Institutionalizing Modular Adaptable Ship Technologies

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The U.S. Navy is tasked within a constrained budget with fulfilling its missions in an environment of evolving threats and a corresponding rapidly evolving mission system technology base. Modular Adaptable Ship (MAS) technologies enable the affordable transformation of a ship over its service life to maintain military relevance.
The views expressed in this paper are those of the author and do not reflect the official policy or position of the Department of the Navy, the Department of Defense, or the U.S. Government.

KEY WORDS: U.S. Navy; design (vessels); economics (design); modernization; systems engineering; warship

INTRODUCTION

The future is uncertain. The U.S. Navy is tasked with fulfilling its missions in an environment of evolving threats and a corresponding rapidly evolving mission system technology base. Affordability of our fleet is also of paramount concern. An alternative to the traditional approach of optimizing a point ship design to meet a specific set of fixed requirements is needed to maintain a sufficiently sized and relevant naval fleet that can be built and supported within the available budget. Historically, naval ship designs have included robustness features in the form of multi-mission capabilities and service life allowances to enable a limited capability to adapt to changing requirements over their service life. For most classes of ships, these robustness features have been adequate as indicated by these ships reaching or exceeding their design service life. Surface combatants on the other hand, have on average not been able to retain sufficient military relevance and on average have been decommissioned well before the end of their design service life. (Koenig 2009)

Modular Adaptable Ship (MAS) technologies offer an opportunity for a ship to affordably transform its mission systems over its service life to maintain military relevance. These benefit has long been recognized and detailed by Jolliff (1974), Simmons (1975), Drewry (1975), Abbott (1977) and Broome (1982). In the 1970's and 1980's, MAS technologies were part of the SEAMOD and SSES Variable Payload Ship (VPS) concepts. Simmons for example states that as of the mid 1970's:

> SEAMOD, then, can be summarized as the use of a variety of modular programs that serve the same general purpose: *to uncouple the development of the payload from the development of the platform.* This uncoupling yields two major benefits, and these are surrounded by a number of satellite benefits. The major benefits are:
>
> 1) By designing the combatant subsystems (payload) in parallel with the platform, rather than in series with it, a new ship can put to sea with a payload that is five to seven years newer than would be the case under current design procedures.
>
> 2) By permitting the relatively rapid changeout of equipment and integration of new items into a new weapon (or any other) system, it is possible to modernize ships without the time and money penalty currently incurred.

While many MAS technologies have been available for many years, and in many cases been installed onboard ships in an ad hoc manner, a design methodology does not currently exist to establish a sound technical basis for determining how much of what type of modularity to install on a ship. Typically, these features are incorporated in a ship design by direction, because leadership recognizes the value of the modularity even though current cost and performance models often show an acquisition cost penalty is incurred to meet a specific set of requirements as compared to an optimized point design.

Furthermore, although many promising technologies have been produced from the Science and Technology community, they have not been adequately developed for use in production across ship classes, nor has the organizational infrastructure been developed to support the technologies. These technologies have not been "institutionalized."

This paper reviews the current status of a number of MAS technologies to include modular hull ships, mission bays, container stacks, weapon modules, aperture stations, off-board vehicles, Electronic Modular Enclosures (EME), and Flexible Infrastructure. These technologies are evaluated against criteria for their readiness for integration into a ship design.

Additionally, this paper will describe and evaluate the current states of processes needed to successfully integrate MAS technologies on a ship. These processes include: cost estimation; valuing modularity and flexibility; acquisition, maintenance and modernization strategies; and optimizing ship configuration. The paper will introduce the possible use of Real Option Theory as part of the solution for measuring value. Additionally, alternate future methods will be explored to bound the range of required ship capabilities. These concepts will be united through an analogy to a classic feedback control system. Specific recommendations will be provided for future work.

Modularity and flexibility is also incorporated within the boundaries of individual Hull, Mechanical, and Electrical (HM&E) systems and Mission Systems. Indeed, Naval Open Architecture does precisely this for Combat Systems.

Furthermore, the Vertical Launching System (VLS) is an outstanding example of a system that enables upgrading of munitions without costly changes to launcher systems. While these applications of modularity are important, this paper will not focus on them. This paper will instead focus on integration across systems.

DESIGN STRATEGIES FOR UNCERTAINTY

As shown in Figure 1, if the requirements for a ship or system are fixed, then it is appropriate to have a ship design that too is fixed. The appropriate design approach would be to use optimization methods to develop the best design to meet the fixed set of requirements. In fact many of the Navy's auxiliaries, such as oilers, have requirements that generally are unchanged over their service life. In the commercial marine sector, many ship types such as cruise ships, ferries, tankers, and ore carriers fall into this category. Because the requirements are fixed, little incentive exists to provide flexibility in their design.

If a ship's requirements are expected to change significantly over its service life, two design strategies have applicability. Robust Design strives to incorporate into the initial design the capability to satisfactorily meet the evolving ships 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 sufficiently acceptable performance over a broad range of possible sets of requirements.

Modular Adaptable Design on the other hand, presumes that the set of requirements possible but unknown at the time of design for a ship is so great that a ship designed using robust design methods alone 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 is deferred to the future. These options are expressed in terms of modules and design adaptability. Modular Adaptable Design therefore incorporates features for morphing a ship's capabilities over time to match the evolving requirements. A successful implementation of Modular Adaptable Design 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. (Abbott 2003)

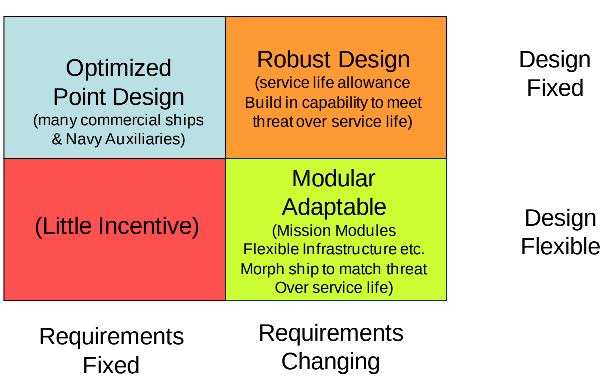


Figure 1: Design Strategies

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. The inclusion of service life allowances for distributed systems, weight and stability has been the predominate accommodation for future growth. The value of the service life allowance used in a particular design was typically based on design criteria and design practices based on historical growth. Of particular note, area and volume have not often included service life allowances (Designs do incorporate a 10% accommodation margin and a number of ships deliver with unassigned space). Prior to recent topside designs with reduced radar signatures, extra area and volume could always be added later in a ship design by incorporating an additional deck house to the superstructure. (Gale 1975) The weight and KG service life allowance provided the means for adding the additional deckhouse.

In examining Figure 1, it is clear that the historic practice is a combination of the top two quadrants characteristic of a fixed design: Optimized point design and robust design. For surface combatants, the historic evidence since World War II has shown that this design strategy has not proven successful on average to ensure our surface combatants achieve their design service life. One study calculated the average actual service for cruisers to be 26.3 years and destroyers to be 25.4 years. These average actual service lives are well short of the design service lives of 30 to 35 years. (Koenig 2009)

A different design strategy is needed to ensure surface combatants remain militarily relevant over their design service life and not decommissioned early. Figure 1 suggests that 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.

