NRAC

Naval Research Advisory Committee Report

Science & Technology for Modular Systems

March 2005

A.

B.

C.

OFFICE OF THE ASSISTANT SECRETARY OF THE NAVY (RESEARCH, DEVELOPMENT AND ACQUISITION)

NRAC 05-1

COPY NO.

REPORT DOCUMENTATION PAGE		Form Approved OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY) 01/03/2005	2. REPORT TYPE Group Study	3. DATES COVERED (From - To) March 2004March 2005

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Science and Technology for Modular Systems	
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)	5d. PROJECT NUMBER
A.M. Andrews, G.W. Caille, J. England, J.M. Feigley, L.A. Felton, E. Horvitz, M.J. Lister, N. Longuemare, J.W. Rodriguez, R. L. Rumpf, T.B. Smith, J.C. Sommerer, W.D. Whiddon, W. Williamson, J. Wolbarsht	
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Research Advisory Committee 800 North Quincy Street Arlington, VA 22217-5660	8. PERFORMING ORGANIZATION REPORT NUMBER NRAC 05-01

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Assistant Secretary of the Navy (Research, Development and Acquisition) 1000 Navy Pentagon Washington, DC 20350-1000	10. SPONSOR/MONITOR'S ACRONYM(S) ASN(RD&A)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This study looked at a comprehensive range of data and perspective on the importance of an S&T foundation for systems engineering processes needed to determine the value of modular designs for Navy acquisition programs. The time is right to harvest value from modularity through disciplined System Engineering. Implementing System of Systems Engineering and adopting modularity effectively can result in flexible and interoperable warfighting systems and the ability to cope with limited resources.

15. SUBJECT TERMS

systems engineering, modularity, technology refresh, acquisition, modular design, system of systems engineering, critical drivers, integration, economies of scale, development risk, interoperability

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE	UU	78	Dr. Sujata Millick
UNCLAS	UNCLAS	UNCLAS			19b. TELEPHONE NUMBER (Include area code) (703) 696-4875

i

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

This page intentionally left blank

NRAC

Naval Research Advisory Committee Report

Science & Technology for Modular Systems

March 2005

This page intentionally left blank

Table of Contents

This page intentionally left blank

Executive Summary

The Panel concluded the concept of modularity is intuitively simple – complex systems are broken into smaller modules for better understanding and manageability. However, deciding on the exact and most beneficial system partitioning can be a multi-faceted and difficult problem. For complex Navy systems, the decomposition into and selection of modules will depend on understanding the business and operational drivers for having a modular system. Defining drivers such as mission reconfiguration, technology refresh, or cost reduction helps set the parameters for the system partitioning and module configuration.

Second, many of the programs examined by the Panel have implemented some level of modularity. The Panel found that most program offices require modularity in their programs; however, implementation details are left to the prime contractors and lead-system integrators. Program managers provide little guidance in terms of configuration for modularity implementation. While systems achieve some degree of modularity, the results usually do not achieve specific business and operation benefits for the overall Navy.

Third, the Panel concluded that as a starting point for developing a process for implementing modular systems, the Navy must define a taxonomy for modularity that characterizes the choices and sets guidance/parameters for implementing modularity. In particular, the Navy needs to develop a systems-analysis capability that looks both vertically and horizontally across Navy systems. This capability will permit the Navy to carry out comprehensive studies of the cross-cutting effects of modularity, which in turn will drive choices for decomposition across systems and establish common drivers. The study also concluded that the Navy must assume ownership of this systems engineering process and can not abdicate responsibility for it to contractors.

Finally, the Navy S&T Community should assist in developing methodology and tools for decomposing systems into modules. This capability will help the Navy define modularity across systems, based on understood drivers and tradeoffs. Navy acquisition managers should understand the limitations of the current methodologies, fund future work to develop new evaluation tools, use innovative platforms to help verify and validate module selection, and use analytical tools and test beds to drive the decomposition decisions.

This page intentionally left blank

REPORT OF THE NAVAL RESEARCH ADVISORY COMMITTEE
Science and Technology for Modular Systems

Introduction

Transformation initiatives introduced to support the Chief of Naval Operations (CNO's) Science and Technology (S&T) Naval Power 21 strategic vision, challenge the Navy's acquisition, requirements, S&T organizations; and Navy industry community to provide fleet operators with new high-performance tactical systems for operations in an information-intensive, network-centric environment. Constrained budgets for systems development and procurement place a premium on prudent systems engineering and modular design and construction to achieve dramatic enhancements in reliability, maintainability, and ease of technology refresh for Navy systems while reducing costs. In recognition of the new focus and importance of modular designs for Navy systems, the Assistant Secretary of the Navy for Research, Development, and Acquisition (ASN(RD&A)) chartered the Naval Research Advisory Committee (NRAC) to evaluate the role of S&T in Navy systems engineering for modularity.

The NRAC Panel was composed of senior scientists and engineers from industry and academia, former senior government officials, and retired flag and general officers of vast operational experience. The Panel studied a wide range of current Navy acquisition programs, system initiatives at U.S. and international defense companies, and research efforts at selected academic institutions. The resulting recommendations propose a number of decisive steps that exploit the considerable talent of the Navy's science and technology community and advocate the use of horizontal systems engineering practices for modular Navy system designs.

This page intentionally left blank

Outline

- **Panel Membership**
- **Terms of Reference**
- **Approach**
- **Briefings Received**
- **Executive Summary**
- **Background**
  - Definitions
  - Types of Modularity
  - Modularity: Why or Why Not?
  - Evaluating Modularity Tradeoffs
  - Pillars of Modular Systems
  - Systems Engineering
- **Study Findings**
  - Navy Programs
  - U.S. Industry
  - International
  - Systems Engineering
  - Literature Survey
  - Summary Findings
- **Recommendations**
- **Conclusions**

Naval Research Advisory Committee

Outline

The NRAC report on S&T for Modular Systems is organized into multiple sections. The first section provides the Panel membership; the second contains the specific taskings from Terms of Reference (TOR) that guided the Panel; the third outlines the approach taken by the Panel to address the taskings in the TOR; and the fourth lists the briefings received by the Panel. The report also includes an Executive Summary, which is followed by several background sections covering key definitions, types of modularity, and an analysis of how modularity can be beneficial to Navy systems. The report then looks at essential elements of modular systems and focuses on the need for a robust Navy process of systems engineering and analysis. Subsequent sections summarize the study findings for Navy programs, commercial and defense industries, international programs, systems engineering, and current literature. The final two sections provide detailed recommendations and conclusions.

This page intentionally left blank

Panel Membership

A broad, accomplished panel of experts contributed to the NRAC study on S&T for Modular Systems. The membership, which devoted more than 3,000 hours to the effort, included former Navy flag and Marine Corps general officers with several years of experience in both operations and acquisition; and, former Senior Executive Service (SES) members involved in the management of both technology development and acquisition programs for the Office of the Secretary of Defense (OSD), the Navy, and the Army. Other Panel members were experts from defense and commercial companies, Department of Defense (DoD) consultants, and senior leaders from university-affiliated research centers and academia. The Panel Executive Sponsor was RDML Charles Hamilton, Program Executive Officer (PEO) Ships.

This page intentionally left blank

Terms of Reference

The TOR reflected perspectives from the Office of the ASN(RD&A) and the Office of Naval Research (ONR). Initially, the TOR focused specifically on an investigation of how S&T could support the development of modularity in Navy programs. However, after some early discussions, it became apparent that several factors are enablers for modular systems and these needed to be addressed in the study discussions as well as the S&T elements. These factors include items such as the acquisition process, spiral development and systems engineering processes. In fact, the Panel determined that a system-of-systems engineering process is one of the over-arching elements necessary to define modularity across programs of record.

The TOR chartered the Panel to (1) review systems engineering and analysis practices and processes within the Navy and industry and (2) determine the extent to which modular open systems, spiral upgrades, and S&T are factored into requirements definitions and the acquisition process. The Panel was directed to identify S&T areas and guidelines that could enhance development of modular systems and enable horizontal implementation of results across platforms and/or mission packages. The Panel was also asked to recommend improvements to the interface between the Navy's S&T planning and the acquisition process.

The complete TOR is included in Appendix A.

This page intentionally left blank

Approach

- Reviewed selected *programs of record* for modularity implementation
  - *Types* of modularity and drivers
  - *Degree* of modularity versus integration
  - *Methodology* (systems engineering and procurement requirements) used to define modularity
  - *Spirals* – provisions to incorporate future capabilities (S&T)
  - *Benefits* – business and operational cases
- Baselined *commercial and defense industry* (U.S. and International) for modularity drivers, business models, implementation methodologies and benefits
- Reviewed *systems engineering practices*, especially regarding modularity
- Surveyed *literature* for implementation methodologies, business drivers, metrics for measuring success and prior Government/Industry studies

Naval Research Advisory Committee

Approach

The Panel's approach to gathering information and data covered four areas. The Panel reviewed information on: selected Navy programs of record; defense-industry programs, which included international projects; and commercial and academic activities that had applicability to the subject areas. When reviewing a program, the Panel looked specifically for: the type and degree of modularity used in the system; the methodology used to implement a modular design; planned spirals and their relation to a modular system design; and, finally, the business and operational benefits, planned or achieved, through modularity. In addition to briefings, presentations, and site visits to gather basic information, the Panel conducted a survey of the literature. Finally, the Panel examined current spiral implementation methodologies in the Department of the Navy (DoN) and ways in which the S&T community within the DoN could contribute to the long-term development of a "modular Navy."

