NPS-AM-09-044

EXCERPT FROM THE PROCEEDINGS

OF THE

SIXTH ANNUAL ACQUISITION RESEARCH SYMPOSIUM

SUPPLY CHAIN PLANNING WITH INCREMENTAL DEVELOPMENT, MODULAR DESIGN, AND EVOLUTIONARY UPDATES

Published: 22 April 2009

by

Marie E. Bussiere, Betty C. Jester and Manbir Sodhi

6th Annual Acquisition Research Symposium of the Naval Postgraduate School:

Volume II: Defense Acquisition in Transition

May 13-14, 2009

Prepared for: Naval Postgraduate School, Monterey, California 93943

The research presented at the symposium was supported by the Acquisition Chair of the Graduate School of Business & Public Policy at the Naval Postgraduate School.

To request Defense Acquisition Research or to become a research sponsor, please contact:

NPS Acquisition Research Program
Attn: James B. Greene, RADM, USN, (Ret)
Acquisition Chair
Graduate School of Business and Public Policy
Naval Postgraduate School
555 Dyer Road, Room 332
Monterey, CA 93943-5103
Tel: (831) 656-2092
Fax: (831) 656-2253
E-mail: jbgreene@nps.edu

Copies of the Acquisition Sponsored Research Reports may be printed from our website www.acquisitionresearch.org

Conference Website:
www.researchsymposium.org

Proceedings of the Annual Acquisition Research Program

The following article is taken as an excerpt from the proceedings of the annual Acquisition Research Program. This annual event showcases the research projects funded through the Acquisition Research Program at the Graduate School of Business and Public Policy at the Naval Postgraduate School. Featuring keynote speakers, plenary panels, multiple panel sessions, a student research poster show and social events, the Annual Acquisition Research Symposium offers a candid environment where high-ranking Department of Defense (DoD) officials, industry officials, accomplished faculty and military students are encouraged to collaborate on finding applicable solutions to the challenges facing acquisition policies and processes within the DoD today. By jointly and publicly questioning the norms of industry and academia, the resulting research benefits from myriad perspectives and collaborations which can identify better solutions and practices in acquisition, contract, financial, logistics and program management.

For further information regarding the Acquisition Research Program, electronic copies of additional research, or to learn more about becoming a sponsor, please visit our program website at:

www.acquistionresearch.org

For further information on or to register for the next Acquisition Research Symposium during the third week of May, please visit our conference website at:

www.researchsymposium.org

THIS PAGE INTENTIONALLY LEFT BLANK

Supply Chain Planning with Incremental Development, Modular Design, and Evolutionary Updates

Presenter: Marie E. Bussiere is employed by the Naval Undersea Warfare Center (NUWC) Division, Newport. She is a graduate of the University of Rhode Island, where she earned a Bachelor of Science degree in Electrical Engineering. Bussiere also earned a Master's of Business Administration from Salve Regina University and received a diploma from the Naval War College for coursework in the areas of Strategy and Policy, National Security Decision Making, and Joint Maritime Operations. She is currently the Head of the Undersea Weapons Acquisition and Life Cycle Engineering Division in NUWC Division Newport's Torpedo Systems Department. Bussiere is responsible for Torpedo Test Equipment; Propulsion and Mechanical Systems; Production, Logistics, and Quality Assurance; and Fleet Engineering Support.

Marie Bussiere
1176 Howell Street
Code 811, Building 148/1
Newport, Rhode Island 02841
Phone: 401-832-1420
Fax: 401-832-4194
Email: marie.bussiere@navy.mil

Presenter: Betty C. Jester is employed by the Naval Undersea Warfare Center (NUWC) Division, Newport. She has extensive experience in torpedo systems, having worked on torpedo programs since graduating from the University of Rhode Island with a Bachelor of Science degree in Electronic Computer Engineering. Jester also earned a Master's of Business Administration from Salve Regina University. She derives her technical expertise from working on all aspects of torpedo lifecycle development, from requirements definition through development and test, production and support, and maintenance for both lightweight and heavyweight torpedoes. Jester is currently the Technical Program Manager for Torpedo Production.

Betty Jester
1176 Howell Street
Code 8191, Building 990/3
Newport, Rhode Island 02841
Phone: 401-832-2303
Fax: 401-832-6859
Email: betty.jester@navy.mil

Presenter: Dr. Manbir Sodhi is a Professor of Systems and Industrial Engineering in the Department of Mechanical, Industrial and Systems Engineering at the University of Rhode Island. He obtained his graduate degrees from the University of Arizona and has taught courses in Systems Design, Systems Simulation, Deterministic and Stochastic Optimization, etc. In addition to consulting for several companies, he has also worked as a visiting scientist at the Naval Undersea Warfare Center (NUWC) Division, Newport and at the NATO Undersea Research Center in La Spezia, Italy. His recent work has appeared in professional journals such as the *Journal of Scheduling*, *International Journal of Production Research*, and *IIE Transactions*. He is currently exploring decision models that support supply-chain planning in defense operations and is developing tools and concepts of operations for the use of unmanned undersea vehicles (UUVs) for a variety of search operations.

Dr. Manbir Sodhi
2 East Alumni Drive
Industrial and Systems Engineering
University of Rhode Island

Kingston, RI 02881
Phone: 401-874-5189
Fax: 401-874-5540
Email: sodhi@egr.uri.edu

Abstract

The policy specified by *DoDI 5000.02* (DoD, 2008, December 8) prescribes an evolutionary acquisition strategy. Products with long lifecycles such as torpedoes, evolutionary updates via incremental development, modular design updates, technology refreshes, technology insertions, and Advanced Processor Builds are all in play at the same time. Various functional elements of the weapon system are often redesigned during the lifecycle to meet evolving requirements. Component obsolescence and failures must also be anticipated and addressed in upgrade planning. Within each weapon system's evolutionary acquisition, cycle-changing requirements may expose weaknesses that have to be rectified across the inventory. New acquisition paradigms such as modular design have to be introduced into the supply chain while maintaining inventory levels of previously designed weapons at a high level of readiness. Thus, a diverse set of requirements must be satisfied with a finite set of resources. The acquisition policy does not provide guidance on how to address cross-coordination and optimization of project resources. This paper explores decision models for balancing conflicting demands and discusses the application of how these models address cross-coordination and optimization of project resources in the torpedo acquisition process while keeping the weapon's efficiency and inventory effectiveness at or above minimum specified levels.