Modular adaptable design is not a euphemism for a modular single mission ship such as the Littoral Combat Ship (LCS). LCS is one example of an application of modular adaptable design. Multi-mission ships, such as cruisers and destroyers can (and do) incorporate modular adaptable design. The key to modular adaptable design is incorporating options in the design to be able to defer the exact configuration of the ship to that point in time when the requirements are known, and to have the capability to affordably modify the ship's configuration to meet the requirements when they become known.

The point in time when the options can be exercised are often a function of the modular adaptable technologies. Examples include:

- At the time of a specific mission, such as the weapons load-out of an aircraft.
- Prior to a ship's deployment, such as the weapons load-out of a VLS, the composition of an aircraft carrier's air wing, the installation of a specific mission module on an LCS, or Alteration Installation Team (AIT) installation of new capabilities.

- During a major modernization.
- After start of construction, but before ship delivery or completion of Post-Shakedown Availability (PSA).
- Between different ship acquisitions, such as flight upgrades.

MAS technologies provide options "in" the design. These options "in" the design are contrasted from options "on" the design that exist, but have not been an explicit design feature. Options "on" the design reflect the reality that one can always modify a ship to meet new requirements if one is willing to expend the time and resources to do so.

INSTITUTIONALIZING TECHNOLOGY

To date MAS technology has been incorporated into ship designs in an unstructured manner. In some cases, the MAS technology has been specified as a requirement by the customer, rather than a solution to addressing uncertain requirements. In other cases program managers have incorporated modular adaptable technologies because they intuitively know the value, even when cost and net present value methods based on fixed requirements indicate a more optimized solution would rank higher. Program managers have also incorporated these technologies when the inherent commonality of components enables cost sharing among multiple programs or if the need for a specific future upgrade is clearly known and defendable. The incorporation of Flexible Infrastructure on a number of ship classes is a good example of the latter case.

In general, MAS technologies and associated flexible design methods are not currently institutionalized within the U.S. Navy.

As described by Doerry (2006), a technology is institutionalized when:

- An engineer has sufficient knowledge of the technology to predict its performance and impact on the product design at all stages of design.
- An engineer has sufficient knowledge of the technology to predict the engineering effort required to integrate the technology into the product design in all stages of design
- An engineer has sufficient knowledge of the technology to predict the cost impact of the technology on the production cost of the end product.
- An engineer is able to adequately specify the technology in a product specification to enable the producer to adequately bid a price and produce an acceptable product.
- A customer is satisfied with the performance of the end product, having only characterized the performance requirements with relatively few parameters. In other words, customer expectations are met for product performance in areas that have not been explicitly specified.

For the ship acquisition program manager, institutionalizing a technology reduces the cost, schedule, and performance risk associated with integrating the technology into a ship design. Technology decisions are typically made during the first year following the analysis of alternatives through a series of trade studies that comprise pre-preliminary and early preliminary design. Mature technologies with an acceptable risk best meeting product requirements (including affordability) are generally preferred.

Likewise, new processes are generally not accepted into the ship design process unless deemed mature by the ship design manager and program manager.

Technical Maturity

The following criteria are proposed to evaluate technologies for their maturity and readiness for integration into a ship:

- Technology Readiness Level 7 achieved (TRL 7)
- Industrial base ready to produce the product (Industry)
- Approved specification and/or standard drawings exist (Specifications)
- Approved design guidance and/or handbooks exist (Handbook)
- Government and industry are able to accurately and promptly predict work and costs (Cost)
- Government is able to accurately and promptly evaluate value and cost benefit over the life of the ship including an understanding of the impact of changing requirements (Value)

The Department of Defense defines TRL 7 as:

> "System prototype demonstration in an operational environment Prototype near, or at, planned operational system: Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an operational environment (e.g., in an air-craft, in a vehicle, or in space)" (DOD 2011)

While achieving these criteria by early Preliminary Design is not strictly required, any shortcoming is a program risk that must be weighed against the potential benefit. Established technologies will have achieved these criteria and thus have an incumbent's advantage over a new technology. Designers and program managers generally incorporate incumbent technologies into a baseline design without significant analysis, unless a different technology can prove it is better. A new technology must achieve the criteria listed above to become the incumbent technology.

Process Maturity

The previous section discussed measuring the maturity of technologies associated with equipment and systems installed on a ship. Institutionalizing the processes associated with designing, maintaining, and modernizing ships' MAS technologies is also critical. The following criteria are proposed to evaluate processes for their maturity and readiness for integration into a ship acquisition program:

- Process defined in a handbook or guide (Handbook)
- Workforce trained and ready to implement the process (Training)
- Process tools exist, are ready, and available to the workforce (Tools)
- Valid data required by the process is available to the workforce (Data)

MODULAR ADAPTABLE SHIP TECHNOLOGIES

The following sections present eight modular adaptable technologies and evaluate them for technical maturity. The evaluation will simply assign one of the following to describe the work needed to achieve the criteria:

- **Done**: The criteria has been met
- **Working**: Ongoing efforts are working to meet the criteria, or the criteria has been partially fulfilled
- **Not Started**: No efforts are currently underway to meet the criteria.

The eight technologies described here are not exhaustive, but are representative of the many MAS technologies that have been explored and in some cases implemented. For more technologies, see Abbott (2006), Bertram (2005) and Jolliff (1974).

Modular Hull Ships

Modular hull ship technology provides in the ship design 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 several different acquisition strategies including"

- 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.
- 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 non-recurring cost of keeping the ships relevant is minimized while keeping the learning curve benefits in preserving the same bow and stern.
- 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), 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, we do not know if any 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.

Within the U.S. Navy however, no work has been conducted to develop specifications or handbooks to implement a modular hull ship as part of an initial ship design. Furthermore methods to determine the value and potential cost benefit of modular hull ships have not been formalized. The maturity of Modular Hull Ship technology in the United States is evaluated as:

TRL 7	**DONE**
Industry	**DONE**
Specification	**NOT STARTED**
Handbook	**NOT STARTED**
Cost	**NOT STARTED**
Value	**NOT STARTED**

Mission Bays

Each of the two LCS variants includes a mission bay to house elements of mission packages. 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 compose of mission systems and support equipment. The mission systems are weapons, sensors, and vehicles. The support equipment consists of support containers, communications systems, and computing environment. The support containers house much of the mission module equipment and are based on standard ISO containers (Figure 2). These ISO 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 (Figure 3) and the specifications are captured in the LCS ship specifications as well as the previous X-craft specification (FSF-1 *Sea Fighter*). The remaining issues deal with generalizing the concept in design guidance. Issues such as the following should be addressed:

- How large should the Mission Bay be?
- What is the relative value of different size 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?
- The interfaces between the mission module containers and the ship should be defined as a generalized interface that is not unique to a given ship class. The interfaces developed for LCS are a good starting point.

Figure 2: LCS Outfitted Container for Mission Bay

Figure 3 Mission Bay on FSF-1 Sea Fighter

The NATO Study Group SG-150 recently completed a report (NATO 2011) that advocated the development of NATO standards for various mission module containers to support Humanitarian Assistance/Disaster Relief (HA/DR), counter-piracy, and harbor protection. Follow on work to implement the report's recommendations has been proposed.