The resulting information was grouped into two basic categories. The first consisted of *systems engineering* processes, practices, methodologies, and business models. The second category encompassed *modularity issues* in terms of types, implementation methodologies, critical drivers, and the benefits, liabilities, and metrics associated with modules and modular systems.

This page intentionally left blank

Briefings Received

Programs
- Virginia Class Subs
- SSGN Conversion
- ARCI
- CVN-21
- DD(X)
- MMA
- J-UCAS
- JTRS
- ONR FNC
- LCS Seaframe
- LCS Mission Modules
- Integrated Deepwater System
- FCS System Analysis (Sandia)
- HSV-2
- X-Craft

Systems Engineering/Other
- NAVSEA 05
- ASN RDA Deputy CHENG
- Total Open System Architecture
- PEO IWS Open System Architecture
- Navy Acquisition Management
- NPS/Meyer Institute of Systems Eng.
- MIT Lean Initiative
- AF Systems Engineering Forum
- OSD Open Systems Joint Task Force
- OUSD (AT&L) – Defense Systems

Guidance
- CNR
- DASN (RDT&E)
- PEO Ships

Industry
- Boeing
- IBM
- L3 Communications
- Lockheed Martin
- Microsoft
- Northrop Grumman
- Rockwell Collins

International
- Ericsson
- HDW
- Naval Team Denmark
- Thales

Naval Research Advisory Committee

Briefings Received

The study examined the state of systems engineering and modularity for a total of 14 programs. These included acquisition category (ACAT) I and II programs covering air, sea, land and sub-surface, as well as programs that exhibited a high-degree of modularity. The Panel also received briefings that addressed systems engineering and modularity from Navy leaders, including senior managers from the Naval Sea Systems Command (NAVSEA), the PEO for Integrated Warfare Systems, Air Force and DoD officials, and academic experts such as those from the Massachusetts Institute of Technology (MIT) Lean Initiative.

The Panel received briefings from seven companies on systems engineering and modularity as applicable to commercial systems. For comparison with U.S. defense programs, the Panel visited or received presentations on systems engineering approaches and modular design by four European defense firms as shown above. The motivation for and the advantages/disadvantages of incorporating modularity were an important element in both the international and commercial industry discussions.

The Panel received guidance on structuring its approach to the specific taskings, as well as structuring fact-finding sessions, from the CNR, Deputy Assistant Secretary of the Navy (DASN) (RDT&E) and the Study Sponsor, PEO Ships.

This page intentionally left blank

Bottom Line, Up Front

The slide above provides a key message of the Panel's findings and recommendations. During the discovery process, the Panel determined that the real issue is not the degree of modularity or why or when it is implemented, but the lack of a Navy-wide systems engineering and analysis process that could establish the rationale for implementing modularity.

A Navy-wide systems engineering process would allow the development of architectures across the Navy that would help define decisions on technology-development and acquisition strategies. With ever-increasing system complexity, a system-of-systems, top-down, interactive, recursive, systems analysis process that defines broad naval requirements must be established. The Panel recommended that a systems engineering and analysis function be established and the process applied horizontally across naval programs to enable determination of appropriate levels of modularity.

This page intentionally left blank

Background

Definitions

Systems Engineering

Is a top-down, comprehensive, interactive and recursive system synthesis & analysis process; applied through all stages of development and sustainment

Integrated

An architectural framework where most system functions are mapped to single components. Components have high degrees of interdependency and non-standard interfaces.
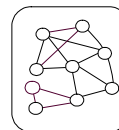
Modular

An architecture where system functions are partitioned into elements consisting of various components. These elements have standard/defined interfaces and minimal interdependencies in the overall system.
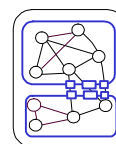
Definitions

One of the Panel's observations is that the term "modularity" is used in different ways; reflecting context, motivations, and approaches. Because a principle study finding is that systems engineering is critical to judicious use of modularity for Navy systems, the Panel defines modularity as one end of an engineering spectrum, with highly-integrated, or monolithically-engineered systems at the other end of the spectrum.

Systems engineering is the critical process that allows an acquisition program or set of programs to determine the appropriate place in that spectrum to optimize the system being developed. The systems engineering analysis must account for (1) operational and business drivers; (2) the state-of-art of relevant technology and future development of that technology; and (3) the existence of or plans for related systems, performance requirements, acquisition, logistics, and life-cycle tradeoffs. This process must be interactive and recursive as the system evolves from conceptualization through acquisition and production, to test and evaluation, and ultimately to operational deployment.

The design of integrated monolithic systems, at one extreme of the engineering spectrum, may be motivated by extremely high performance requirements, or a perception that subsystem reuse may be unlikely (e.g., a highly specialized radio frequency (RF) system) or undesirable (e.g. anti-tamper electronics). In the context of software, an integrated product may be characterized as "spaghetti code" because of the complexity of data flow, or may involve very powerful, but potentially difficult to document techniques like self-modifying code. Such systems are commonly the products of small, possibly isolated engineering teams with specialized expertise. In general, the components of an integrated system have a very high degree of interdependence, and alteration of individual components is likely to have a large number of collateral effects (in practice, frequently unintended side

effects). It is rare for interfaces between different components of the system to be standardized. Such systems present special challenges for knowledge management and technology refresh. It is even possible that a high degree of systems integration can impede competitive procurement.

At the other end of the spectrum are modular systems. Through a systems engineering process, such systems are decomposed into self-contained subsystems that interact via well-defined and well-documented interfaces. Such interfaces may even be openly documented, by agreement within consortia, or through the influence of the procuring authority, such that different modules may even be developed by different engineering teams at different companies. The emphasis on well-documented interfaces between subsystems represents an investment or cost that should be justified by the drivers for the system. Carefully defining interfaces between components that always will be present throughout the system lifecycle represents wasted effort. Technology refresh, maintenance, and multi-functionality may all be achieved at the level of individual modules.

It is important to note that all systems that incorporate modern technology, even integrated ones, represent some degree of modularity. The key question for acquisition programs is whether the systems being procured have the right degree and type of modularity, given existing operational, business, and technology drivers.

Background
Types of Modularity

Capability Swapping Modularity - Mission Packages	Component Sharing Modularity
Bus Modularity	**Construction/Design Modularity**

Naval Research Advisory Committee
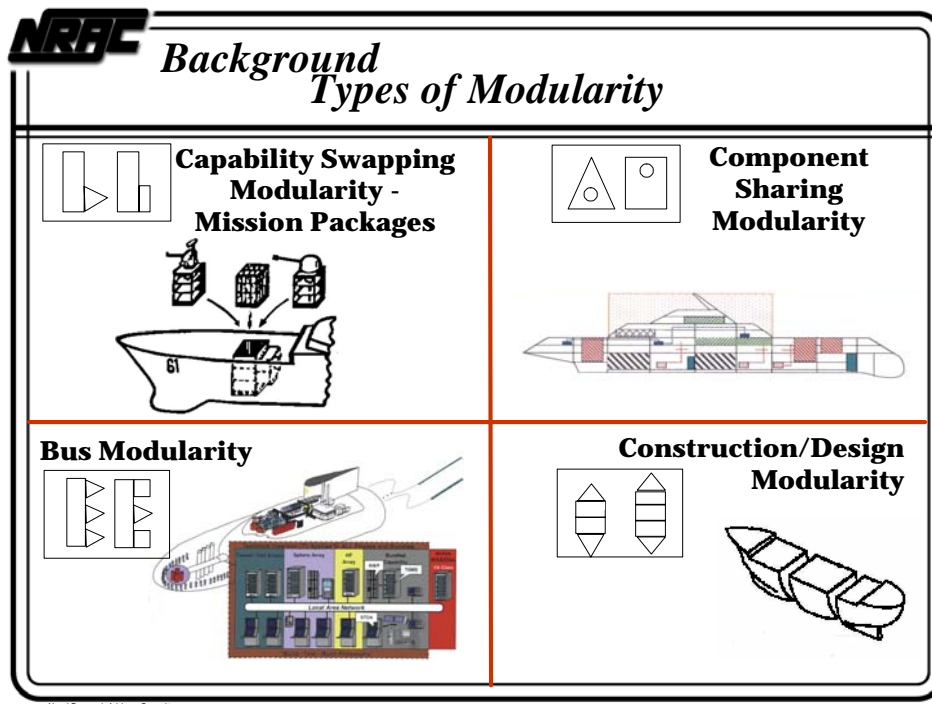
Types of Modularity

The Panel identified four types of modularity: (1) capability-swapping modularity; (2) component-sharing modularity; (3) bus modularity; and (4) construction/design modularity.

In capability-swapping or mission-package modularity, a specific package can be replaced in form-fit with another type of mission package. The Navy's Littoral Combat Ship (LCS), which will accommodate different mission packages for anti-submarine warfare, mine counter measures, and anti-surface warfare, represents an example of this type of modularity.

Component-sharing modularity refers to the use of a specific component for different systems or on different platforms. For example, a central processing unit (CPU) that could be used to perform different functions on a platform, or the same CPU employed on a variety of platform types.

Bus modularity defines the interactions of different hardware and software components through a common backbone. Bus modularity is represented by system architectures that have been decomposed into modular hardware and software designs separated by a middleware layer. The middleware layer provides separation of hardware and software as an alternative to the tight integration of the hardware and software. This approach enables independent technology refresh of both hardware and software applications. The Acoustic Rapid Commercial-off-the-shelf (COTS) Insertion (ARCI) program represents an example of this type of modularity.

In construction or design modularity, a complex system is partitioned into components, to facilitate design or manufacturing. This approach can enable the designers and developers to address each component separately for problem-solving, manufacturing, testing, and other program activities, such that when all those components are brought

together there is a higher likelihood of the entire system working. An example of this modularity is the Virginia-class submarine program.

