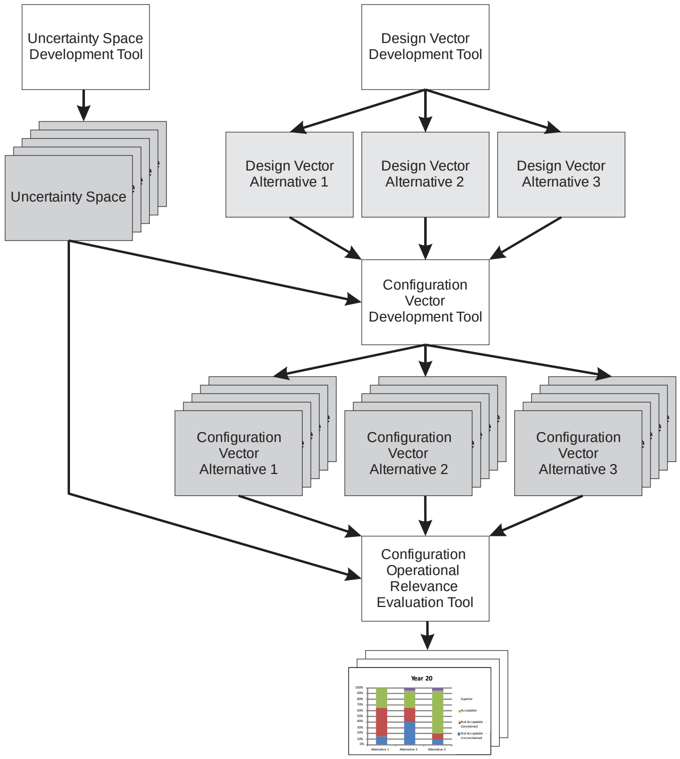

Figure 13: Proposed Modeling Framework

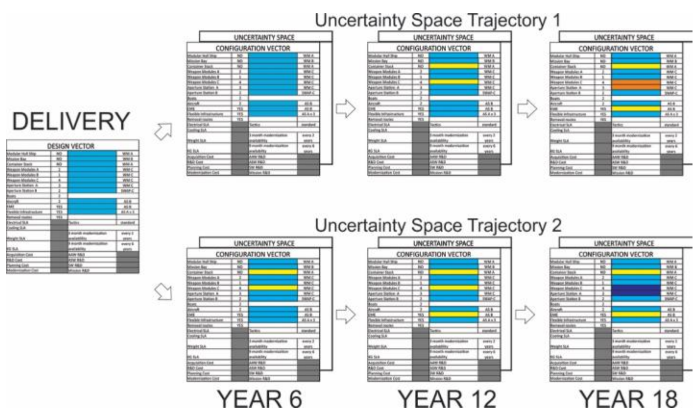

Figure 14: Evolution of a Configuration Vector from a Design Vector in response to an Uncertainty Space

In a typical design study, two or more alternatives for the design vector are under consideration. A design vector development tool is used to create the design vectors. As stated earlier, this design vector consists of the initial ship configuration at delivery, initial tactics to employ the ship and the modernization process. Separately, an uncertainty space development tool creates a set of uncertainty spaces. Each uncertainty space specifies parameters such as a future adversary's capability in a warfare area, future technology breakthroughs, or the conflict environment. The configuration vector development tool applies the modernization process of each design vector to each of the uncertainty spaces to develop a set of evolving configurations called the configuration vector: Each uncertainty space has a corresponding configuration vector for each alternative.

The configuration operational relevance evaluation tool calculates the operational relevance and affordability of the configuration vectors for each design alternative when exposed to each of the uncertainty space trajectories. In any year, operational relevance for a specific configuration vector would normally be the result of warfare modeling of the capabilities represented by the configuration vector when placed in the conflict environment for that year as described in the uncertainty space. This performance could be characterized by one of four levels:

1. Superior: The capability of the configuration is much greater than needed to perform its missions when an opponent (if any) has the

capabilities described in the uncertainty space.

2. Acceptable: The capability of the configuration is sufficient (but not much greater than needed) to perform its missions when an opponent (if any) has the capabilities described in the uncertainty space.