Based on the work accomplished to date, the maturity of integrating Mission Bays into U.S. warships is evaluated as:

TRL 7	**DONE**
Industry	**DONE**
Specification	**WORKING**
Handbook	**NOT STARTED**
Cost	**DONE**
Value	**NOT STARTED**

Container Stacks

ISO containers are used throughout the world for intermodal transport of freight. Containerships have specialized systems to securely connect containers to each other and the ship. Below the weather deck, container guides are typically used to position and secure the containers (Figure 4). Above deck, lashing systems, locking systems, or buttress systems are used. (Figure 5 and Figure 6)

Using ISO containers for military purposes other than freight has proven attractive and viable. The LCS for example, extensively uses ISO compliant containers for its mission systems to simplify "shipping, storage, availability of correct handling equipment, and container movement from shore to ship and ship to shore." (PEO LCS 2011). In LCS and many of the other military applications to date, the containers have been secured to a deck and typically do not include the stacking of containers. Access to the interior of the container is via a door at one end of the container. These applications of containers apply to Mission Bays.

If instead, containers are used as part of container stacks on existing container ships, or if container stacks become part of the design of a future combatant, then provisions must be made for personnel access and distributed system routing. Note that container lashing systems such as those shown in Figure 5 can interfere with container access.

This concept is not new. In the 1970's and 1980's the United States developed the ARAPAHO system to provide ASW helicopter capability to container ships within a convoy using a series of modular ISO containers. In 1983 the Royal Navy leased the ARAPAHO system and installed it on a containership which was subsequently commissioned as the Royal Fleet Auxiliary (RFA) *Reliant*. (Rodrick 1988) *FLIGHT International* (1984), reported that although the Royal Navy was able to successfully operate helicopters using ARAPAHO on RFA *Reliant*, several design issues emerged. These issues included:

- The hangar spanned multiple containers and the joints between containers were not watertight.
- ISO containers were not always the optimal shape or size for workshops

- The steel mesh flight deck surface caused accelerated wear of vehicle tires.
- The containership hull form rolls significantly in heavy weather

RFA *Reliant* was subsequently decommissioned in 1986.

Detail engineering drawings or specifications for the ARAPAHO modules have not been preserved within the U.S. Navy.

As described by Littlefield (2012), the Defense Advanced Research Project Agency (DARPA) Tactical Expandable Maritime Platform (TEMP) program is developing similar technology to perform the Humanitarian Assistance / Disaster Relief (HA/DR) mission and potentially other combatant missions from containership vessels of opportunity. TEMP is developing specifications for core and mission modules. The list of core modules that implement basic infrastructure functions is shown in Figure 8. TEMP has also documented approaches for interconnecting the containers with distributed systems as shown in Figure 9.

Figure 4: Cell Guides in a Container Ship
(http://en.wikipedia.org/wiki/File:Containerlader%C3%A4ume_Schiff_retouched.jpg)

Figure 5: Container Lashing Systems (UK P&I Club 2004)

Figure 6: Twist Lock and Lashing Rods
(Picture by Hervé Cozanet from the marine-marchande.net)

Figure 7: RFA Reliant with ARAPAHO (RFA Nostalgia)

Core Module	Remarks	Core Module	Remarks
Generator	Based on two C200 Microturbines per TEU	Chill Stores	
Switchboard, Main	One switchboard per generator	Provisions (dry food)	
Switchboard , Distribution	One per habitability and mission block	Ship Stores/general stowage	Consumables, supplies, etc
Engineering Control	Power Plant & Machinery control, alarm and monitoring	Water makers	Two reverse osmosis making 6K gallons per day
Fuel Tank	5500 gal tank	Potable Water Storage	one day min storage, generation 50gal/man/day. TEU tank of 5800 gallons
Berthing	6 person per FEU (30sqft/man), incl wet space	Armory	optional: self defense / shotguns, small arms
Deck Water Closet	For remote locations	Access	Stairways, Passageways & Platforms
Liquid Waste Processing	Contains Maritime Sanitation Device	Office	OIC/Admin
Black Water Holding	5.5 (VCHT) gal/man/day, storage capacity = 4 day minimum, TEU tank= 5800 gal	Sick Bay	1 medical TEU provided for all crew sizes. Basic care and isolation beds
Gray Water Holding	based on 4 days minimum of 50gal/man/day, TEU= 5800 gal	Laundry	1 washer/dryer per 20 persons; 3 w/d per TEU
Garbage Processing	Plastics, paper, cardboard, glass, etc	Workshop	Parts and basic hand tools
Garbage Holding	Requirement to hold garbage on station in certain situations	Hazmat Storage	Separation of flammables, grease, oils, etc
Galley	One FEU per 150	Life Boat / Life Rafts	Each contains life boat and life raft for 30+
Messing facilities	26 seats per FEU, must seat 1/2 crew	Rec Room	Basic gym equipment and entertainment
Frozen Stores			

Figure 8: TEMP Core Modules

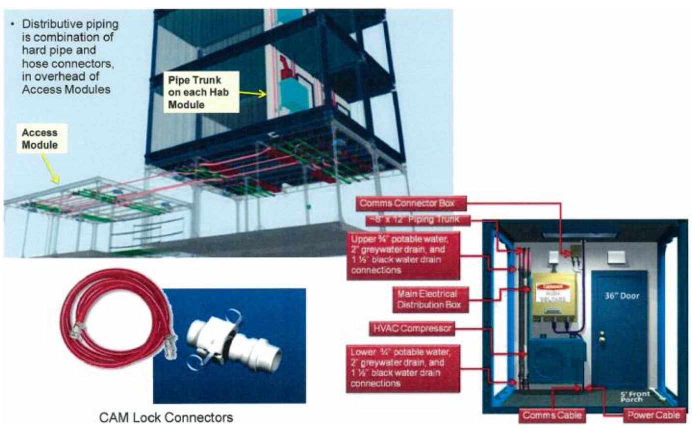


Figure 9: TEMP Distributed Systems Concepts

The Military Sealift Command (MSC) operates two Aviation Logistics Support ships: SS *Wright* (T-AVB 3) and SS *Curtiss* (T-AVB 4) (Figure 10). These ships provide intermediate maintenance facilities for the Marine Corps packaged in containers. While these facilities are primarily designed to operate ashore, these ships are configured to allow maintenance operations to be conducted onboard ship.

Figure 10: SS *Curtiss* (T-AVB 4)

The existing ISO standards for the containers and tie down system are mature for transporting containers onboard a ship. Based on the past success with ARAPAHO and the Aviation Logistics Support ships, the basic technology associated with implementing mission and support services within ISO containers in container stacks is well known. The ongoing work with DARPA's TEMP program is establishing the industry base, specifications, and handbooks for employing containers that are designed to be operational while onboard ship. Little work has been done to date to enable the Government or shipbuilders to properly cost ships or establish good value metrics for incorporating this technology. The maturity of Container Stack technology in the United States is evaluated as:

TRL 7	**DONE**
Industry	**WORKING**
Specification	**WORKING**
Handbook	**WORKING**
Cost	**NOT STARTED**
Value	**NOT STARTED**

Weapon 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. Within the U.S. Navy, the 32 cell ("A" Module) and 64 cell ("B" Module) VLS installed on the DDG 51 class are the best known examples of weapon modules (Figure 11). SSES created standards for a family of four weapons modules as shown in Figure 12. While VLS is the only U.S. application of the SSES module definitions, Blohm + Voss of Germany incorporated the SSES standards for weapons modules into their MEKO small warship product lines. The use of weapons modules enabled Blohm + Voss to rapidly and affordably create customized warship designs for domestic and foreign military sales using standard components. Blohm + Voss sold over sixty MEKO vessels in over 15 configurations.

While generalized interface drawings and standards do not exist for the SSES modules, considerable detail is provided by NAVSEA (1985). The following DDG 51 Contract Drawings and Contract Guidance Drawings could form the basis of generalized interface drawings.