Modularity: Why or Why Not?

Drivers	**Tradeoffs**
• Technology Refresh	• Performance
• Interoperability	• Development Risk
• Increased Readiness	• Flexible & Enhanced Operational Capabilities
• Mission Reconfiguration	• Manpower & Skills
• Capability Upgrades	• Schedule/Time
• Construction/Manufacturing	• Economies of Scale
• Design Re-use & Qualification	• Best of Breed Technology
• Logistics & Maintainability	• Acquisition Cost
• Training	• Physical (size, weight, power)
• Navy Total Ownership Cost	

Decisions for modularity require understanding operational/business drivers and tradeoffs

Modularity: Why or Why Not?

As a first step toward making the decision about whether or not to decompose a system into modules, it is essential to identify the drivers for having a modularity system. Once the drivers are selected, it is possible to choose an approach to modular decomposition to produce the effect desired; or, alternatively, determine that modularity is not the appropriate design option. The Panel identified some likely drivers as shown above; technology refresh, increased readiness, capability upgrades, and reduced total ownership costs.

Once the business and operational drivers are understood, the implication of a modular design needs to be recognized. The trade space may include positive and negative effects. For example, trying to achieve rapid technology refresh capability may require the system to be larger, weigh more, need more power and initially cost more. However, the end result will be a system that can easily be upgraded to better technology, cost less over the total life span of the system, require less manpower training, and have reduced development risk.

Modularity and decomposition choices affect many parameters including performance, acquisition costs, and schedule. Thus, the decision on whether or not to implement modularity should be based on an understanding of both the near-term and far-term operational/business drivers and tradeoffs.
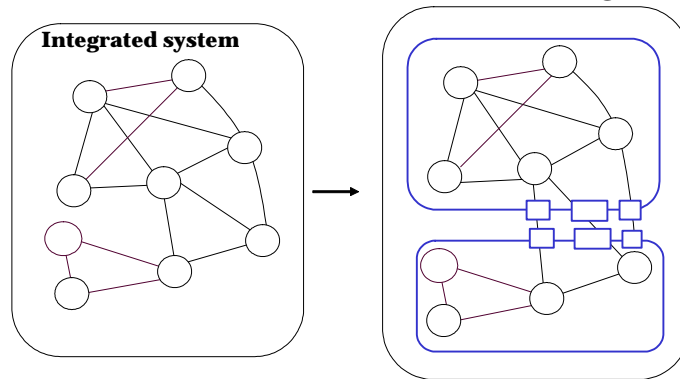
This page intentionally left blank

Evaluating Modularity Tradeoffs (1)

Technically, all systems can be described in terms of components and dependencies among components. In relatively non-modular or integrated systems, components are woven together tightly and are not easily addressed as individual components for the purposes of upgrading (for technical refresh, obsolescence, etc.), diagnosing, repair, or reuse.

Modular designs are characterized by an intelligent partitioning of systems into sets of well-defined modules with clear and standard interfaces. The modules mask the complexity of their internal designs from one another and transmit and receive only necessary information or resources from other modules or the external environment via the interfaces.

Typically, there are multiple ways to partition systems into modules. Decisions about the decomposition or partitioning of a system into well-defined modules have been part of the heuristic art of systems engineering. In the past, such partitioning has relied on the intuitions of engineers or been split along lines of demarcation from roles that different sets of components might play in a system. Other times, the partition is based upon the provision of different types of components by specific groups or organizations recognized as expert sources for those particular components or modules.

There is opportunity for developing methods and tools for reasoning about the costs, benefits, and tradeoffs associated with different decompositions. The relative value of different system decompositions and the associated modules generated by the partitions, depend on key desired attributes.

The tightly integrated system (diagram on Slide-left) can be decomposed in different ways depending on objectives. For example, if the goal is to minimize the complexity of interfaces among modules, the system could be decomposed in two modules with three

simple interfaces, as shown on the right side. In developing such a decomposition, a utility or objective function might capture a measure of the cost associated with maintaining and writing modules that are consistent with and abide by the defined interfaces. Such an objective function might evaluate the cost of an overall system as being some monotonically increasing function of the number of interfaces.

Background
Evaluating Modularity Tradeoffs

- **What are good decompositions?**
  - **Introduction of multiple considerations**
  - **Understanding tradeoffs**

"Prepare for technical refresh of A"

Integrated system

A   B
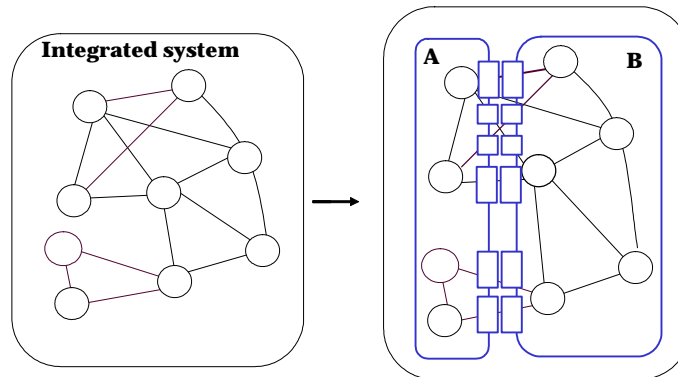
Naval Research Advisory Committee

Evaluating Modularity Tradeoffs (2)

Consider now decompositions aimed at another objective—that of preparing for new technology insertion, based on expectations about a fast-paced competitive area of technology. If the goal of decomposition is to prepare for a technical refresh of a set of components that comprise the module (subsystem A), a different partition of components of modules may be more valuable. In this case, preparing for the technical refresh of technologies embodied by components in subsystem A requires a greater number of interfaces than the system partition shown on the previous page. However, in the future, subsystem A can be easily decoupled and replaced with updated technology.

This page intentionally left blank

NRAC *Background*
Evaluating Modularity Tradeoffs

- **What are good decompositions?**
  - **Introduction of multiple considerations**
  - **Understanding tradeoffs**

"Prepare for technical refresh of A, and ready for failure of B"

Integrated system

A   B

C

Evaluating Modularity Tradeoffs (3)

For system design, assuming a single objective often is unrealistic; co-existence of multiple objectives is more common. The illustration above is an example of two objectiv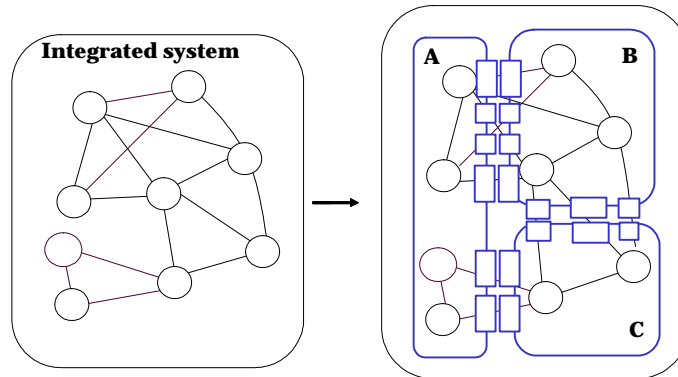es. A designer may seek both technical refresh of A, and also the cost-effectiveness of replacing a subset of components, contained in Module B, that are known to have a short mean time to failure relative to other components in Module B. Now, another decomposition, that of partitioning out Module C from other components in Module B, may lead to cost savings and higher operational availabilities. The new decomposition, while it may promise to yield a system that is less expensive to maintain, contains a new module, as well as additional associated interfaces between the new module and other modules in the system.

Multiple objectives should be identified and reviewed; attributes of some or all of these objectives may be in conflict; leading to consideration of tradeoffs in determining good partitions. Decisions on decompositions into modules must be sensitive to the objectives. A fundamental starting point for analyzing the value of alternative partitions is a clear and explicit definition of desired attributes followed by a qualitative or quantitative exploration of the benefits, costs, and tradeoffs associated with different system decompositions.

Although there is opportunity for formal mathematical optimization as part of a methodology for decomposition of a system into modules, considerations of multiple objectives and alternate decompositions can be used to build insights during typical qualitative design evolutions.

Insights about alternative decompositions and better choices for ultimate modularization, can be achieved by assessing multiple objectives that capture differing intentions behind developments of systems. Such objectives should be shared among involved parties and refined as part of the process of deliberating about alternative

decompositions. The availability of the objectives can support deliberation about measures of goodness of different system decompositions.

Pillars of Modular Systems

- **Systems Engineering**
- **Standard Interfaces**
- **Open System Architecture**

Systems Engineering Drives Standards and Open System Architecture

Naval Research Advisory Committee

Pillars of Modular Systems

As the Navy seeks to harvest the benefits of modularity to support and enhance naval warfighting capability, three technical "pillars" must be considered: systems engineering, standard interfaces, and open systems architectures. The pillars represent processes that allow decisions concerning modularity to be based on requirements for joint interoperability, horizontal utility, and compatibility across naval programs and platforms.

Systems Engineering: A systems engineering process is essential for examining and determining the driving factors for modularity. A systems engineering process consists of two elements: first, the technical knowledge needed to engineer specific systems; and second, the systems engineering management that permits the engineering of systems-of-systems, at the highest programmatic level, to ensure that decisions are based on organized input and analysis. The systems engineering management process must be a top-down, comprehensive, interactive, and recursive problem-solving process that is applied sequentially through all stages of development and sustainment.

Standard Interfaces: Standard interfaces go hand-in-hand with open systems architectures. Open systems architecture definitions are intended to define non-proprietary interfaces that are available to all suppliers. Free access to interface standards fosters a competitive environment, which should encourage expanded product innovation and result in "best-of-breed" capability at lowest cost. In order for modules to be used in multiple applications, interfaces must not only be "open," but also be common or standard. For example, if several platforms choose to use computers that interface with open systems, computer modules cannot be used on multiple platforms unless they incorporate the same open system interfaces. Some level of standardization, even for so-called "open" systems, must be adopted to maximize the benefits of interchangeable modules.