Introduction

The policy specified by *DoDI 5000.02* (DoD, 2008, December 8) prescribes an evolutionary acquisition strategy. The Defense Acquisition Management System, as depicted in Figure 1, provides a framework in which to accomplish evolutionary updates in the Torpedo Enterprise. Evolutionary acquisition processes are deployed in the maintenance and upgrade of complex systems in an incremental manner to maximize the overall system efficiency and effectiveness. Technology-intensive products such as weapon systems are often redesigned during the lifecycle to meet changing requirements. Component obsolescence and failures must be anticipated and addressed in upgrade planning. Acquisition paradigms such as modular open systems approach (MOSA) are introduced while continuously maintaining unmodified inventory levels of previously designed weapons at a high level of readiness.

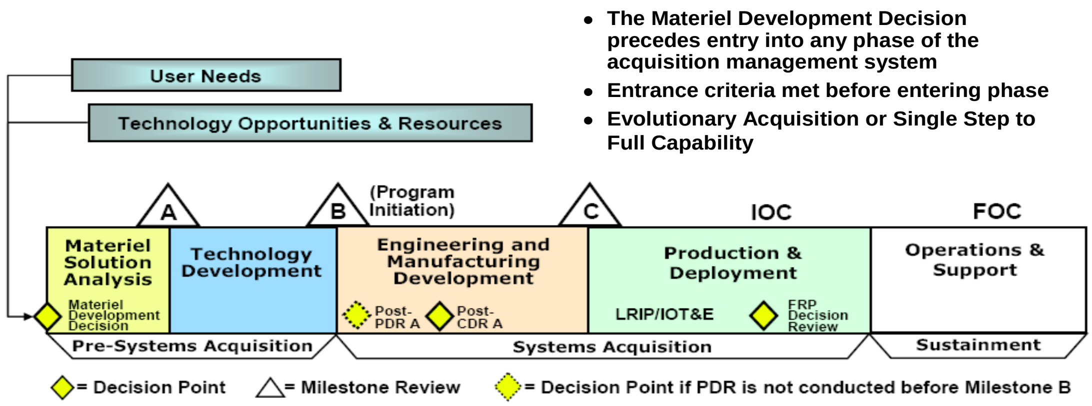

Figure 1. Overview of Defense Acquisition Management System

Prior to discussing how planning is conducted in the torpedo acquisition process, we define key terms used in the Torpedo Enterprise. These include evolutionary update, incremental development, modular design, technology refresh, technology insertion, Torpedo Modular Update, Advanced Processor Build, backwards compatible, lifecycle sustainment plan, weapon efficiency, and inventory effectiveness.

Evolutionary update: Planned or opportunistic updates to system hardware and software that address requirements relating to new customers, new technologies or innovations. Evolutionary updates can be fully implemented in a single step or implemented via an incremental development approach.

Incremental development: A development process in which hardware and/or software capability is delivered in increments, recognizing up front the need for future improvements. Each increment is a militarily useful and supportable operational capability. Each design increment goes through the entire design cycle of prototyping, testing, and release.

Modular design: A design in which hardware and software components are designed to be independently sustainable. The goal is for each module to stand on its own and interface to the required components via a standard set of Application Programming Interfaces (APIs).

Technology refresh: Planned obsolescence upgrades on existing product baselines. A technology refresh involves repairs/fixes/upgrades for existing components in an incremental manner.

Technology insertion (TI): Planned hardware capability upgrades either on existing or new product baselines. A technology insertion involves the introduction of new components that are functionally equal to or superior to existing components.

Torpedo Modular Update (TMU): An integrated/collaborative development, production and in-service approach to improve the overall effectiveness of torpedo inventories while addressing obsolescence issues and reducing Total Ownership Cost (TOC).

Advanced Processor Build (APB): Incremental software-capability improvement on either existing or new product baselines.

Backwards compatible: Hardware, technology refresh evolutions and software upgrades must be compatible with previous product baselines.

Lifecycle sustainment plan: The ability to maintain the product from the time that the user receives it to the time the product is disposed of.

Weapon efficiency: Weapon or torpedo efficiency is equivalent to torpedo effectiveness (T_{eff}). (This is not the weapon system's effectiveness but only that of the torpedo itself.) Torpedo effectiveness (T_{eff}) can be defined as the probability that all elements of the torpedo will work correctly after it is successfully launched and deployed in a manner that affords the torpedo an opportunity to detect a target that is acoustically and dynamically within the design capabilities of the torpedo. For a 100% reliable torpedo, all the subsystems of the torpedo (i.e., propulsion, guidance, detection, homing, and warhead) will function successfully until target destruction.

Inventory effectiveness: Inventory effectiveness is a gauge of how successful our inventory of torpedoes will be in eliminating a defined set of specific threat targets given precise operational scenarios. The threat target would be a class of submarines with a defined, acoustic signature/dynamic operational capability, operating with or without countermeasures. The operational scenario would be defined as the ocean environment in which the threat targets would be operating (i.e., shallow water, high sea states, specific world locations, and under ice). Given that the defined threat and the operating scenario are known, the number of torpedoes needed to eliminate the set of target threats can be calculated via simulation exercises. These exercises will give an indication of how effective our torpedo inventory is in eliminating the given threat under various environments. Such exercises establish torpedo inventory requirements. As torpedoes become more effective (T_{eff}), their ability to counter the enemy threat in all given conditions becomes greater, and the inventory levels required can be reduced with confidence.

For weapons or products with long lifecycles such as torpedoes, evolutionary updates via incremental development, modular design updates, technology refreshes, technology insertions, and Advanced Processor Builds are all in play at the same time. A wide-ranging and extensive set of requirements must be satisfied with a finite set of resources. The goal of keeping the weapon's efficiency and inventory effectiveness at or above minimum specified levels while optimizing program resources makes program planning very challenging. In this paper, we explore decision models for balancing these conflicting demands.