3. Not Acceptable Constrained: The capability of the configuration is not sufficient to perform its missions when an opponent (if any) has the capabilities described in the uncertainty space. The technology exists for acceptable performance, but funding or schedule was insufficient to incorporate the technology into the configuration.

4. Not Acceptable Unconstrained: The capability of the configuration is not sufficient to perform its missions when an opponent (if any) has the capabilities described in the uncertainty space. The technology does not exist for acceptable performance.

Within a design study, many uncertainty spaces would be developed. The number would depend on the ease of creating and evaluating the configuration vectors. Ideally, hundreds or thousands of configuration vectors for each alternative (design vector) would be developed and evaluated. The key is to base decisions on many possible uncertainty space trajectories instead of focusing on only a single possible future. One way of depicting these results is shown in Figure 15. For each time increment, a stacked column chart shows the fraction of configuration vectors that are evaluated in each of the different categories. In this example, alternative 3 has the highest probability of acceptable performance as compared to the other alternatives. Note that in any given year after the first year, the configurations for each alternative need not be identical. Each configuration would evolve based on how the modernization strategy reacts to each of the uncertainty spaces.

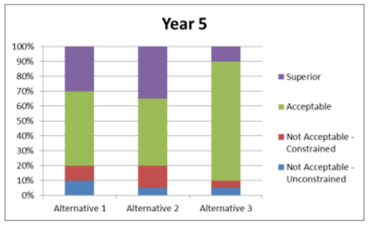

Figure 15: Alternative Comparison of Operational Relevance (Year 5)

Comparing alternatives later in their service lives (Figure 16) can also provide valuable insight. Alternative 1 indicates a design vector that is not sufficiently flexible or adaptable; fiscal constraints often preclude incorporating the technology required for acceptable performance. Alternative 2 reflects a weak science and technology / research and development process that often is not capable of producing the technology needed for acceptable performance. Alternative 3 reflects a design vector which can usually adapt to the evolving uncertainty space in an acceptable manner. If a service life of 20 years or greater is desired, alternatives 1 and 2 are not likely to achieve the desired service life; they will likely be retired early due to unacceptable performance.

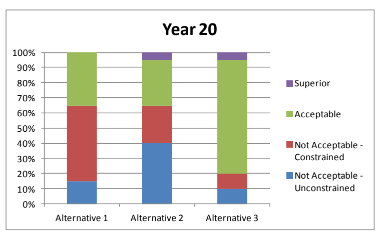

Figure 16: Alternative Comparison of Operational Relevance (Year 20)

The tools depicted in Figure 13 do not exist in a form that can be immediately used to implement the framework. A number of existing tools can be adapted to fulfill some of the required functionality, but additional work is needed to fully implement the framework.

Conclusions

The technology of naval warfare is in flux and naval ship designers and force structure planners face high and rising costs in naval construction. Concurrently, the geopolitical situation is evolving in an increasingly unpredictable manner, with an unsettling potential for renewed great power competition, and for new challenges to the international order that has been in place since the end of the Cold War. These developments add considerable risk to the naval ship design requirements definition process, stimulating a need for ship design features that economically allow for ship design adaptation.

In the past, it has been difficult to economically justify extensive modular and adaptable design features. This has been in large part due to weaknesses in engineering economic analysis methods. Real options can provide an analytical basis for determining how much of what type of flexibility features should be incorporated. In this way, a judicious mix of modularity and adaptability features can be integrated, to enable a ship design to remain affordable within current budget constraints, while equipping it to evolve throughout its planned service life, as the world changes around it.

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Author's bios

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Dr. Philip Koenig is the Director of the NAVSEA Industrial and Economic Analysis Division (SEA 05C1). His current work focuses on projections of cost, capability and capacity in the shipbuilding industrial base, and on the influence of production on design. His previous experience was in the Future Ship and Force Architecture Concepts Division (NAVSEA 05D1), the Office of Naval Research, NSWC Carderock, Chevron Shipping Company, and Vickers Shipbuilding Group Ltd. (England). He teaches courses in shipbuilding at MIT and at the University of British Columbia