31

Open Systems Architectures: Open systems architectures permit the use of common modules across multiple systems by enabling the design, engineering, acquisition, testing, and fielding of non-unique modular components. As noted in the charter for the Open Systems Joint Task Force (OSJTF), " an opportunity exists to make a significant impact on the cost, interoperability, modularity, technology transparency, supportability, and a host of other important aspects of the electronics in future weapon systems by sponsoring and accelerating the adoption of an open systems approach for new systems and system upgrades." Although these words address open systems associated with electronic components, they are applicable equally to all systems that are attempting to gain the benefits of modularity.

Platform/Program Model

Sea Strike Concept

CRD   CRD   CRD

Sys A   Sys B   Sys C

Fleet Integration

Naval Research Advisory Committee
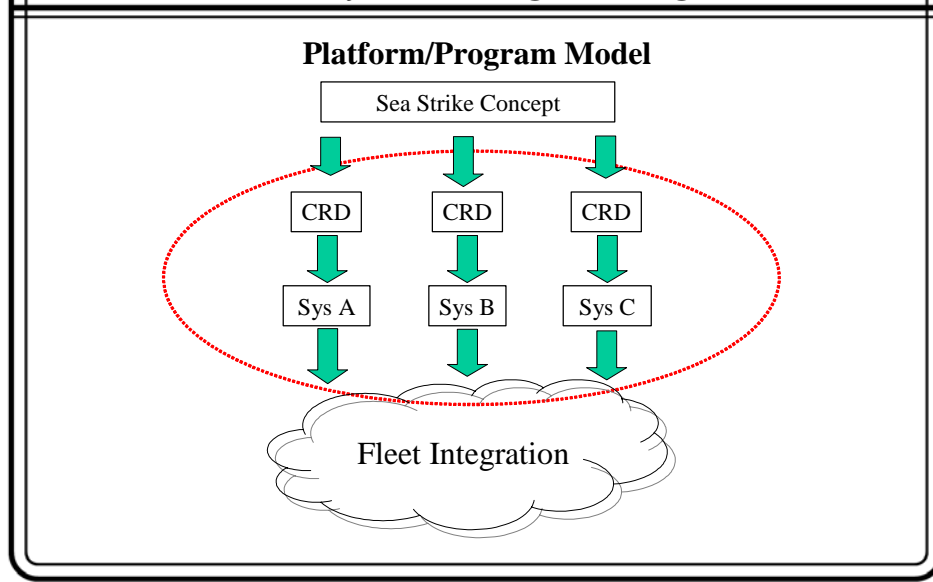
Systems Engineering (1)

The slide above shows the nominal "concept to material" systems engineering process currently used by the Navy. It is a vertical, single-dimensional methodology that derives individual platform requirements from over-arching Navy operational concepts. This platform/program model does not provide a construct by which to identify or evaluate similar needs across multiple platforms or to attain interoperability benefits. The same holds true for intra-system modularity requirements. Modularity only occurs by fiat (via a Concept Requirements Document (CRD) statement).

The other most significant limitation to this model is that any system-of-systems integration that takes place, does so in the fleet or operating forces. This places a significant burden on the forces because of the competing realities of optempo and the need for resources to conduct unplanned systems integration functions. This "product-line" or "stovepipe" model has well-recognized and well-understood limitations; not the least of which is an inadequate process for systems engineering and interoperability.

This page intentionally left blank
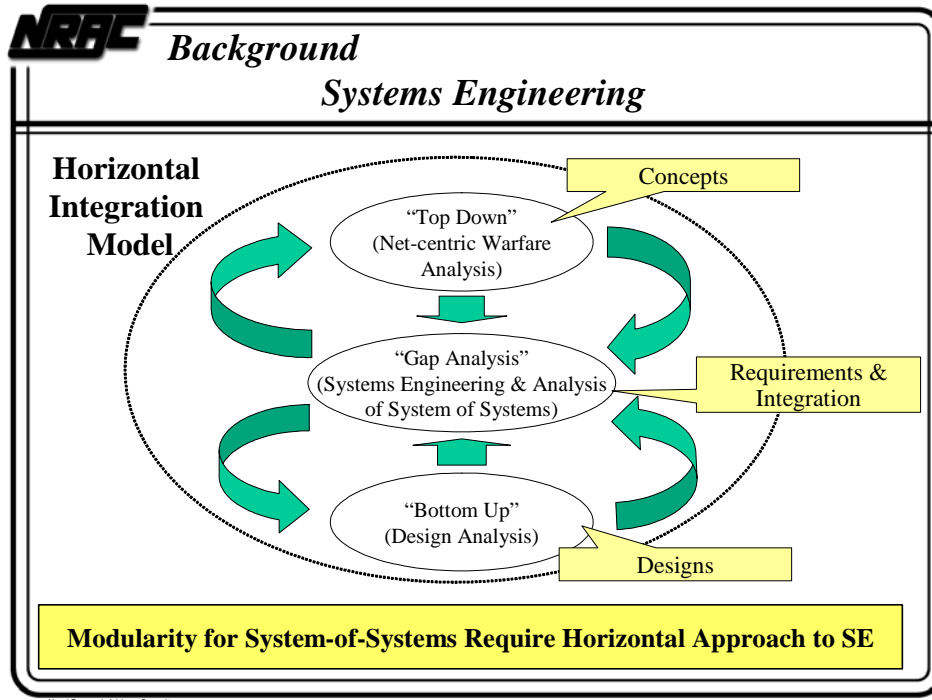
Systems Engineering (2)

The horizontal integration model above for system-of-systems engineering is an interactive model consisting of three elements: the customer (concepts), the acquisition process (Requirements and Integration), and the S&T community (designs).

The Top-Down element is composed of the capability-based methodology that starts with strategic direction. The strategic direction flows from joint operational concepts, joint-service operating concepts, and joint capability.

The second element of the model performs a Gap Analysis of the system-of-systems to uncover weaknesses in current plans. The analysis is based on the joint capabilities assessment, which is provided by the topdown systems engineering element. A Bottom-Up element provides current system capabilities and technologies. Alternatives postulated from the Bottom Up analysis feed into the Gap Analysis process and are viewed within the context of the Top Down analysis to determine individual comparative worth. The resultant analysis forms the basis for future system requirements.

The Bottom-Up element takes the requirements from the Gap Analysis and performs the detailed physics-based design/systems engineering. It does tradeoffs, CONOPS assessment, evaluation of various measures of effectiveness (MOEs), measures of performance (MOPs), interdependencies, and total cost of ownership, among others. From this assessment, spiral technology development programs which encompass technology-insertion options, are presented for the Gap Analysis. Development options, when refined further, are presented as recommendations to the Top-Down element, which reviews them and forwards them to the Navy's Program Objective Memorandum (POM).

This page intentionally left blank

Findings

The Panel's findings are grouped into five categories:
- Navy Programs
- U.S. Industry
- International Programs & Industry
- Systems Engineering
- Literature Survey

The following section describes the key findings in each of these areas and sets the context for the final recommendations and conclusions.

This page intentionally left blank

Navy Program Findings

- No actionable *policy, guidance, definitions, or principles* for modularity
- Shortage of *systems engineers* and lack of experience with modularity

Decision Process
- *Motivators* for modularity not understood or articulated
- Inconsistent *system analysis* (if any), program/platform centric, done by primes

Acquisition Implementation
- LCS, SSGN, and ARCI reflect transformational use of modularity
- In general, programs have delegated decision responsibility for modularity to primes without guidelines or incentives
- No serious commitment to spiral development observed; S&T community largely decoupled
- Impact of modularity on T&E, training, and logistics not well understood

Navy Program Findings (1)

Among the programs reviewed, including the ones that have embraced some degree of modularity, none were structured based on any Navy policy or formal Navy guidance on modularity. The Panel determined that no consistent definition of "modularity" or "standard interfaces" exists. Second, all PEOs and program managers (PMs) interviewed reported a shortage of systems engineers. In general, the Panel concluded that very few engineers were available who were experienced with modular systems.

Decision Process: The Panel found that the reasons for using modularity are neither well-understood nor well-articulated. The Panel attributed this shortcoming to the inconsistency of available modular-systems analyses and the relative newness of approaches for assessing capabilities in a net-centric warfare environment versus assessing platform requirements to meet mission objectives.

Acquisition Implementation: The following are some of the general findings the Panel cited relative to the acquisition process.

- Three of the programs reviewed, the LCS, cruise missile submarine (SSGN), and the ARCI (Acoustic Rapid Cots Insertion) program, are good examples of modularity and reflect a paradigm shift in Navy acquisition programs. These programs understood the drivers for modularity and had established parameters for decomposition based on these drivers.
- Several of the new programs reviewed addressed a spiral development structure within their acquisition model. Yet, all of the program managers who briefed the Panel reported that there was no firm plan or funded program structure within the S&T community to underpin this acquisition program and to ensure success and reduce risk through spiral/modular developments.

- Due to the lack of quality and numbers of systems engineers and the lack of firm guidance or policy on modularity, most program managers have delegated the decision for modularity to their prime contractors or LSIs without contractual incentives.
- The Panel felt that the Navy could benefit greatly from modularity implementation in three areas -- test and evaluation (T&E), training, and logistics. However, the Panel did not find a Navy program official who could quantify the effect of cost or schedule on development or operational testing (DT/OT) if modularity were employed in their programs. Likewise, the impact of modularity on training requirements and logistics support was not understood by program managers.