Contract Drawings
5774129 Forward A-Size Weapon Zone
5774130 Aft B-Size Weapon Zone

Contract Guidance Drawings
802-5959340 A-Size Structural Guidance Drawing
802-5959341 A-Size SIR Support Systems Composite Guidance Drawing
802-5959342 A-Size Fluid Systems Guidance Drawing
802-5959343 A-Size Fan Room and Ducting Guidance Drawing
802-5959344 B-Size Structural Guidance Drawing
802-5959345 B-Size SIR Support Systems Composite Guidance Drawing
802-5959346 B-Size Fluid Systems Guidance Drawing
802-5959347 B-Size Fan Room and Ducting Guidance Drawing

Figure 11: Standard Missile Three (SM-3) emerging from a vertical launching system (VLS)

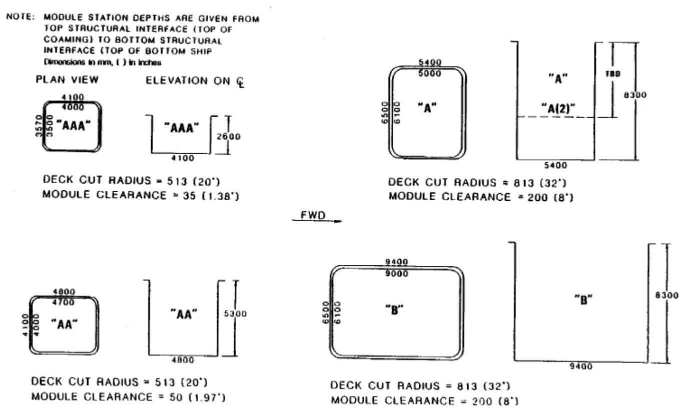


Figure 12: SSES Weapons Modules (Abbott 1994)

Within the U.S. Navy, there has not been a strong demand for weapon modules. VLS and 5 inch guns have provided flexibility and adaptability through their munitions. Except for "repair by replacement" concepts, complete replacement of the VLS or gun has not been necessary. Gun technology in particular has not radically changed over the past twenty years. In fact the SSES standards for weapon modules have not been applied to guns within the U.S. Navy. The LCS provides a gun module that is interchangeable with a missile launcher module. Although these modules use interfaces that are similar to the SSES "AA" weapons module standards, they are unique to the LCS (Figure 13.)

With the ongoing development of railguns and directed energy weapons, it may be desirable now to employ weapon modules for gun systems. These weapons modules could decouple ship development timelines from the advanced weapon system developments. Once an advanced weapon is ready for fleet introduction, it could then be more easily backfit into the in-service ships.

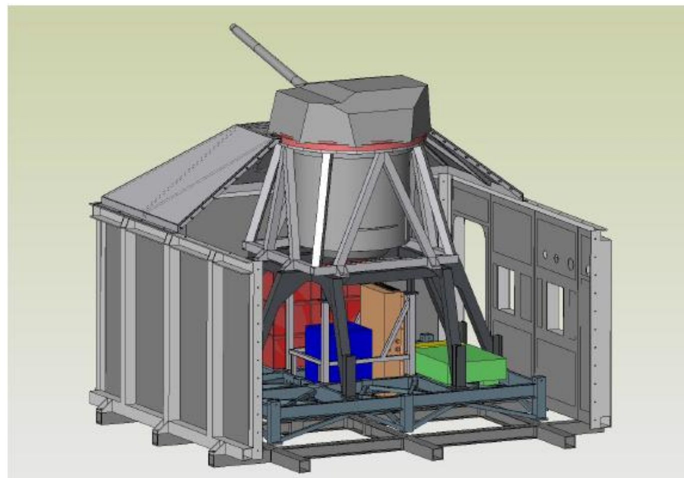


Figure 13: Littoral Combat Ship (LCS) Weapon Station Module

The technology for implementing weapon station modules is well understood and within the capability of industry. Ship specific interface specifications exist, and could be adapted into general purpose interface standards.

The general process for incorporating weapon modules are described in two guides from NAVSEA 05T: "A Guide for the Design of Modular Zones on U.S. Navy Surface Combatants" by Vasilakos et al. (2011) and "Modular Adaptable Ship (IMAS) Total Ship Design Guide for Surface Combatants" by Garver et al. (2011). While these guides provide good information, they should be formalized into a Design Data Sheet or a formal NAVSEA technical document (such as a manual associated with a NAVSEA instruction or a NAVSEA Technical Manual) approved by the NAVSEA Standards Improvement Board (SIB).

The ability to accurately predict the impact of weapon station modules on acquisition or life cycle cost is extremely limited at this time. Likewise, a standard method for evaluating the value of weapon station modules as a function of time has not been established. The maturity of Weapon Modules technology in the United States is evaluated as:

TRL 7	**DONE**
Industry	**DONE**
Specification	**WORKING**
Handbook	**WORKING**
Cost	**NOT STARTED**
Value	**NOT STARTED**

Aperture Stations

The topside arrangements of all the 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, these RF equipment may require replacement or upgrading to remain interoperable with the fleet and militarily relevant. 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 extremely 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 uses a frequency selective surface radome to reduce radar cross-section and help with EMC and EMI. (Compneschi 2001) Although facilitating upgrading and modernization of antennas was an objective of AEM/S, this capability has not been demonstrated. Specifications and handbooks for developing an AEM/S for a new class of ships do not currently exist. Some AEM/S technology did transition to the DDG 1000 program.

The ONR Integrated Topside (INTOP) Innovative Naval Prototype (INP) program is approaching the problem by using integrated, multifunction and multibeam arrays to fulfill multiple functions that currently require dedicated antenna systems. (Figure 14) By significantly reducing the number of antennas, the EMI and EMC challenges are simplified.

As described by Tavik et al. (2010):

> "The InTop program objectives include the following:
>
> • Develop, integrate, and demonstrate new apertures and subsystems that will support RF multifunctionality and that are based on modular, scalable, open architecture, in order to enable greater flexibility to adapt platform capabilities to rapidly changing tactical and strategic environments.
>
> • Demonstrate the integration and coordinated control of many critical shipboard RF functions implemented across a multitude of systems and subsystems, via a common resource allocation manager (RAM), in order to optimize the use of available RF spectrum and hardware.
>
> • Develop, with the Naval Sea Systems Command (NAVSEA), ship design initiatives to incorporate InTop integrated communications/sensor systems to optimize ship size and performance factors.
>
> The goal of the InTop program is to evolve to an integrated Navy capability 10 to 12 years in the future that has the following characteristics:
>
> • Modular, open RF architecture
>
> • Software-defined functionality
>
> • Synchronized RF functions for mission support and EMI mitigation
>
> • Reduced size, weight, and power requirements relative to a federated topside
>
> • Reduced cost (acquisition and total ownership) relative to a federation of systems
>
> • Scalability in order to derive systems of appropriate capability to match each particular platform's requirements
>
> • Reduced life-cycle costs
>
> • More RF functions optimally sited topside
>
> • Rapid adaptability to new threats/requirements through software upgrades
>
> • Integrated antenna/array topside designs that are seamlessly compatible with the associated platform architecture and design