Historical Background

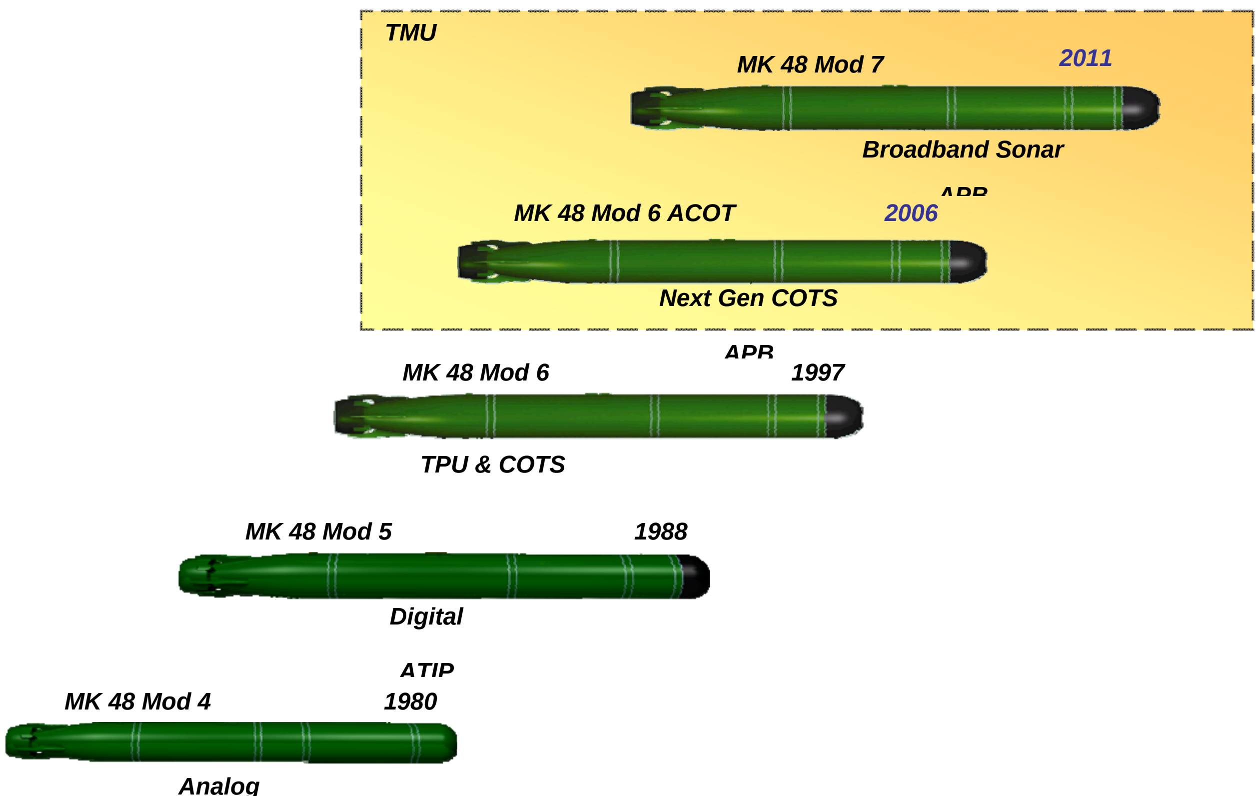

Figure 2. Torpedo Evolution

Since the Fleet introduction of the Torpedo MARK (Mk) 48 Modification (MOD) 4 in December 1980, the basic Torpedo Mk 48 has undergone several modifications. The torpedo evolution is shown in Figure 2. The most recent upgrade to the Fleet Torpedo Mk 48 occurred in December of 2006 with introduction of the Torpedo Mk 48 Mod 7 version.

In the '70s, the surprise emergence of a very fast and very deep-diving Soviet SSN (Alpha type) presented the US Navy a challenge. The new threat speed exceeded the Doppler detection/tracking capabilities of the mostly analog-based Torpedo MK 48 Mod 3 electronics, and the postulated threat depth capability was beyond the Mod 3's original design capability. In response, the MK 48 Mod 4 Ordnance Alteration (ORDALT) was initiated in late 1979 to address these shortcomings, and the first MK 48 Mod 4 was provided to the Fleet in December 1980. The Torpedo Mk 48 Mod 4 was gradually replaced by the upgraded versions of the Torpedo Mk 48, and in March 2008, the last Torpedo Mk 48 Mod 4 was withdrawn from the last US Navy submarine.

In parallel, the MK 48 Mod 5 Advanced Capability (ADCAP) heavyweight torpedo was designed in the early 1980s as a modular weapon based on a state-of-the-art, multi-beam, low-noise acoustic sensor array with very low self-noise. To counter the emergence of Soviet high-speed and deep-diving SSNs, the Mod 5 employed a modified MK 48 Mod 4 propulsion system that fully exploited the design margin in the engine and allowed operation at higher horsepower. The Mk 48 Mod 5 was introduced to the Fleet in August 1988.

With the end of the Cold War came the reduction in the Soviet's nuclear submarine fleet and the emerging growth of modern diesel-electric submarines; as a result, the US Navy began to give more serious attention to the development and proliferation of modern, very quiet, diesel-electric and air-independent propulsion submarines and advanced torpedo countermeasures in Rest-of-World (ROW) countries. In contrast to the Cold War, when Soviet submarines operated primarily in open-ocean *blue water*, these ROW diesel-electric submarines operated primarily in shallow, coastal, littoral waters where the environment presented a different, and more significant, set of challenges for acoustic torpedoes.

By the late 1990s, the concern that the next ASW operations might occur in the challenging *brown water* of the littorals against small, very quiet diesel-electric submarines prompted a review of the capabilities of US Navy torpedoes in shallow waters around the world. Testing confirmed that operation in the littoral presented problems to both the US submarine trying to detect and classify a threat and to the torpedo in effectively prosecuting an attack on that threat.

To fulfill this need, the Mk 48 ADCAP Torpedo Propulsion Upgrade (TPU) and the MODs Programs were initiated. This resulted in a program for the design of the Mk 48 Mod 6 torpedo. The MK 48 Mod 6 entered the Fleet in August 1997 at the Naval Submarine Base, New London, when USS Alexandria (SSN 757) loaded the first warshot MK 48 Mod 6 torpedoes.

In 2001, a partial redesign of the guidance hardware of the torpedo was undertaken to resolve critical parts obsolescence issues. In addition, the change incorporated component commonality with existing torpedoes for the guidance hardware. These changes, along with all future torpedo changes, were defined and developed as part of a newly implemented Advanced Processor Build (APB) process for the MK 48 and MK 54 torpedo programs. The APB process relied on rapid improvement in commercial off-the-shelf (COTS) advancements and was instituted to more rapidly field improved performance by finding the best-of-the-best sonar-signal processing algorithms from industry, academia, and Navy researchers and applying them to both lightweight and heavyweight torpedoes. Naval Undersea Warfare Center Division, Newport took on the APB leadership role to evaluate and integrate improved software and hardware capabilities into the torpedo inventory.

Although the Mk 48 Mod 6 upgrade addressed littoral operations, the fundamental challenge presented by these operations for active acoustic systems is the high levels of reverberation that often effectively mask low-target strength targets. One approach that mitigates this reverberation masking is using a broadband acoustic system that can take advantage of various waveforms and frequency diversity to discriminate target returns from the background reverberation.