Navy Program Findings

Examples of Best Practices

- LCS, SSGN: Navy taking responsibility for upfront SE
- ARCI: good use of modularity, spiral development, commercial standards, & technology to enhance capability
- Virginia Class: good example of benefits of modular construction
- X-Craft and HSV2 potential test beds for SE and operational mission module evaluations

Areas for Improvement

- UUVs (approximately 70 types): lack of modularity, policy, guidance, and standards
- MMA: program office and prime have different visions
- MMA, ACS, BAMS, J-UCAS: minimal horizontal systems engineering
- LCS and Deepwater: MOU in place; questionable commitment
- DD(X), CG(X), CVN21: technology sharing opportunity
- FORCEnet: System of Systems Engineering an absolute requirement

Navy Program Findings (2)

Examples of Best Practices: The Panel found examples of best practices for modularity in several individual programs. The LCS and SSGN programs reflect cases in which the Navy demanded modularity for capability-swapping of mission modules to provide flexible operations. The ARCI took the initiative to reduce cost and yet achieve technology refresh by using component and bus modularity, spiral development, and commercial standards to enhance capability through technology insertion and refreshment. The Panel considered the Virginia-class submarine program to be an excellent example of modular construction that has matured to an even higher level than its predecessor, the Seawolf class -- the first submarine program in which modular construction was used.

The Panel felt the joint service HSV-2 and the Office of Naval Research X-Craft programs offer promising testbeds for systems engineering and mission module evaluation. Their flexible cargo area designs will provide the Navy with very-affordable, quick-look evaluations of new mission modules while in an early prototype phase, offering the potential of finding design flaws that would cost more to correct in a later stage of system maturity.

Areas for Improvement: The PEO for Littoral and Mine Warfare (LMW), in briefing the Panel, reported that the Navy has developed 70 different types of unmanned underwater vehicles (UUVs)—a clear example of the lack of modularity policy, guidance, and standards.

In a related example, the Navy program manager for the Multi-Mission Aircraft (MMA) program told the Panel that the contractor would be providing an airborne "truck" to replace the aged P-3 airframe while retaining the mission equipment. Yet the MMA prime contractor openly applauded the opportunity to insert common mission modules from other programs, taking advantage of newer technology and an open systems architecture to support modularity and lower total cost of ownership from an acquisition support and training

perspective. These different views demonstrated the lack of coordination in the Navy and contractor influence in modular system designs.

The Panel concluded that other new programs, including the Aerial Common Senor (ACS), Broad Area Maritime Surveillance (BAMS), and Joint Unmanned Combat Air System (J-UCAS) all could benefit from effective horizontal systems engineering and analysis. The payloads, peripherals and backbone architecture for these systems appeared to be ripe areas for developing commonality.

The Panel also initially noted a questionable commitment on behalf of the Coast Guard and its contractor, Integrated Coast Guard Systems (ICGS), to work together on a common seaframe (HM&E) and other common equipment which could satisfy both the Navy's LCS and the Coast Guard's national security cutter requirement, even though a memorandum of understanding (MOU) was in place between PEO (Ships) and PEO Integrated Deepwater Systems (IDS). However, the Panel was later advised that the Coast Guard plans to assign 10 personnel to the Navy's X-Craft crew, an indication of Coast Guard interest in a more cooperative role on the LCS program.

The Panel also concluded, that in addition to potential radar designs and antennas, other areas of commonality can be identified among the Navy's DD(X), CG(X), and CVN-21 programs. The Panel considered FORCEnet to be an example of a major effort that requires a system-of-systems engineering discipline to ensure success for this very complex net-centric program.

U.S. Industry Findings

- No common definitions or standards for modularity (***Defense***)
- Company interests dominate modularity decisions (***Defense***)
- Need for Systems Engineering recognized, not uniformly implemented, and shortage of expertise (***Defense & Commercial***)
- Software an enabler for open-system architectures and modularity (***Defense & Commercial***)
- Low percentage of software re-use; high opportunity for cost savings (***Defense & Commercial***)

Defense Industry Specifics
- ***Capability Swapping Modularity/Mission Packages -*** industry not developing unless directed by government
- ***Construction/Design Modularity*** – both government and industry in harmony
- ***Bus Modularity*** - commercial companies ahead of defense in implementation
- ***Component Sharing Modularity -*** defined by company business models not by customer

U.S. Industry Findings

The Panel received briefings from Boeing, IBM, L3 Communications, Lockheed Martin, Microsoft, Northrop Grumman, and Rockwell Collins. The topics included: the application of modular systems to multiple platforms or systems; systems engineering principles for modular open system architectures (MOSA); processes, guidelines, and metrics for modularity; and S&T recommendations to enable MOSA development and implementation. The companies also were asked to provide examples of programs employing MOSA across multiple platforms and recommendations for future programs.

In general, the Panel found that defense companies were requested but not incentivized by their DoD customers to provide modularity. Companies described some examples of modularity that supported multiple programs, but these modular designs and their applications were based on internal business decisions. Companies with both commercial and defense business sectors provided examples of how modular designs were used between sectors. In conclusion, the use of modularity seemed to depend mostly on internal business models and only to a limited degree on DoD customer direction.

The Panel found that all companies embraced systems engineering as a key set of processes for design and management. Yet the companies provided many different views on the topic, not only in terms of the scope of systems engineering, but also in the use and definition of terms. Many of the companies viewed the scope of systems engineering only in terms of specific individual products, or program stovepipes. Few addressed the expanded scope of integration across programs as a system of systems. The Panel felt this lack of common understanding of systems engineering concepts has caused confusion and restricted the Navy's progress in achieving intelligent use of modularity. For example, the terms "open systems" and "modularity" were used interchangeably, although they are not the same.

The Panel also noted differing interpretations of "modularity" both in terms of the levels of a system to which it is applied, and in terms of type of modularity being used. To evaluate these diverse views, the Panel adopted two frames of reference: the level of application and the type of modularity. The level of application looked at (a) weapon-system level (a Navy warfighter issue); (b) system level (an acquisition and prime contractor issue); (c) subsystem level; and (d) component level. The type of modularity looked at (a) mission/package modularity, (b) bus modularity, (c) component-sharing modularity, and (d) construction/design modularity being used.

Although industry used modular approaches during World War II to build vast numbers of ships, it wasn't until the 1970s that the Navy began to reconsider modular approaches. Currently there are few examples, such as LCS, SSGN, and ARCI, where the Navy has asked industry to use mission modular approaches. The Panel found that if the Navy does not request a modularity-based approach, industry will determine whether or not to use modular designs based on business interests.

The Panel heard from industry about a variety of company motivators. Examples of these are: improving competitive position, reducing production costs, and/or maximizing reuse of products across programs. The Panel asked companies to address their systems engineering principles for MOSA. One company cited the new OSD Task Force report, "A Modular Open Systems Approach to Acquisition – Version 1.2, February 2004," as an excellent description of MOSA principles and benefits. The companies described the importance of systems engineering and their particular implementation approaches for different levels of modularity. However, when reviewing company integrated technical and business strategies, the Panel found that industry does not have an uniform process for implementation of systems engineering. More important, given such diversity, the Navy has no standard method for judging the quality of the systems engineering approaches of different companies either during proposal evaluation or during execution phases of programs.

The Panel also found a shortage of systems engineers in both industry and government. During the past decade the government experienced roughly a 50 percent reduction in people associated with systems engineering (Hon. Michael Wynne, in Defense AT&L Magazine, July-August 2004). Industry also saw significant reductions in its systems engineering workforce.

A common theme that emerged during the industry briefings is that software is a key enabler for achieving meaningful and effective modularity. Clearly, as systems have moved toward digital implementation, developers have moved rapidly toward making the hardware generic and common, with functionality resident in the software. As a result, many of the commercial pressures that have driven the electronics and software industries toward object-oriented software and plug-and-play hardware interfaces are also driving defense systems. The Panel felt that the Navy must require that system architectures are "open" to ensure the long- term ability to competitively facilitate technology and functional modular upgrades.

In terms of weapon system modularity, Navy-industry teams of necessity have evolved the construction and modular design of weapon system platforms since early 1972. Completed modules are assembled, integrated, and tested before they are joined. This type of modularity was driven primarily by two factors: first, considerations of the viability of the

industrial base; and second, cost. For example, the Virginia class attack submarine program was developed by two shipyards, General Dynamics Electric Boat and Newport News, and is being built, assembled and tested in both locations. This same philosophy has been applied to surface ships and aircraft.

Weapon system developments have been driven by software complexity. Prior to the emphasis on open system architectures, adding or improving a function for a defense weapon system was expensive and time consuming. Most weapon systems are tightly integrated and make limited use of standard interfaces and have been developed primarily by commercial companies. New systems being developed for the Navy, Army, and Air Force have started to introduce open system architectures. Some examples include Navy Multi-Band Terminal (NMT) and the Joint Tactical Radio System (JTRS). In theory, open architectures permit adding functions as software applications without the need to change hardware, promoting competition on the function or waveform as long as the hardware and software interfaces are clearly defined. But, because standards don't exist, hardware and software interfaces and protocols are left to the individual contractors. Thus, the customer may not achieve modularity between platforms and be saddled with proprietary systems.

When the Navy asks industry to respond to a stated modularity need without clear guidance, companies will look first to their internal products. Company objectives are to maximize their particular modular approach across as many of their own platforms as possible and achieve economies of scale for price competitiveness. Although this is not necessarily an inadequate response to a modularity need for a platform, it may come with company proprietary limitations. From a DoN perspective of looking horizontally across many different platforms, a single company's modularity approach may not produce the desired DoN product with its particular performance, size, or other commonality characteristics.