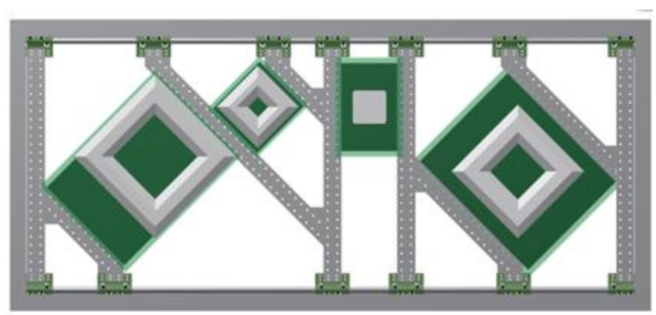


Figure 14: Modular Mechanical Architecture concept for INTOP antenna subsystem (Courtesy ONR)

Considerable work remains to institutionalize Aperture Station technology. Although AEM/S technology is at sea today, it is not clear if the technology has been captured in a manner that it could be successfully employed at reasonable cost on a new ship acquisition. The InTop technology has not yet achieved TRL 7, Generalized specifications, standards, and design guidance do not exist and the ability of the Navy to accurately predict cost or benefit is lacking. The maturity of Aperture Station technology in the United States is evaluated as:

TRL 7	**WORKING**
Industry	**WORKING**
Specification	**NOT STARTED**
Handbook	**NOT STARTED**
Cost	**NOT STARTED**
Value	**NOT STARTED**

Off-Board Vehicles

Surface combatants have successfully integrated small boats and helicopters for many years. 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 wide variety of rotary aircraft. Likewise, the Navy's transition from motor whaleboats to Rigid-Hull Inflatable Boats (RHIB) was not traumatic. More recently however, the U.S. Navy has started to operate with unmanned vehicles as shown in Figure 15 and Figure 16. 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 15: MQ-8B Fire Scout Unmanned Air Vehicle

Figure 16: Unmanned Influence Sweep System (UISS)

Based on the ongoing work to integrate unmanned vehicles into LCS and other ships, this technology is evaluated as:

TRL 7	**WORKING**
Industry	**WORKING**
Specification	**WORKING**
Handbook	**WORKING**
Cost	**WORKING**
Value	**NOT STARTED**

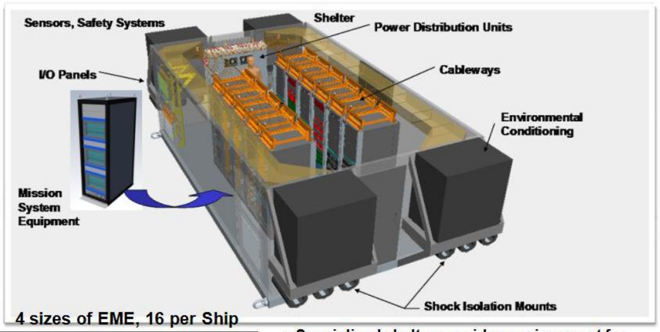
Electronic Modular Enclosures (EME)

As described by McWhite (2010) Electronic Modular Enclosures (EME) are structures designed to enable use of commercial off the shelf (COTS) electronics in a naval environment. The EME isolates the COTS equipment from shock, vibration, EMI and Electromagnetic Pulses (EMP) and provides the physical security, noise isolation, cooling and electrical power of the requisite type and quality needed by the equipment. The EME is designed to enable a straight forward process for replacing existing COTS equipment with newer versions as a means to avoid obsolescence and provide new capability.

The EME concept was developed for the DDG 1000 program. DDG 1000 incorporates a total of 16 EMEs of four different sizes (mini, small, medium, and large). These EMEs are used for housing the ship's Mission System Equipment (MSE) electronics. (Figure 17)

EMEs have been produced for DDG 1000 and all the technologies within the EMEs are at least TRL 7. The existing specifications and design guidance are unique to DDG 1000 and would require modification to generalize for broader applicability to other ship classes. While material costs for procuring EMEs are now known based on return data, the impact of EMEs on ship acquisition cost and life cycle cost is not well understood to enable accurate trade studies in other ship classes. In particular, understanding of the impact of enclosure tare weight on total ship weight and cost is not fully developed. Likewise methods for measuring the value and cost benefit of the EME are not mature. EMEs are therefore evaluated as follows:

TRL 7	**DONE**
Industry	**DONE**
Specification	**WORKING**
Handbook	**WORKING**
Cost	**NOT STARTED**
Value	**NOT STARTED**



	Length	Width	Height
Mini	18 ft	7 ft	7.45 ft
Small	25 ft	11.8 ft	7.45 ft
Medium	30 ft	11.8 ft	7.45 ft
Large	35 ft	11.8 ft	7.45 ft

- Specialized shelter provides environment for Commercial Off The Shelf (COTS) Hardware
- 16 shelters house 236 cabinets
- Shock, Thermal, EMI, Security, & Noise Reduction
- Power Distribution and Control
- Enables Integration of electronics in factory

Figure 17: DDG 1000 Electronic Modular Enclosures

Flexible Infrastructure

Flexible Infrastructure (FI) consists of several product families which enable spaces within a ship to be reconfigured rapidly, inexpensively, and without welding. (Figure 18) FI technology is described by Cheung et al. (2010), DeVries et al. (2008) and some elements of FI are currently on aircraft carriers (Deaton 2010), 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.

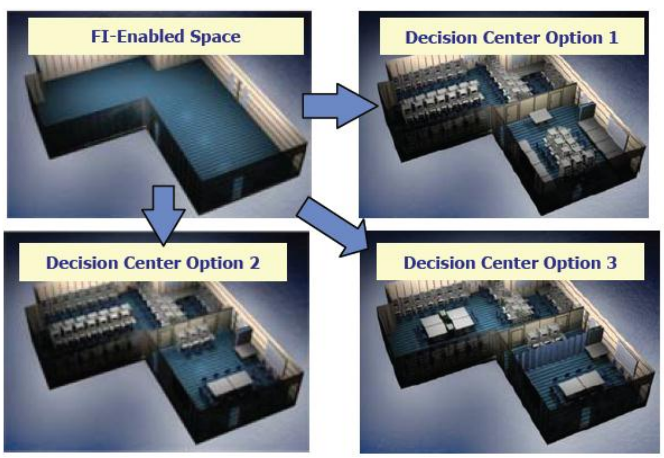


Figure 18: Space Reconfiguration using Flexible Infrastructure

The "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. (Figure 19) The FI Open Structure components have successfully completed MIL-S-901 shock tests. NAVSEA standard drawings for the FI Open Structure elements are currently undergoing the review and approval process.

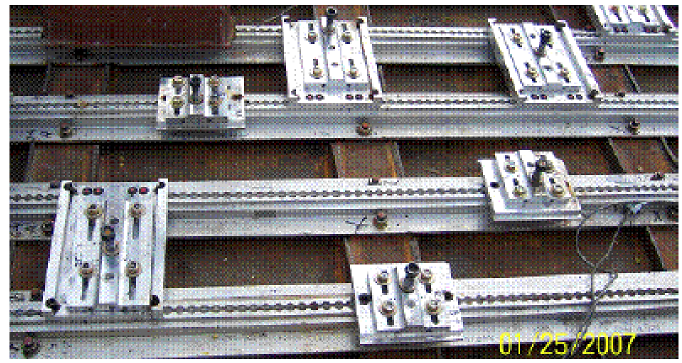


Figure 19: FI Open Structure Foundation Track and Fittings

The FI Open Power is based either on a legacy connectorized power panel (Figure 20) or on an Integrated Power Node Center (IPNC) described in MIL-PRF-32272and by Ykema (2007). (Figure 21)

While the remaining FI technologies (Open HVAC, data cabling, and lighting) are based on COTS products and technically mature, specifications and standards do not yet exist for integration into a naval ship.