In 1996, a concept-definition torpedo program was started in parallel with the Mk 48 Mod 6 upgrade. This torpedo configuration was referred to as the Torpedo Mk 48 Common Broadband Acoustic SONAR System (CBASS) and officially designated the Torpedo Mk 48 Mod 7. The CBASS program evolved as a result of concerns identified in reports that highlighted future vulnerabilities of US Navy torpedoes and noted that evolving threats will eventually reduce the effectiveness of the current torpedoes, Mk 48 Mod 5 and Mk 48 Mod 6. By employing a broadband sonar system and advanced broadband signal processing algorithms to enhance the detection and prosecution of threats, the Mk 48 Mod 7 program implemented the necessary hardware modifications and advanced software algorithms required to sustain undersea superiority well into the future.

The Mk 48 Mod 7 program was a two-phased evolutionary APB acquisition program. Phase I provided the enabling hardware required to support Phase II software enhancements. Phase I built upon current capabilities and introduced several guidance and control (G&C) performance enhancements, including new beam sets, narrow-band frequency agility, frequency selection, and enhanced target rejection tests. Phase I attained Initial Operating Capability (IOC) in FY06 with the preparation of four warshot Mk 48 Mod 7 torpedoes by a certified Fleet Intermediate Maintenance Activity (IMA). Phase II will incrementally improve, via the structured Torpedo Modular Upgrade (TMU) process, the sonar characteristics of the Mk 48 Mod 7 from a frequency-agile system to a fully coherent broadband system through three planned software APBs.

In April 2003, the United States of America and the Commonwealth of Australia signed an Armaments Cooperative Program (ACP) agreement for Mk 48 Mod 7 engineering and manufacturing development, production, and in-service support. Introduction of the Torpedo Mk 48 Mod 7 had a profound effect upon the Torpedo Enterprise both from a performance perspective and from an inventory management perspective. The overarching plan will convert the entire Mk 48 ADCAP inventory to the Mk 48 Mod 7 configuration through a cost-effective and controlled conversion program via an engineering change to the Mk 48 Mod 5, Mk 48 Mod 6, and the Mk 48 Mod 6 Advanced Common Torpedo (ACOT). The Mk 48 Mod 7 Full Operational Capability (FOC) is scheduled for FY11.

The Torpedo Acquisition Process

As noted in the historical background, torpedo evolution is a continuous process, which can be driven not only by a series of detailed, long-range plans but also by exigencies that emerge as the long-range plans are being implemented. Torpedo evolution is typically incremental and evolutionary versus revolutionary in scope.

In response to shortfalls in undersea weapon capability, identified in the Joint Requirements Oversight Council (JROC), approved Initial Capabilities Document (ICD), CNO-N87 together with PEO (SUB) and PMS 404 have initiated analysis to identify the best technical approach to deliver the capability identified in the ICD. A Capabilities Development Document (CDD) is currently being worked on to describe the approach for a material solution needed to deliver the capability required to meet the operational performance criteria specified in the ICD. With approval of the CDD, the Milestone Decision Authority (MDA) will be able to initiate a development program.

Through an examination of undersea weapon technology available in the current technology base, a phased technology integration approach through incremental development and technology insertion has been defined. Technology from the Defense Advanced Research Projects Agency and the Office of Naval Research will be assessed in terms of potential to improve weapon capability through technological advances in areas such as guidance and control processing, fiber connectivity, sonar signal and classification processing, sensing systems, processor systems, and hybrid propulsion systems.

Technologies are grouped in bundles and aligned to each incremental phase based on compatibility with current and planned technology insertion baselines, technology maturity, and relevance to fielding the required capability as defined by the CDD. Technologies identified for transition into system development and demonstration baselines are acquired using the Small Business Innovative Research (SBIR) program, competitive contracts with industry, University Affiliated Research Centers (UARCs), federally funded research and development centers such as the Massachusetts Institute of Technology Lincoln Laboratory, and through annual task negotiation with the Naval Undersea Warfare Center. Material solutions to the capability needs defined in the ICD and further developed in the CDD follow the Torpedo Modular Upgrade/Advanced Processor Build (TMU/APB) process for transition in torpedo acquisition and delivery to the Fleet.

At the completion of each incremental development phase, a Capability Production Document (CPD) will be developed to describe the actual performance of the undersea weapon system going into production. The approved CPD becomes the basis for the MDA decision to begin production of hardware technology insertions and/or operational software.

The current torpedo evolutionary acquisition process presents a number of challenges and benefits to torpedo program managers during each phase of the acquisition lifecycle. Although various torpedo programs may require increased or decreased emphasis on specific acquisition-lifecycle elements, Figure 3 and the narrative below provide a description of the general flow of torpedo hardware acquisition activities within the Defense Acquisition Management Framework.