This page intentionally left blank

International Findings

- Global Market Drives Business Behavior

- Effective Joint Government-Industry Collaborations
    - Naval Team Denmark

- European defense products reviewed incorporate more modularity than U.S.
    - Systems Engineering used to determine type and degree of modularity

Naval Research Advisory Committee
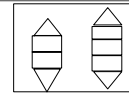
International Findings

The Panel's interactions with overseas firms; selected because they achieved some desirable goals through modularity; illustrated the potential impact of a constrained acquisition environment in motivating systems engineering and modularity. The Panel recognized that operational commitments, capabilities achieved, and government–industry relations differ considerably in Europe from the United States. The Europeans have embraced and engineered modularity to their benefit in a constrained environment. The United States may face different constraints, but it is likely that a systems engineering process similar to that employed by the European companies would help the U.S. face those constraints with similar or greater success.

First, the European governments procure for their domestic use smaller numbers of systems than U.S. defense contractors, therefore, requiring access to a global export market to achieve economies of scale and amortize costs of non-recurrent engineering. Modularity plays an important role in allowing the delivery of customized products that, for the importing customer, are both valuable and affordable. Further, the need to access non-domestic markets encourages more flexibility in business behavior (such as partnerships, joint ventures, consortia, and open architectures) than has been common among United States defense contractors.

Second, the Panel observed that the Europeans have employed government-industry collaborations successfully: to facilitate the systems engineering process, to help define and articulate interface standards, and to socialize procurement approaches. Naval Team Denmark represents an outstanding example of government leadership of a collaborative systems engineering process that met Danish Navy needs within a constrained environment. The Danish government-industry collaboration, also, did not interfere with the integrity of the competitive procurement process.

The Panel emphasizes that the European examples show strong systems engineering and a clear understanding of underlying motivations behind their employment of modularity. The Panel did not see modularity pursued as a purely aesthetic or stylistic approach.

International Findings

Specific Examples	Primary Motivation	Approach
HDW / small submarines (*Construction Modularity*)	• Custom offerings to diverse market (design reuse) • Construction efficiency	• Modular hull sections • Optional capabilities

Naval Research Advisory Committee

International Findings (2)

The Panel's fact-finding sessions with international industry representatives indicated, in general, a more open embrace of modularity than their U.S. defense industry counterparts. The Panel observed examples of each of the four types of modularity discussed earlier.

Howaldtswerke-Deutsche Werft (HDW) of Germany aggressively employs construction/design modularity to customize their submarines in order to appeal to a diverse market. This customization, enabled by the use of modularity, allows customers to select from various options when specifying systems. As a result, HDW sells submarines to a variety of nations and customers.

This page intentionally left blank

NRAC

International Findings

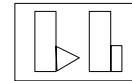| Specific Examples	Primary Motivation	Approach
HDW / small submarines (*Construction Modularity*)	• Custom offerings to diverse market (design reuse) • Construction efficiency	• Modular hull sections • Optional capabilities
Naval Team Denmark / Stanflex (*Mission Pkg Modularity*)	• Mission reconfiguration • Increased readiness	• System-level mission packages

ASW   COMBAT   SURVEILLANCE

POLLUTION CONTROL   MINE COUNTER MEASURE   MINELAYER

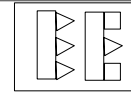Naval Research Advisory Committee

International Findings (3)

The Stanflex family of small vessels, developed under Danish government leadership by Naval Team Denmark, demonstrates the implementation of capability-swapping modularity. This approach was guided by the Danish Navy's need to meet a variety of operational commitments, some distinctly non-military, with a very limited number of platforms. Through careful systems engineering, they met their planned commitments by developing interchangeable mission modules with standardized interfaces for power, hotel plant, and data.

A collateral benefit of the Stanflex system-of-systems has been increased readiness, since the combat systems within the architecture can be maintained and tested ashore. The approach also simplifies training of both operators and maintenance technicians. Rapid reconfiguration of naval vessels--within a few hours--is possible with minimal shore-side infrastructure, suggesting forward area reconfiguration is eminently practical.

The Stanflex system has been sufficiently successful that it has been extended, essentially unchanged, to the next generation of substantially larger offshore patrol vessels and frigate-class flexible support ships. Notwithstanding different drivers, the Panel feels that the Stanflex effort is a best-of-class example that is significantly relevant to the U.S. LCS program.

This page intentionally left blank

International Findings

Specific Examples	Primary Motivation	Approach
HDW / small submarines (*Construction Modularity*)	• Custom offerings to diverse market (design reuse) • Construction efficiency	• Modular hull sections • Optional Capabilities
Naval Team Denmark / Stanflex (*Mission Pkg Modularity*)	• Mission reconfiguration • Increased readiness	• System-level mission packages
Thales / TACTICOS TERMA / T-Core ® Thales / UBMS (*Bus Modularity*)	• Capability upgrades • Enable market penetration • Design reuse • Scalability	• Open Architecture infrastructure

Naval Research Advisory Committee

International Findings (4)

The Panel observed several examples of bus modularity in European programs. Those examples reflected several diverse driving factors or motivations. One motivation was to enable straightforward capability upgrading by allowing software modules to be changed as required. Another driving factor was the ability to reuse either internal or third party applications. This approach enabled customers or other developers to add sensitive or proprietary modules, even while interacting with the rest of the systems through standard interfaces.

Additionally, several of these architectures were scalable, thus able to support requirements from a variety of potential customers. This scalability was facilitated by the implementation of an open architecture. Taken together, these factors permitted additional global market penetration by the companies that adopted them.

This page intentionally left blank

International Findings

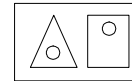| Specific Examples	Primary Motivation	Approach
HDW / small submarines (*Construction Modularity*)	• Custom offerings to diverse market (design reuse) • Construction efficiency	• Modular hull sections • Option capabilities
Naval Team Denmark / Stanflex (*Mission Pkg Modularity*)	• Mission reconfiguration • Increased readiness	• System-level mission packages
Thales / TACTICOS TERMA / T-Core ® Thales / UBMS (*Bus Modularity*)	• Capability upgrades • Enable market penetration • Design reuse • Scalability	• Open Architecture infrastructure
Thales / Sea Guardian (*Component Modularity*)	• Fixed & mobile implementations	• Sensor subsystem modularity • Integration at combat system level

International Findings (5)

The Thales Sea Guardian swimmer-detection system represents an example of component modularity. An integrated port security system with extensible geographic coverage, a forward deployed own-ship protection system, or a mobile search system can be implemented with modular mirror sonar elements. Components were designed with the intent of becoming elements in a much larger adaptable, modular system.

This page intentionally left blank

Systems Engineering Findings

- **Processes -** poorly defined, inconsistently implemented

- **System Engineers** - significant deficiencies in numbers, education and experience – Government & Defense Industry

- **No horizontal integration** - Systems engineering, when performed, at platform/program level and stove-piped

- **Systems engineering tools** - no comprehensive, standard set

- **S&T** - decoupled from systems engineering enterprise

- **NPS** - has systems engineering curriculum, performs military oriented systems engineering studies; Navy needs more thoughtful process to determine future assignments of graduates

Naval Research Advisory Committee

Systems Engineering Findings

Processes: The Panel found that approaches to robust systems engineering and analysis were incomplete, due to poor definition, lack of understanding, and inconsistent application of the elements of systems engineering and systems analysis.

Systems Engineers: The Panel found that within the Navy and the contractor base, clear evidence of an erosion in the number of the systems engineers existed. It determined that the undergraduate and graduate-level engineering curricula were not adequate in providing the tools needed by students to address the broad horizontal problems of net-centric horizontal system-of-system architectures.

No horizontal integration: The study team concluded that systems engineering and systems analysis, when performed, was carried out at a platform level only; thereby perpetuating the business-as-usual "stovepiped" results that do not cut across programs in a horizontal manner.

Systems-Engineering Tools: The Panel believes that robust system-of-systems tools are required to perform comprehensive systems engineering and systems analysis. That process must address the following priorities: (a) complexity of systems; (b) CONOPS; (c) joint forces integration and operations; (d) spiral technology development and insertion options; and, (e) autonomous and semi-autonomous systems.

A system-of-systems process also must consider a number of other factors, including interdependencies; interface requirements; trade-space explosion; MOEs, MOPs and trades; as well as uncertainty characterization and propagation. Other issues to be explored are the ability to respond to changing threats, effective developmental T&E planning, total cost of ownership, and human behavior in system performance.

S&T: The Panel found no evidence that the S&T community is integrated into the systems engineering enterprise at any level. The separation or decoupling occurred at the system and program level. The study found no interaction activities beyond the baseline of record, such as; planned spirals or other evolutionary activities of the future. There are also no coherent S&T activities planned or implemented to cut laterally across programs of record in any operational domain or individual Future Naval Capability (FNC).

NPS: While the Navy has begun to develop a Systems Engineering Curriculum at the NPS, it has not implemented a post graduation assignment policy or process to effectively capitalize on this resource. The Panel believes that the NPS curriculum is very much suited to helping solve the challenges identified by this study. Its graduates are ideally suited for assignment to the Navy organizations that could best employ their systems engineering education and experience.

- Limited information on DoD implementations of modularity
    - Critical military factors (e.g. mission flexibility, acquisition tradeoffs) not considered in modularity optimization
    - Some studies related to systems engineering and modularity to Navy ships
    - No formal DoD analysis with explicit focus on S&T for modularity and systems engineering

- Several recent articles and reports have explored *methodologies for design and evaluation of modular systems*
    - Some preliminary work defining degrees and types of modularity
    - Focus on *commercial applications*
    - More mature for software than hardware – but still largely heuristic

Naval Research Advisory Committee

Literature Survey Findings

The Panel carried out a search of professional literature accessible through the Defense Technical Information Center (DTIC) database and the Georgia Tech library databases in the areas of systems engineering, open systems architectures, and modularity. The study team paid special attention to the subject of modularity with respect to military systems.