In designing a space using FI technologies, one of the challenges is determining how much capacity distributed systems should allocate to these spaces. How many amps should the feeder cable to an IPNC be rated for? How many IPNCs should be installed in a space? Formal guidance approved by appropriate technical warrant holders for developing answers to these and related questions do not currently exist. As a step to developing such guidance, two useful documents (Garver 2011 and Vasilakos 2011) have been created that can guide ship design teams.

Figure 20: Connectorized Legacy Power Panel

Figure 21: FI Open Power with IPNC (Ykema 2007)

FI technologies are therefore evaluated as:

TRL 7	**DONE**
Industry	**DONE**
Specification	**WORKING**
Handbook	**WORKING**
Cost	**WORKING**
Value	**NOT STARTED**

MODULAR ADAPTABLE SHIP PROCESSES

The following sections present four MAS processes and evaluate them for process maturity. The evaluation will simply assign one of the following to describe the work needed to achieve the criteria:

- **Done**: The criteria has been met
- **Working**: Ongoing efforts are working to meet the criteria, or the criteria has been partially fulfilled
- **Not Started**: No efforts are currently underway to meet the criteria.

The four processes described here are those most critical to institutionalizing MAS technologies.

Estimating Cost

Decisions as to whether or not to incorporate a technology into an acquisition program usually are based on evaluations of cost, risk, and benefit. Unfortunately, accurately estimating the cost associated with MAS technologies has been challenging. These challenges are not unique to MAS technologies and apply to many new technologies as described by Bowers (2010). Most cost models are based on correlations of design variables with historical return cost data. These purely correlation-based models are usually only accurate when presented with new designs that are similar to the data used to create the correlations. For shipboard systems, costs are typically correlated with weight and size. These models will estimate that the cost of implementing a technology that results in larger or heavier equipment will rise; even if the technology (like MAS) was developed to reduce cost. Some of the cost reduction mechanisms for MAS technologies during ship construction are detailed by Thompson (1982).

In making cost engineering decisions, correlation of cost data alone is not sufficient. The underlying mechanism for the true cost of the ship must be identified. An activity or process-based cost modeling effort is needed. When an optimization procedure is performed based on a correlation-based model, the optimum solution will be for the model alone, and not necessarily an optimum with respect to reality as represented by the true underlying mechanisms. Within the shipbuilding industry, The Product Oriented Design and Construction (PODAC) Cost Model (Ennis 1997) (Trumbule 1999) is an example of an activity-based cost model (NSRP 1996) that has been implemented to support detail design and construction. These models however, generally require a level of product and production process detail that historically has not been available during the early stages of ship design when the decisions as to whether or not to incorporate MAS technologies are made.

Because of the limited availability of data currently produced in early stage design, Garver (2010) proposes that traditional weight based cost algorithms be augmented with algorithms that are sensitive to process.

To incorporate activity-based cost modeling in concept and preliminary design, the design organization must develop design products not normally produced today. For example, developing a notional build strategy that ties the physical features of a ship concept to design and production activities could provide the a better linkage between the underlying mechanisms for cost and the physical attributes of the ship. Only by modeling these underlying mechanisms can design optimization methods be trusted to produce an optimal solution in reality. This optimal solution reflects costs associated with the initial design of a ship, modernization of that ship, and modified repeat designs of future ships. Unfortunately, methods, tools, and data to support such an early stage design optimization process do not currently exist. Therefore, estimating cost is evaluated as:

Handbook	**NOT STARTED**
Training	**NOT STARTED**
Tools	**NOT STARTED**
Data	**NOT STARTED**

Valuing Modularity and Flexibility

Traditionally, Net Present Value (NPV) has been used as the principal tool in business case analysis. NPV however, is only useful in discriminating among multiple choices if these choices have the same value. Furthermore, traditional NPV techniques rely on a system meeting a pre-specified set of requirements, and cannot accommodate the ability to accommodate uncertainty very well. MAS technologies however, promise to better meet evolving uncertain requirements at less cost as compared to a traditional system optimized for a specific set of requirements. Summers (1997) recognized the value of deferring decisions to the future. However, demonstrating this benefit analytically has been challenging. Gregor (2003) observed:

> Current valuations in naval ship design tend to focus on valuing a point designed product. Although there have been efforts to more completely explore the design space for the optimal solution, the optimal solution is based on a fixed set of requirements and preferences. In addition, optimization infers certainty. There is no way in the current system to value adding flexibility to the design, since under certainty, flexibility has no value. Flexibility instead, has value, in situations with high uncertainty.

Lawson (1977) proposed that the effectiveness of a weapon system can be modeled as an exponentially decaying curve which has unity value at IOC and decays with a characteristic half-life. (Figure 22) Weaknesses of this method include a lack of a physical basis for why effectiveness should follow a decay curve as well as the basis for establishing the half-life. For example, it would seem that the effectiveness of a weapons system would remain constant if an opponent is not developing systems or tactics to counter our systems. In fact a weapon system may gain effectiveness if other systems, such as surveillance systems or command and control systems synergistically improve our own forces ability to employ a given weapon system.

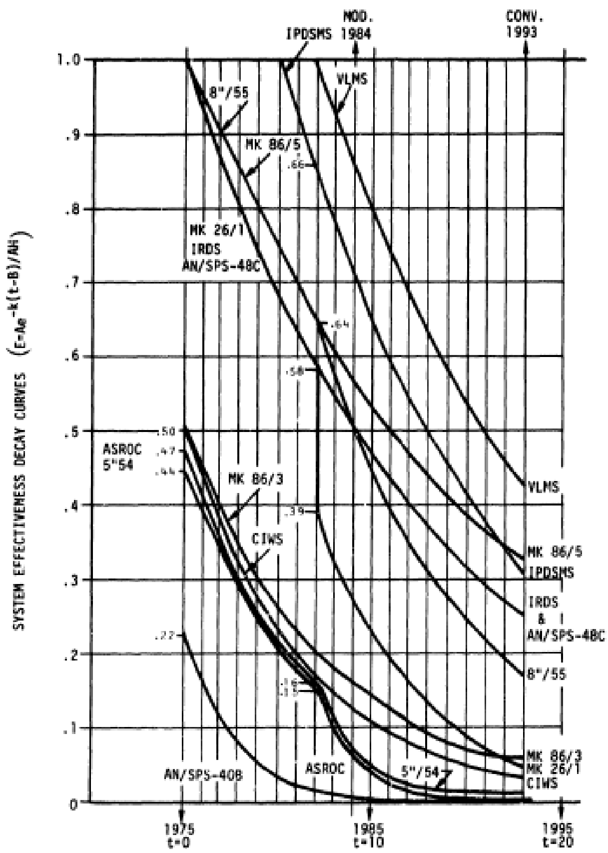


Figure 22: System Effectiveness Decay Curves (Lawson 1977)

More recently, Real Options Theory has been proposed for evaluating the value of MAS technologies. Real Options Theory proposes to apply financial options and analysis techniques to non-financial applications. As shown in Table 1, ship acquisition programs are characteristic of projects that benefit from investment options. MAS technologies provide those options. Real Options theory projects the value of being able to make decisions in the future when better information is available to make a better decision. Gregor (2003), Koenig (2009) and Page (2011) provide good insights in the benefits and limitations of applying real options theory to naval ship acquisitions. While financial options are grounded in accepted theory, more theoretical work is needed to develop analytically rigorous methods to apply real options theory to ship design.