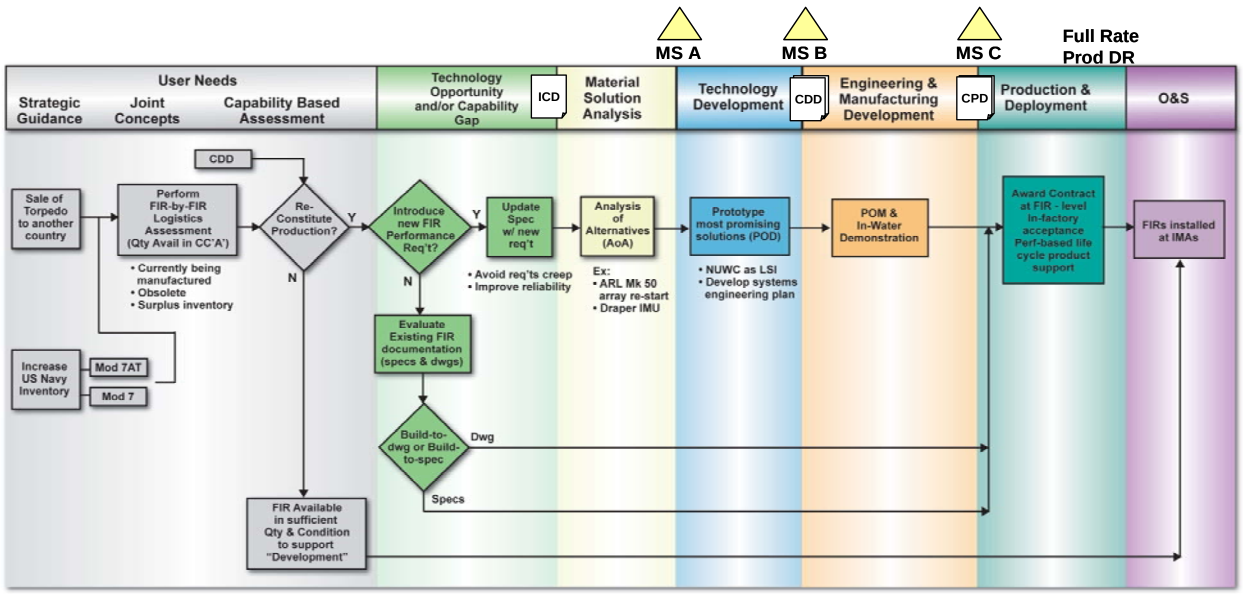

Figure 3. Acquisition Planning in the Torpedo Enterprise

User needs are the prime driver of the evolutionary acquisition process. From an operational perspective, user needs take the form of increased US Navy inventory requirements or the sale of torpedoes to other countries. The user demand signal triggers a logistics assessment at the lowest modular level of procurement. In the case of torpedoes, this is at the Functional Item Replacement, or FIR, level. This FIR-by-FIR logistics assessment provides insights into the availability of the required material and provides answers to such questions as:

1) Is there a surplus in current inventories to address the new user need? If there is a surplus, user needs can be satisfied by issuing the material to the Fleet for installation via the associated torpedo IMAs.

2) Are the needed items currently in production?

3) Are there any real or potential obsolescence issues which must be addressed via technology refresh?

4) Are there any near- or long-term program objectives or TIs planned that might impact the FIRs being considered for procurement? Torpedo near- and long-term program objectives are assessed via a continuous six-year Capability Development Document (CDD) generation process. The CDD forms the basis for formulation of a comprehensive Torpedo Technology Roadmap and subsequent focal point for a TMU/TI/APB program which addresses the full scope of future torpedo development and support initiatives. Feedback from the CDD/TMU/TI/APB and obsolescence assessments will contribute to the decision to either reconstitute production of the items or to perhaps merge the new user needs with a larger CDD/TMU/TI/APB effort and blend in the added quantities with ongoing redesign initiatives for the needed FIRs.

Once it is determined that the user needs can only be met by producing additional hardware, the information gathered relative to applicable obsolescence concerns and the CDD/TMU/TI status are used to determine if changes are needed to the affected FIR requirements. This assessment includes a review of reliability and availability factors to ensure that they are at acceptable levels before proceeding.

If no changes are needed to the FIR requirements, applicable and existing FIR documentation (i.e., specifications and standards) is reviewed and updated, if necessary, so that it can be utilized in a build-to-drawing or build-to-specification contract. The contract is awarded at the FIR level. An in-factory acceptance process and applicable performance-based lifecycle product support considerations are typically included in the contract.

If changes are needed to the FIR requirements, the applicable specifications are updated along with any necessary reliability/availability enhancements. The Defense Acquisition Management Framework is used as a guide to develop a set of specific acquisition-lifecycle elements that must be completed as the new FIR design proceeds through the various gates of the acquisition process. This process will vary with the scope of the FIR redesign being undertaken and will include at a minimum an analysis of alternatives, prototyping, Proof of Development (POD) and Proof of Manufacturing (POM) units, laboratory and in-water test and evaluation as well as modeling and simulation, if necessary. Once the upgraded design has been demonstrated as acceptable, a production contract will be competitively placed and hardware will be delivered to the Fleet IMA, following successful factory acceptance testing.

Torpedo software acquisition activities via the Torpedo APB program solicit inputs from the Science and Technology (S&T) community, including small businesses, as well as leveraging advancements from other undersea programs. It evaluates and selects the most promising solutions using common development and evaluation tools prior to implementation. Types of APB improvements include Signal Processing Algorithm Enhancements and Weapon Control Improvements. The Torpedo APB process for software enhancements is based on the existing and proven Submarine Acoustic APB four-step process:

1) Evaluation,
2) Assessment,
3) Implementation, and
4) System Assessment.

TMU/APB is embodied in three primary thrusts. First, obsolescence upgrades address production obsolescence and reduce total-ownership cost. Upgrades are planned every two years to leverage the APB cycle. Second, Advanced Processor Builds focus on software product to improve performance through increased effectiveness. Hardware compatibility is maintained within a technology insertion baseline. Third, hardware technology insertions are major hardware upgrades to enable further increase in torpedo effectiveness. Hardware technology insertions are accomplished at the inventory-maintenance due date.

Table 1. Torpedo Configurations

ACQUISITION PHASE

	"Technology Development" and "Engineering and Manufacturing Development" (RDT&E) Introduce New Capability	"Production and Deployment" (WPN) Build FIRs	"Operations and Sustainment" (OMN) Maintain the Inventory
Mod 6 baseline			• Sustainment "severe" obsolescence kit upgrade candidate • Reliability
Mod 6 ACOT			• Sustainment • Reliability • Maintenance s/w build
Mod 7 CBASS	• TMU Program • CBASS FOC (APB Spiral 4) • Develop New s/w algorithms (APB Spiral 5)	• CBASS Kit Production • Obsolescence • Open Architecture (APB Spiral 5)	• Sustainment • Reliability • Maintenance s/w build
Mod 8	• TMU Program • CDD requirements • Develop new h/w solutions (APB Spiral 6)		

Table 1 applies to torpedo lifecycle phases and various configurations of the active torpedo inventory, as described in the previous section. The information in this table shows the current activities that are occurring in each phase.

From the perspective of the "Technology Development" and "Engineering and Manufacturing Development" phases, the focus is on introduction of new capability. Introduction of new capability is tied to user requirements and transitioning technology developed by the Office of Naval Research (ONR). The CDD is currently being updated, and Tech Insertion 1 (new array ~ MK48 Mod 8) is being defined. The Enterprise is examining new CDD requirements and determining whether the existing capability of the MK48 Mod 7 CBASS can address any requirements gaps and whether the schedule for a new array is compatible. If so, then funding associated with the new array (Tech Insertion 1) could be re-programmed. From the software perspective, specific focus at this time is on delivery of an APB Spiral 4 software product, which provides the Full Operating Capability (FOC) for CBASS Mod 7. APB Spiral 5 software is currently being defined per the CDD.