The search revealed that software modularity is considered a more mature process than hardware modularity, with numerous opinions available on how to achieve it. The Software Engineering Institute (SEI) addresses configuration management, training, and certain format issues. Educational institutions also address different schemes for software modularity in their computer science curricula. Due to the time limitations, the search did not address software modularity specifically.

Extensive literature and textbooks are available on systems engineering, open systems architectures, and operational analysis. These topics have been combined with industrial systems engineering and logistics literature and are focused mainly on the commercial market and manufacturing. Significant data exists on the need for and setting of standards and agreement on interfaces.

The modularity of military systems, particularly ship capability-swapping, has been addressed in summary articles. The modularity of avionics systems for mission flexibility also has been addressed, but only at a high level. No formal DoD analysis was obtained that dealt with the S&T of modular systems.

The search findings indicated that the use of modular system design is increasing in commercial manufacturing, but provide no general agreement as to the proper methodology for implementation. The commercial driving functions are business based and generally

result from reuse of parts, logistics, and the selection of parts that require no corporate development. The Panel found that optimization models and methodologies are being developed that attempt to quantify the degree of system modularity. These efforts tend to be focused on manufacturability, connections, and component reuse of the product and are still preliminary.

A discussion of the driving functions or optimization criteria and methodologies necessary for developing modular military systems appear to be missing. Most commercial systems have short development and life cycles, relative to military systems. Consequently, commercial systems do not consider technology insertion, technology refresh, maintenance, and technology obsolescence in the optimization or quantification process to the extent needed in military systems.

Needed: Tools and Methodologies for Evaluating System Decompositions

- **Capture, represent, analyze** *multiple concurrent objectives*
- **Optimization for benefits**—*quantitative* or *qualitative*

"Minimize interface complexity for reconfig."

"Prepare for technical refresh"

"Prepare for technical refresh & ready for failure"

i   *j*   *k*

Utility(Partition *i*)=

f [cost$^\$$(refresh), cost$^\$$(interfaces), cost$^\$$(failure), cost^{avail}(failure), ...]
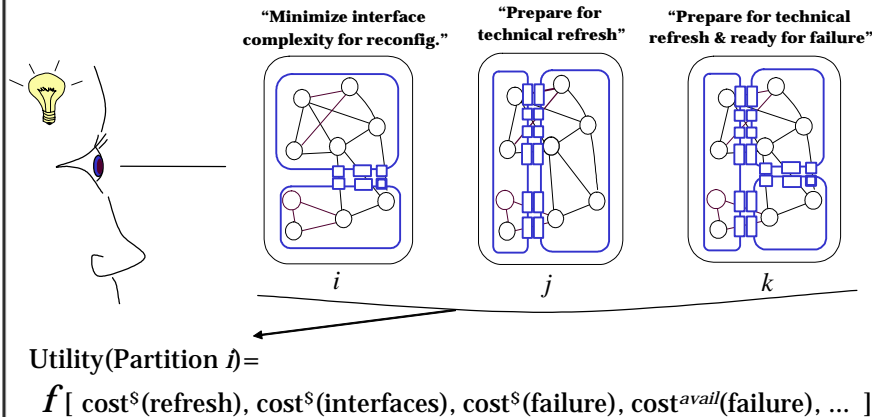
Naval Research Advisory Committee

Tools and Methodologies

From the literature survey, the Panel concluded that more study and work needs to be done in developing the tools and methodology for evaluating system decompositions.

Alternate decompositions of a system are often feasible, and can be valuable in considering the costs, benefits, and tradeoffs associated with different partitions of a system into modules and interfaces among modules. Decomposition of systems into sets of components and interfaces, in order to capture dependencies among components is still an art and may remain an art for the long term. However, the art of system decomposition can be supported and extended via insights derived from formal and/or informal optimizations of modularity, based on elucidating objectives and considering more global cost functions.

There has been preliminary work on reasoning about the goodness of alternate partitions of a system into a set of modules. Such work promises the development of tools and methodologies, including both qualitative approaches—aimed at assisting designers as they probe alternate decompositions so as to build insights—and more formal quantitative optimization methods. These tools and methodologies can be used to build insights about the value of alternative partitions.

Key functions of tools and methodologies supporting analysis of alternate partitions include: (1) the capture, in an explicit manner, of multiple objectives; (2) the construction of formal utility functions that identify the contributions to costs and benefits of different partitions, based on attribute configurations associated with the partitions; and (3) a method of representing and searching among different partitions, on whether the partitions are constructed manually, automatically, or through a process of mixed-initiative interaction, with input coming from both engineers and automated processes.

61

The slide on the previous page shows that the utility of the modularity yielded by a specific decomposition may depend on multiple factors. As shown, good modular designs must consider the overall utility associated with balancing the costs and benefits of various factors. Formal objective functions may be constructed that express the overall value or utility of a decomposition as a utility function, that takes as arguments the monetary and mission-centric costs of building, maintaining, and deploying a system.

With the use of a formal utility function, the contributions of multiple factors can be scaled to a uniform measure of value, such as dollars. Such an approach permits even non-monetary factors such as the unavailability of a component or system during a critical mission to be mapped to a dollar value. For example, in order to consider the merit of different partitions. Also, uncertainty in attributes or in cost can be considered explicitly with the assessment from data or from experts of probability distributions over these outcomes, and such probability distributions can be employed to generate expected values of alternate designs.

Summary Findings

- **Navy Programs** – implementation of modularity delegated to primes; no horizontal systems engineering

- **U.S. Defense Industry** – systems engineering and modularity not uniformly applied within programs

- **International industry** - ahead of the U.S. defense industry in judicious use of modularity

- **Systems Engineering** – systems engineering fundamental to implementing modularity but current practice inadequate

- **Literature Survey** – early work on methodologies for decomposition of systems

Naval Research Advisory Committee

Summary Findings

The Panel summarized the study findings in five areas: Navy programs, U.S. defense industry, international industry, systems engineering, and literature survey. It concluded that for Navy programs, implementation of modularity is delegated usually to prime contractors without adequate horizontal systems engineering analysis. This shortcoming highlights a structural issue with the current program-centric, or stove-piped systems acquisition process. Currently, modularity is being pursued only on a program-by-program basis, with little specific guidance on what modularity is, and how or why it is to be used.

No mechanism in the Navy ensures that modularity is focused across programs to the overall benefit of the Navy. Individual programs do not have the charter or ability to do so, and prime contractors are only able to work across programs within "their own house." System-of-systems concepts will continue to suffer unless this issue is addressed.

The Panel concluded, that within the U.S. defense industry, systems engineering and modularity are not uniformly applied within programs. Panel members observed that virtually all companies embraced the concepts of modularity and systems engineering, but understanding and implementations of these concepts varied widely. Because of the absence of uniform Navy guidance and definitions, each program had established de facto operating definitions and guidance.

Systems developed using the four categories of modularity (defined by the Panel) will not necessarily be interoperable or mutually compatible. The missing ingredient is systems engineering at the system-of-systems level, to ensure requirements have been traded and coordinated horizontally across programs to achieve interoperability.

In the international area, European companies examined were ahead of the U.S. defense industry in judicious use of modularity. This advantage appears to have been driven

by economics. The European programs have been forced by budgetary constraints into forming joint customer/contractor teaming and adopting specifically defined modularity concepts for cost avoidance or have done so in order to tailor products to a diversity of customers and missions. The Panel's observations did not extend to an assessment of operating effectiveness or functional suitability.

A key finding was that systems engineering is fundamental to implementing modularity. The Panel recommended that the Navy perform up front system-of-systems analysis and synthesis, which is currently either not done, or inadequately done.

Prime contractors typically have "in house" rules and definitions for systems engineering, but they typically do not consider cross-platform operations, unless specifically directed to do so. Furthermore, there appeared to be a shortage of appropriately qualified, experienced systems engineering staff within both DOD and the U.S. defense industry.

The Panel devoted considerable effort to a search of literature on modularity. The single most important finding of the literature search is that significant efforts currently are being initiated to address the issues of decomposition strategies/techniques and metrics for measuring the merits of various competing strategies. These efforts have a high potential payoff and would be an excellent area of focus and research for the Navy.

Recommendations

- ASN (RD&A), with VCNO and ACMC, take lead in *developing a Naval-wide System-of-Systems Engineering function* that follows a top-down, interactive, and recursive system synthesis & analysis process to define requirements.

- CNO & CMC *identify driving factors* for modularity and develop Naval policy and guidance for implementing modularity.

- CNR *lead as technology change agent* for (1) development of methodologies for understanding complex systems, enabling modular design; (2) experimentation with modular systems to support acquisition spirals (starting with LCS); (3) development of M&S tools to enable system of systems engineering analysis; and (4) development of advanced concepts & tools for software optimization & re-use.

Recommendations

The Panel found that effective modularity in naval systems must be derived from a system-of-systems level analysis cognizant of operational and business drivers, technology, deployment, and life-cycle issues. The Panel concluded that many Navy and DoD programs are at an early enough stage to benefit from this type of cross-cutting analysis and engineering. The study members found early stage research suggesting that modularity can be derived from a rigorous analysis methods and explicit optimization. Accordingly, the study recommendations address the Navy leadership at several levels.