The inability to formally apply Real Options theory however, does not preclude applying "Options Thinking" to develop acquisition arguments to better value flexibility. As described by Gregor (2003):

> For managing technology projects, much of the analysis lies in determining when and how to implement options. This analysis is broken into three phases: discovery, selection, and monitoring. In these ways, real options seek opportunities to build flexibility into designs, evaluate the possibilities, and implement the best ones, without being required to do so.

Table 1: Project Characteristics that lead to Significant Investment Options. (Koenig 2009).

1. The project is a large capital investment and uncertainty is large enough to provide value to flexibility and waiting that can be traded off
2. Contingent investment decisions and/or mid-course changes can be made as expected future information becomes available and uncertainty is resolved
3. Late-stage project costs are high but can be re-evaluated stage-by-stage and do not need to be irrevocably allocated at project start
4. Future investments are large compared with the cost to resolve some uncertainty
5. Technical alternatives exist at various stages of development
6. Project value is affected by strategic interactions and external forces
7. There are long lead times to achieving uncertain cash flows
8. The ability to terminate a project places a cap on down side risk

The application of Real Options Theory to ship design is an ongoing topic of discussion with the ASNE/SNAME joint panel on naval ship design (SD-8). Two workshops have been dedicated to presentations and discussions on the ship design applications of Real Options Theory.

Because of the immaturity in the theory for establishing the value of the options provided by MAS technology, the dearth of ongoing research in this area with respect to ship design, the process for valuing modularity and flexibility is evaluated as:

Handbook	**NOT STARTED**
Training	**NOT STARTED**
Tools	**NOT STARTED**
Data	**NOT STARTED**

Optimizing Acquisition, Maintenance, and Modernization Strategies

Incorporating MAS technologies into a new ship design will in of itself not result in benefits. The supporting acquisition, maintenance and modernization strategies must be optimized to take advantage of the flexibility offered by MAS technology. Figure 23 and Figure 24 for example, show the benefit in military worth of implementing incremental modernization as compared to modernization by system replacement or major modernization.

Figure 25 presents the Design and Modernization Process and Ship Configuration & CONOPS as an analogy to a feedback control system. Over the life of the ship, its requirements are a stochastic function of time that depends on the geo-political climate, threat capabilities, force architecture, and fleet strategy and tactics. At any given time, the ship's configuration and associated Concept of Operations (CONOPS) establish a given level of capability that is compared to the requirement; any deficiency is a capability gap. This capability gap, and its projection into the near future, drives the design and modernization process to produce modifications to the ship's configuration & CONOPS which close the capability gap. Hence the Design and Modernization Process should be developed coherently with the MAS technology incorporated into the ship design. Since the decision as to whether to incorporate MAS technology is typically made in early Preliminary Design, having the capability to develop and model the modernization process during this early stage of design is needed.

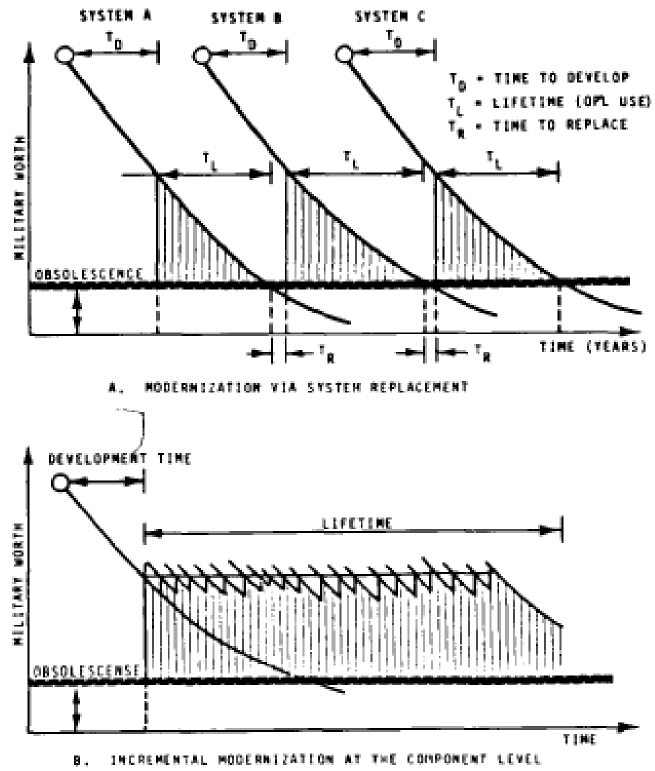


Figure 23: Incremental Modernization vs System Replacement (Drewry 1975)

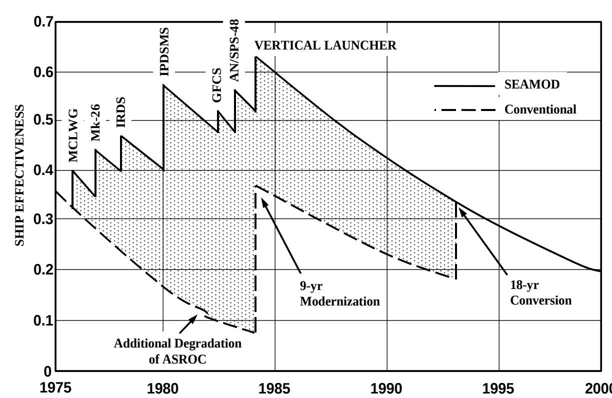


Figure 24: Average Ship Effectiveness for SEAMOD and Conventional Units (Abbott 2006)

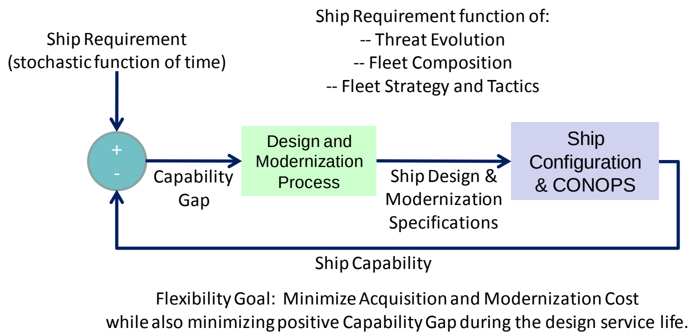


Figure 25: Design and Modernization Process as part of a feedback control loop.

Page (2011) modeled Figure 25 for two different sets of Design and Modernization Processes and Ship Configurations. The first, inflexible, set consists of a ship design without significant MAS technologies and a modernization strategy based on small annual investments and a large mid-life upgrade. The second, flexible, set in contrast features many of the MAS technologies and spreads the total modernization funds and effort evenly across all the years in the ship's service life. Page used a Monte-Carlo simulation to determine the ability of each set to respond to the stochastic capability gap. As shown in Figure 26, the flexible set consistently performed better in meeting the stochastic requirement than the inflexible set.