From the perspective of the "Production and Deployment" phase, the government buys to a performance specification (government-controlled baseline). Also, the government awards annual production contracts and is prohibited from buying any material in advance of need (i.e., the torpedo program does not have multi-year procurement authority). Obsolescence issues with the current, contractor-controlled hardware design are discovered at contract-award on an annual basis. The extent of the obsolescence issues can result in reducing the quantity of kits procured. Furthermore, changing the design can result in unplanned software builds, which can also affect the quantity of kits procured. Reduction in kit quantity affects in-service supportability planning, particularly for the oldest torpedo configuration being supported since this configuration is the candidate pool for upgrade hardware coming off the production line. In addition, the Torpedo Enterprise is in the market-research phase of separating hardware/software interdependence via investment in Open-architecture solutions. Future upgrades in this area may necessitate changing the design and can result in further unplanned software builds.

As seen in Figure 4, from the perspective of the "Operations and Sustainment" phase, there is a fixed budget year-to-year, and the Torpedo Enterprise has three configurations in the Fleet that they are required to maintain: MK48 Mod 6 baseline, MK48 Mod 6 ACOT, and MK48 Mod 7 CBASS.

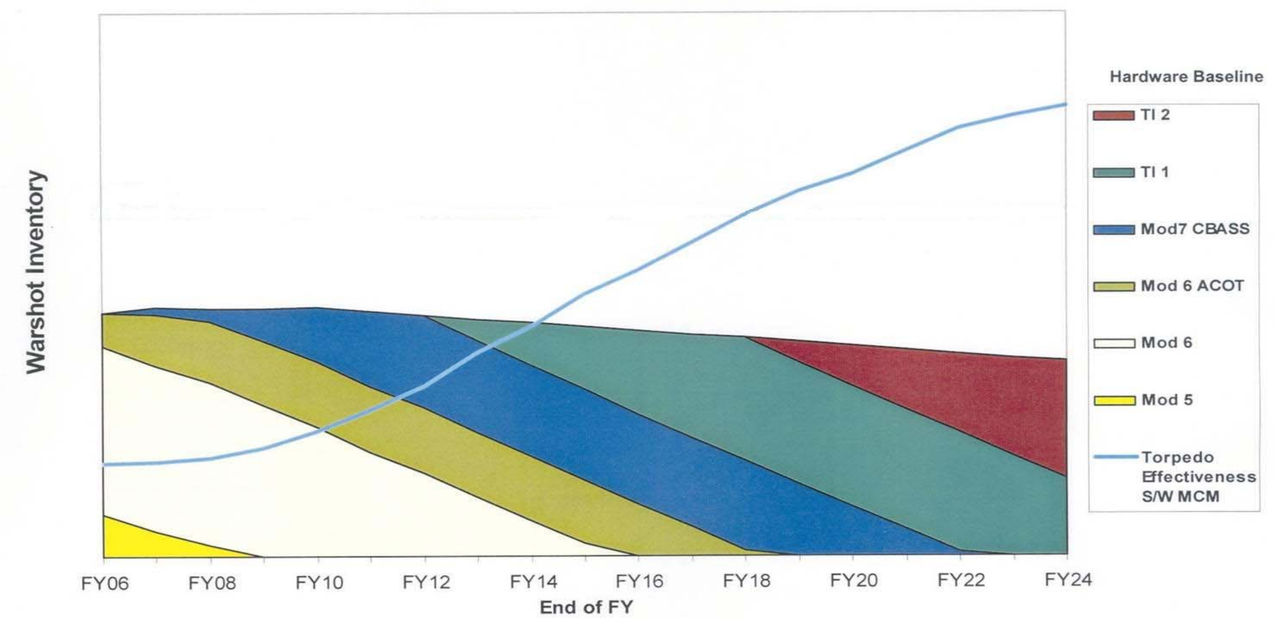

Figure 4. Planned Torpedo Configurations per Fiscal Year

The MK48 Mod 6 baseline configuration is faced with the most severe obsolescence impact and, therefore, the worst-case sustainment problem. These torpedoes are the candidate upgrade torpedoes (i.e., they will receive the resulting new production torpedo kits). The upgrade process creates spare parts for sustainment of the balance of the MK48 Mod 6 baseline inventory. Unexpected delays in receipt of production hardware for any reason mean that sustainment of this torpedo configuration is extended and is more costly than initially planned. Typically, software upgrade builds are not associated with the MK48 Mod 6 baseline configuration.

The MK48 Mod 6 ACOT configuration must be sustained since it comprises a large percentage of the inventory and will be in the inventory for many years. There may be high-priority software problems, which require unplanned maintenance builds that are not part of the APB process.

The MK48 Mod 7 CBASS configuration is just entering the "Sustainment" phase as CBASS units make their way from production to in-service. The supportability strategy is still evolving. Currently, all MK48 Mod 6 ACOT and MK48 Mod 7 CBASS torpedoes are produced by the same prime contractor. The Torpedo Enterprise FY09/10 procurement is competitive.

This could result in a different hardware baseline (the contractor controls the drawing baseline and the government controls the specification baseline). It remains to be seen what types of unplanned sustainment problems we will encounter with MK48 Mod 7 CBASS over its lifecycle.

Unplanned software builds for the MK48 Mod 6 ACOT or MK48 Mod 7 CBASS configurations divert resources from ongoing sustainment and reliability efforts, which are planned within the fixed budget.

Planning in the Torpedo Enterprise

In any given year, the program office has finite Research Development Test & Evaluation (RDT&E), Weapon Procurement, Navy (WPN), and Operations and Maintenance, Navy (OMN) budgets. The decisions to be made on how to expend these budgets are challenging. On a yearly basis, there is a torpedo production contract for some number of torpedo kits from the contractor. This raises several questions that must be answered. Is it possible to purchase the materials for the current design? If not, how extensive is this obsolescence problem? Is this just a matter of form, fit or functional replacement, or should effort be expended on the design of a new piece of hardware? Since the torpedo does not fully conform to a modular open system approach (MOSA), the implications of designing a new piece of hardware to meet a production contract are numerous and potentially expensive since a new software build will need to be synchronized with the hardware design. This will require careful planning as to where to introduce it into the program as well as resources to enable it to come to fruition. Another budget consideration is in the area of RDT&E, with respect to evolutionary acquisition of hardware and software. The Enterprise plans for technology insertions, and Advanced Processor Builds are in the forefront of the development community.