First, the current acquisition structure makes it difficult to implement cross-cutting, horizontal systems engineering and analysis across program lines. The Panel urged the Vice CNO, the Assistant Commandant of the Marine Corps (CMC), and the ASN (RD&A) to direct the development of a naval-wide, system-of-systems engineering function to enable a broader perspective than that acceptable for a single acquisition program. This approach also could empower a capabilities based perspective rather than platform-based view in the development of future warfighting requirements and systems.

The Panel discussed several possible organizational alignments of such a function, but did not reach a consensus. Support from the senior naval leadership is essential for such a systems engineering function to gain traction and enable truly transformational warfighting capability. It is therefore most appropriately placed where the naval leadership can ensure empowerment.

Secondly, the Panel concluded that effective modularity only results from a clear understanding of motivating factors. Different types and degrees of modularity result from different motivations. For example, if the primary driver of the Navy's future warfighting capability is total-cost of ownership in a highly uncertain threat environment, the resulting modular systems likely will be somewhat different than if the primary driver was the ability

to leverage commercial technology development. It is critical that the driving factors for systems engineering that support modular decomposition of acquisition programs are clearly articulated, universally understood, and accurately specified. The Panel felt that this policy guidance should come from the CNO/CMC level.

Lastly, the technology for optimizing module selection is potentially rich, but still immature. The Panel recommended that the CNR serve as a change agent and focus on the tools that would enable optimal decomposition of systems and selection of modules. Additional technology is required to support cross-cutting systems engineering analysis, specifically top-level modeling and simulation tools. There is also a need for development of advanced concepts and tools that enable software reuse. Finally, the Panel endorsed the use of experimentation and innovative prototypes to develop and test modularity concepts and to support spiral development.
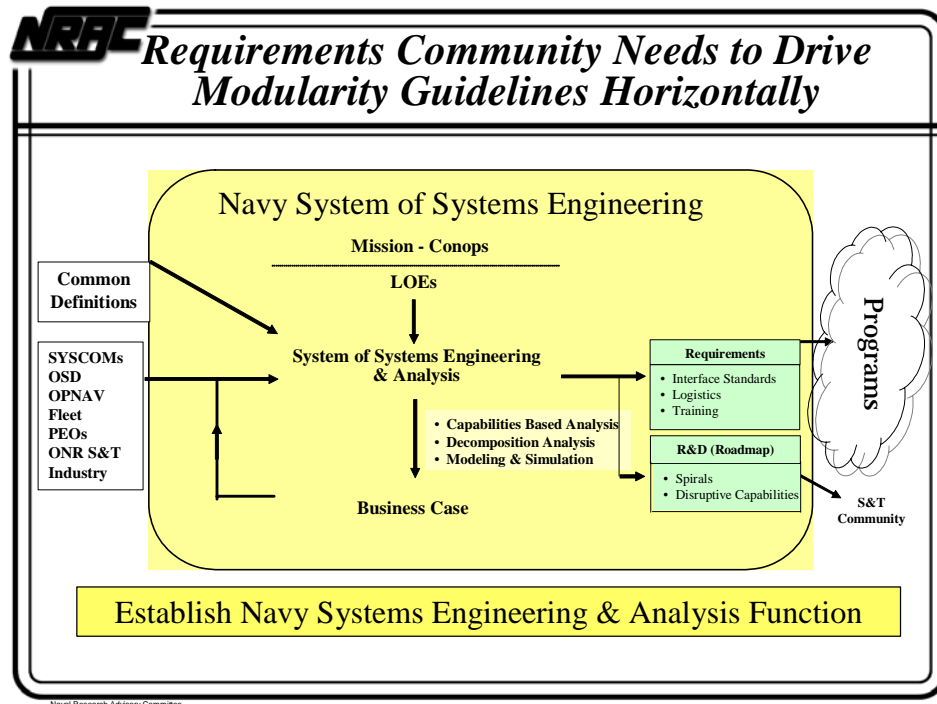
Modularity Guidelines

The slide above defines the Panel's version of a naval-wide systems-of-systems engineering and analysis function. Such a function would receive input from all of the leadership and acquisition entities (OSD, Navy Secretariat, fleet, OPNAV, and the acquisition community), analyze these inputs, carry out tradeoff studies, develop a gap analysis of current programs of record, and give direction that could shape FNCs and influence naval R&D investment. This function should rely on systems engineering and analysis, using structured methods and tools, across the entire spectrum of naval programs to ensure that future guidance is compatible with naval mission needs and modularity drivers.

This page intentionally left blank

Conclusions

The time is right to harvest value from modularity through disciplined Systems Engineering

Implementing System of Systems Engineering and adopting modularity effectively can result in:

• Flexible and interoperable warfighting systems that can better address an uncertain future

• Ability to cope with limited resources

Naval Research Advisory Committee

Conclusions

The study looked at a comprehensive range of data and perspectives on the value of modular designs for Navy acquisition programs. The Panel concluded an undeniable value in modular approaches, as demonstrated in the international arena, and for several major Navy programs. However, the Panel emphasizes that, depending on the findings of a meticulous systems engineering assessment of drivers and tradeoffs, modular design may not be necessary or appropriate for some types of systems.

The value of modular design is shown to pay clear dividends for advanced systems that incorporate commercial components and subsystems, as commercial vendors move decisively towards modularity. The value of a modular approach for the LCS, SSGN, and ARCI programs is indisputable, in terms of enhancing interoperability and supportability, while cutting costs—all critical priorities for today's Navy. The benefits of construction modularity have been validated extensively in ship and aircraft construction.

The in-depth explorations that support the Panel's findings showed the clear impact of modular design for platforms, weapon systems, and subsystems. Nevertheless, the study also revealed that the Navy has not established the policy and direction that are essential to guide acquisition managers to consider the value of modular design for their programs and implement consistent modularity principles. For that reason, the Panel urges naval leadership at the highest levels, within the Secretariat and the operational, acquisition, and the S&T communities, to adopt the study's recommendations and establish that policy and that direction, as they seek to preserve and extend the capabilities of the fleet for a new century in the midst of increased resource pressures.

This page intentionally left blank

Appendix A

Terms of Reference
S&T for Modular Systems

Objective

To review and assess the relationship of Science & Technology (S&T) to modular systems acquisitions, systems engineering, open architectures and spiral development and make recommendations for improving these relationships where appropriate.

Background

New systems are being developed using open system architectures and modular constructs that allow for "flexible mission modules", spiral development enhancements as technologies mature, and interoperability in net-centric systems of systems. Examples include LCS, MMA, BAMS, SSGN, DD(X), F-35, JTRS and X-Craft. Robust systems engineering practices will be key to the success of these efforts.

Minimal work has been done to investigate whether S&T programs, with potential application to multiple types of systems and mission packages, can or should be planned in conjunction with acquisition systems engineering. There could be high payoffs if advanced capabilities could be developed in S&T with a "modular" vision. Payoffs could be realized in terms of faster transition, lower development costs, economies of scale for production, reduced logistic support costs, and decreased training requirements.

If systems engineering analysis is done at the early stages of concept development with the involvement of the S&T community, the needs of future mission modules and spiral upgrades can be used to guide S&T investments. This may require a more structured type of interaction between the S&T and acquisition communities than currently exists.

Specific Taskings

This study will specifically address the linkage between the S&T community and modular system developments.

- Review and assess Navy systems engineering efforts on programs of record and the extent to which modular open systems and provisions for spiral upgrades and S&T are factors in the requirements definition and acquisition processes.

- Identify candidate high-payoff S&T areas for modular development and horizontal integration; and assess the opportunities for S&T engagement with systems engineering efforts.

- Where appropriate, recommend guidelines for structuring modular S&T initiatives that would enable utilization of results in multiple platforms/missions packages.

- Recommend changes required to improve the interface between Navy's S&T planning and acquisition processes.

Appendix B
Acronyms

ACAT   Acquisition Category
ACS   Aerial Common Sensor
ARCI   Acoustic Rapid (COTS) Insertion
ASN (RD&A)   Assistant Secretary of the Navy (Research, Development and Acquisition
BAMS   Broad Area Maritime Surveillance
CMC   Commandant of the Marine Corps
CNO   Chief of Naval Operations
CONOPS   Concepts of Operation
COTS   Commercial of-the-Shelf
CPU   Central Processing Unit
CRD   Concept Requirements Document
DASN   Deputy Assistant Secretary of the Navy
DOD   Department of Defense
DoN   Department of the Navy
DT   Development Testing
DTIC   Defence Technical Information Center
FNC   Future Naval Capability
HDW   Howaldtserke-Deutsche Werft
HSV   High Speed Vessel
IDS   Integrated Deepwater Systems
JTRS   Joint Tactical Radio System
J-UCAS   Joint Unmanned Combat Air System
LCS   Littoral Combat Ship
LMW   Littoral Mine Warfare
MIT   Massachusetts Institute of Technology
MMA   Multi-Mission Aircraft
MOE   Measure of Effectiveness
MOP   Measure of Performance
MOSA   Modular Open Systems Architectures
MOU   Memorandum of Understanding
NAVSEA   Naval Sea Systems Command
NMT   Navy Multi-Band Terminal
NPS   Naval Post Graduate School
NRAC   Naval Research Advisory Committee
ONR   Office of Naval Research
OSD   Office of the Secretary of Defense
OSJTF   Open Systems Joint Task Force
OT   Operational Testing
PEO   Program Executive Officer
PM   Program Manager
POM   Program Objective Memorandum
RDT&E   Research, Development, Test & Evaluation

RF	Radio Frequency
S&T	Science & Technology
SEI	Software Engineering Institute
T&E	Test and Evaluation
TOR	Terms of Reference
UUV	Unmanned Underwater Vehicle