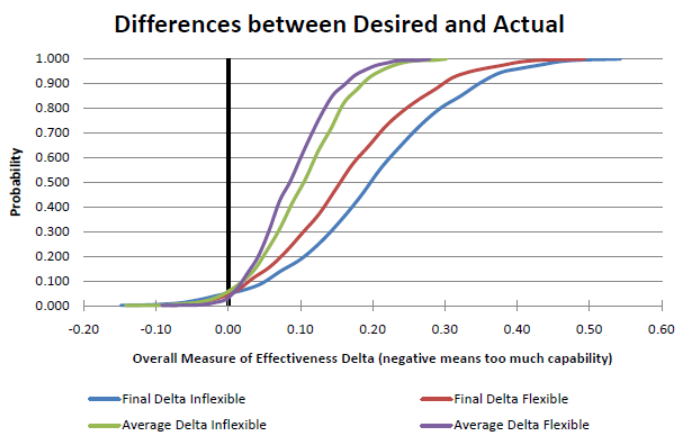


Figure 26: Cumulative Distributions of Capability Gaps (Page 2011)

In developing his model, Page made a number of assumptions that would have to be verified or modified to use in an actual ship design process. As compared to the decay curves proposed by Lawson, this method promises to better model the military value of MAS technology and its associated design and modernization processes in the face of changing and uncertain requirements.

Because modeling design and modernization processes are not currently part of the ship design process, the process maturity is evaluated as:

Handbook	**NOT STARTED**
Training	**NOT STARTED**
Tools	**NOT STARTED**
Data	**NOT STARTED**

Optimizing Ship Configuration

If the design and modernization process are viewed as a control system (Figure 25), then the MAS features incorporated into the design provide the "control authority" for being able to react to the uncertain and changing requirements. Incorporating MAS technology typically requires an investment up front to enable options that can be exercised in the future. The question then becomes: how much of which MAS technologies should optimally be incorporated into a ship design? Investing too much could result in excess flexibility that is likely not to be used over the ship's service life. Likewise, investing too little could result in excessive modernization costs, or the ship retiring before the end of its design service-life. The modeling methods proposed and demonstrated by Page (2011) are likely a good starting point for developing the theory and tools for optimizing ship configurations with respect to the amount and type of MAS technologies.

One approach to addressing how to incorporate MAS technologies into ship design is suggested by Rhodes and Ross (2010). As shown in Figure 27, state of the practice in complex system design, including ship design, addresses the structural and behavioral aspects of the ship. Rhodes and Ross propose that these aspects be augmented with Contextual, Temporal, and Perceptual aspects as well. The MAS technologies directly address the ship's Temporal opportunities. Rhodes and Ross refer to Epoch and Multi-Epoch modeling to address the changing properties of the contextual aspects. Within the naval engineering community, this type of modeling has been incorporated into Future Force Formulation (Rice 2005, Moreland 2008, and Doerry 2009). In Future Force Formulation, alternate futures are postulated. A ship concept can be evaluated for each alternate future in terms of how affordably modifications can be made to its configuration to meet its allocated force requirements. A good design will be adaptable and affordable across the range of likely alternate futures.

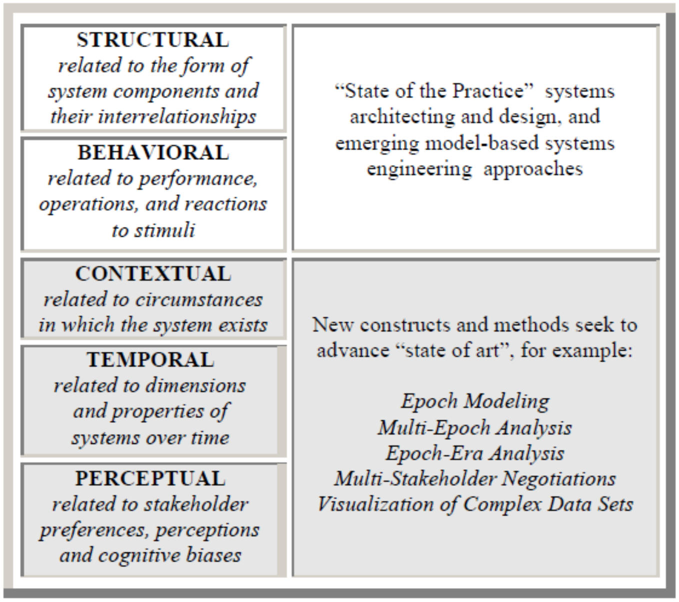


Figure 27: Five Aspects of Engineering Complex Systems (Rhodes 2010)

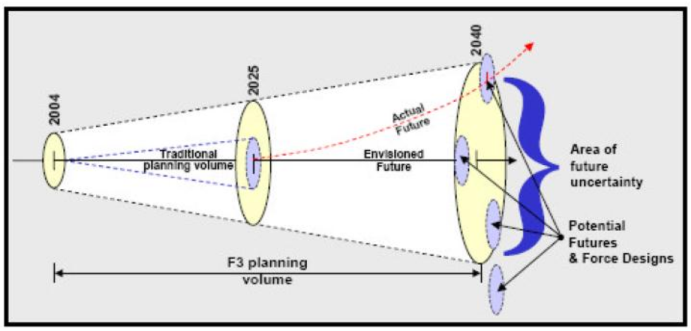


Figure 28: Future Force Formulation alternate futures (Rice 2005)

Since little effort has been expended to incorporate these techniques into ship design, the process maturity is evaluated as:

Handbook	**NOT STARTED**
Training	**NOT STARTED**
Tools	**NOT STARTED**
Data	**NOT STARTED**

CONCLUSIONS

The evaluations of MAS technologies and processes are summarized in Figure 29 and Figure 30. Note that while there has been considerable progress in maturing technology, no single technology has successfully met all the criteria for being institutionalized. Processes on the other hand, are very immature.

	TRL 7	Industry	Specs	Handbook	Cost	Value
Modular Hull Ship	green	green	red	red	red	red
Mission Bay	green	green	orange	red	green	red
Container Stacks	green	orange	orange	orange	red	red
Weapon Modules	green	green	orange	orange	red	red
Aperture Station	orange	orange	red	red	red	red
Off-Board Vehicles	orange	orange	orange	orange	orange	red
Electronic Modular Enclosures	green	green	orange	orange	red	red
Flexible Infrastructure	green	green	orange	orange	orange	red

Note: Done = green; Working = orange; Not Started = red

Figure 29: Summary of Modular Adaptable Technology Maturity

	Handbook	Training	Tools	Data
Cost Estimation	red	red	red	red
Valuing Modularity & Flexibility	red	red	red	red
Optimizing Acquisition, Maintenance and Modernization Strategies	red	red	red	red
Optimizing Ship Configuration	red	red	red	red

Note: Done = green; Working = orange; Not Started = red

Figure 30: Summary of Modular Adaptable Processes

To facilitate the institutionalization of MAS technology in the near term, the U.S. Navy should invest in:

- Developing and documenting the four MAS Processes in Technical Warrant Holder approved handbooks, manuals, guides, or design data sheets.
- Developing MAS Process Tools and gathering Data to support these tools.
- Training the work force to implement the four MAS Processes and use the MAS Process tools.
- Developing specifications and handbooks for Flexible Infrastructure. Developing specifications and handbooks for Modular Hull Ships, Mission Bays, Container Stacks, Weapons Modules, and Electronic Modular Enclosures.
- Training the work force to appropriately use MAS technologies in acquisition programs.
- Developing Aperture Station and Unmanned Vehicle (Off-Board Vehicles) interface technology.

Priority should be given to maturing the processes. Of the four processes listed, estimating cost and valuing modularity and flexibility should be emphasized first. The processes are key to developing the analytic rigor and justification for incorporating

MAS technology into a ship. Institutionalizing the more mature MAS technologies should be the second priority. Of the mature MAS technologies, Flexible Infrastructure should have the highest priority since it is most easily retrofitted on existing ships.

Finally, maturing the currently immature MAS technologies should be pursued. Once the currently immature MAS technologies have been matured, they too should be institutionalized.

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