Unlike many other programs, the Torpedo Enterprise is not currently procuring new all-up-round torpedoes. At this time, FIRs are being procured to support upgrade of inventory quantities. The torpedo inventory is exercised in the Fleet, and torpedoes may become candidates for the upgrade pipeline based on budgets and “op-tempo” requirements. The torpedo has a number of FIRs and several specialized cable interconnects. Most mechanical and some other subassemblies are available in sufficient quantity and are maintained during routine turnaround periods. The persistent question is whether there are enough subassemblies on-hand to continue to keep up with current inventory requirements. If production is to be re-initiated, how will this be done? A decision to begin production of one or more FIRs is also an opportunity to consider upgrading other FIRs that may currently meet the needs but have not taken advantage of technological advances that could significantly increase capabilities.

Other complications may be introduced if the strategic guidance points to the sale of the torpedo to a foreign ally, or if there is a requirement to increase US inventory. A new torpedo variant may be produced with FIRS either off-the-shelf (existing designs), new (new production of an existing design) or newly designed. In addition to this complex combination of requirements is the desire to shift business models and move from a sole-source contract with a major industry partner to a competitive, cost-plus contract with potentially multiple industry partners for single FIRs.

Based on the challenges presented, it was decided that the Torpedo Enterprise would benefit from a decision model capable of balancing these conflicting demands while keeping the weapon’s efficiency and inventory effectiveness at or above minimum, specified levels. Typical scenarios and questions that face the decision-maker are listed below:

1. Given an incremental development strategy and a minimum system-effectiveness level, what budget do we need? Is it cost effective to maintain the current torpedo configurations?
2. Given that we know we have to plan for obsolescence and maintain inventory, which component, in which year, and in what quantity should we replace?

The system maintenance and upgrades are performed in cycles—each cycle focuses on technology insertions and refreshes for a set of components only. As is the case in real-world situations, there are budget and time constraints that limit the number of components that can be selected for upgrade as part of any cycle. The goal of the decision-maker is to identify the components for upgrade during each cycle, with the cycles being distributed over the lifetime of the system to ensure that some metric related to system performance is satisfied or maximized.

3. In the phase of "Operations and Sustainment," if an unplanned software build is required, what do we forgo in the area of reliability improvements and sustainment? If a downward trend in component reliability becomes apparent, what do we forgo in the area of software maintenance improvements and sustainment? Is unit quantity on the production contract impacted?
4. How should we allocate budgets between design upgrades and sustainment to maintain inventory at a minimum effectiveness level? If we progress to a modular design in the near-term, what budget becomes available for sustainment?
5. If we have fixed resource levels (other than budgets), what work can we accomplish given a minimum effectiveness requirement level?

Resource Optimization Modeling

A basic mathematical model for planning in the evolutionary acquisition process, as well as optimizing the budget required to maintain minimum system efficiency, is developed below. A single product efficiency maximizing model is first constructed. Given that the product is assumed to consist of N components, let the efficiency of component *i* in period *t* be denoted by f_{it}. The overall efficiency of the product is, for now, assumed to be a linear product of the efficiencies of all the constituent efficiencies. Thus, the efficiency in period *t* is:

$$S_t = \prod_{i}^{N} f_{it} \qquad (1)$$

Various definitions of efficiency and effectiveness can be used to obtain a measure like Equation 1. For example, one definition of efficiency is the competence in performance (Blanchard, 2003). With this definition, the efficiency of each component can be referenced against the current capability of an opposing technology threat. Thus, a typical torpedo component such as an IMU, which is capable of maintaining a specified precision that met the needs at design-time, may be considered to have a lower efficiency when placed in operation against a newly developed, opposing technology threat that requires greater precision to neutralize. Another definition of efficiency is the accomplishment of or the ability to accomplish a job with a minimum expenditure of time and effort—if the existing range and endurance of the weapon is not capable of meeting current threats under all conditions, this can be captured by a degraded performance/efficiency metric. A related concept that can be applied instead is that of effectiveness. Effectiveness is usually defined as the adequacy in accomplishing a purpose (Fabrycky & Blanchard, 1991).

If B_t is the budget available for upgrading the product in period *t*, a mathematical formulation for determining the optimal upgrade strategy for maximizing the minimum efficiency required can be constructed. For this, let the value of binary variable X_{it} determine whether or not a component is upgraded in period *t*. The formulation follows:

Maximize Minimize System Effectiveness = Z (2)

subject to:

$$Z \leq S_t \quad \forall t \tag{3}$$

$$S_t = \prod_{i}^{N} f_{it} \quad \forall t \tag{4}$$

$$f_{it} = \max\{X_{it}, f_{it} * f_{i(t-1)}\} \quad \forall i,t \tag{5}$$

$$\sum_{i=1}^{N} X_{it} * c_i \leq B \quad \forall t \tag{6}$$

$$X_{it} \in \{0,1\} \quad S_t \geq 0 \tag{7}$$

In this model, the objective function represents the minimim efficiency attained by the product over the planning horizon. This minimum obtains its value from Equation 3, where SE_t is the efficiency of the product in period *t*. Inequalities (Equation 4) compute the efficiency of the torpedo in each period as the product of efficiencies of the constituent components. Equation 5 sets the efficiency of a component by either degrading the efficiency of the same component in the previous period by a discount factor (assumed constant here) or, if the component has been renewed, the efficiency is set to 1. In Equation 6, the cost expended in each period is maintained within the budget for the period—in this case, this is assumed to be the same throughout. Finally, the binary variables and system-efficiency variables are appropriately designated in Equation 7.

As formulated above, this model is non-linear; however, it can be log-linearized. Using a log-linearized version, a hypothetical scenario is illustrated using parameters from Table 2.

Table 2. Parameters for a Log-linearized Version Model

Component	1	2	3	4	5	6
Replacement Cost (x1000)	$100	$50	$120	$50	$75	$120
Degradation Factor/yr	0.95	0.98	0.92	0.99	0.875	0.92

Table 2 shows the replacement cost of a component and the degradation factors that are applied to the component on an annual basis. Thus, if component 5 is not replaced for three years, its effective degradation factor is $(0.875)^3 = 0.67$, and if all components other than component 5 are renewed annually, the system efficiency in period 3 would be 0.67 as well.

Using this data, the optimal solutions for a 10-year horizon, obtained using the formulations given in Equations 2-7 and a continuous replacement budget of $250,000 per year, are shown in Table 3.

Table 3. Optimal Solutions for a 10-year Horizon with $250,000-per-year Replacement Budget

Period	Component Replacement						Expenditure	System Effectiveness
	1	2	3	4	5	6		
1	1	1	1	1	1	1	515	1.00
2			1			1	240	0.81
3	1	1			1		225	0.83
4			1			1	240	0.79
5	1	1			1		225	0.81
6			1			1	240	0.77
7	1			1	1		225	0.81
8		1			1	1	245	0.80
9			1	1	1		245	0.81
10		1			1	1	245	0.78

The minimum system efficiency attained over the planning horizon is 0.77 in year 6. The model above is a highly simplified version of what occurs in reality. Practical matters that require inclusion in any "real" solution should include a more realistic deterioration factor. The formula used here is an exponential representation that assumes a constant deterioration rate, regardless of the state of the system. In practice, the deterioration functions are substantially more complicated. For mechanical components, the deterioration changes with the age of the part in a non-linear manner. Some electronics components fail at a higher-than-normal rate during an initial "burn-in" period but subsequently stabilize and are then subject to "random" failures.

Returning to the operational questions posed in the previous section, the model presented above can be restructured to provide answers as detailed below.

1. **Given an incremental development strategy and a minimum system-effectiveness level, what budget do we need? Is it cost effective to maintain the current torpedo configurations?**

This question is immediately addressed by altering the basic model configuration of Equations 2-7 in the following manner. The objective is reconfigured as a cost function, say, Minimize $\sum_{t=1}^{T} Budget\ for\ period\ t$,

and the system effectiveness for each period is constrained to meet a minimum requirement, η. This gives the efficiency constraints as:

$$\eta \leq S_t \quad \forall t \tag{8}$$

The budget for each period is then included as a decision variable, and constraints (6) are dropped from the formulation.

Using the data from Table 3, if a minimum system effectiveness of 0.75 is required for any given year, the upgrade strategy and minimum budgets necessary for meeting this requirement, computed using the modified model, are calculated as shown in Table 4.

Table 4. Upgrade Strategy and Minimum Budget Requirements

Year	1	2	3	4	5	6	7	8	9	10
Budget $ (X1000)	515	75	295	240	220	295	220	175	195	195
Component Upgrades	All	5	1,3,5	3,6	2,4,6	1,5,6	2,3,4	1,5	5,6	3,5

Figure 5 shows the budget requirements for the entire planning horizon (10 years) as a function of changing system-effectiveness specifications.

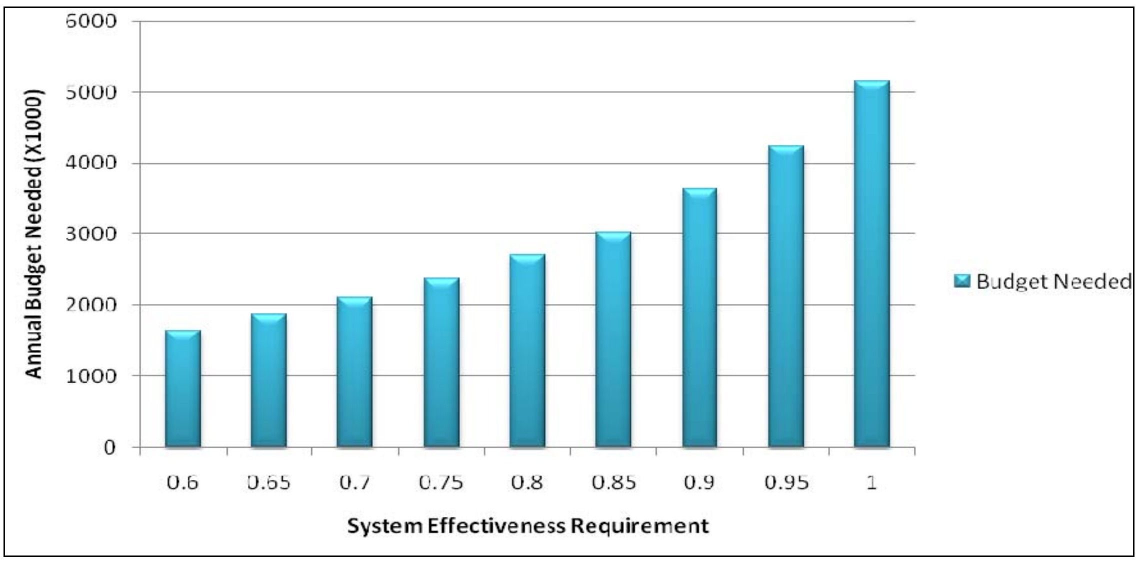

Figure 5. Budget Requirements as a Function of System Effectiveness

2. Given that we know we have to plan for obsolescence and maintain inventory, which component, in which year, and in what quantity should we replace?

Given the long lifecycle of torpedoes and the emphasis on the use of COTS components, the issue of obsolescence can occur frequently. Based on the analysis by Porter (1998), obsolescence can be addressed in several ways, as shown in Table 5.

Table 5. Obsolescence in COTS Components

Obsolescence Solution	Applies to (Components)	Cost
By selecting interchangeable replacement component	All	Minimal
Selecting alternate sources for components (which can require recertification)	All	Low/Medium
Use of alternate "upscalable" components found to be suitable based on screening to meet or exceed performance requirements	Electronic	Low
Part emulation, using newer-technology components that are packaged in the same form factor as the original part, that will emulate the component's functionality	Electronic, Electrical	Low
Use of a 3rd-party source to hold the manufacturing plans for the component at a future point in time	Electronic, Mechanical	Medium
Use of newer fabrication techniques for replacement of either a component or a component group	Electronic	Medium
Last-time buy of components	All	Medium
Line Unit Redesign (LRU)	All	High

In most cases, there is some advance notification of obsolescence. As shown in Table 6, the cost of mitigating obsolescence can vary, and, as it becomes clear that lower-cost solutions are not available, valuable budget- and effort-resources must be diverted from other activities in a timely manner for this purpose. The problem of planning resource expenditures to meet obsolescence has been previously considered in Brown, Lu, and Wolfson (1994), Rajagopalan (1992), Rajagopalan, Singh, and Morton (1998, January), and Singh and Sandborn (2006, April-June). In Brown et al. (1994), the obsolescence of a single item is evaluated under the assumption that obsolescence can occur unpredictably in future periods. Rajagopalan et al (1998) considers a planning model that determines how much capacity in current technology must be procured, assuming that deterioration and breakthroughs are uncertain—but distributionally known—for future periods.

This model can accommodate future obsolescence by adjusting the component efficiency appropriately. In particular, the parameters $f(i)$ can be replaced by $f(i,t)$, and a change can be forced in period t by setting $f(i,t)$ to 1 for the appropriate period.

3. **In the phase of “Operations and Sustainment,” if an unplanned software build becomes required, what do we sacrifice in the area of reliability improvements and sustainment? If a downward trend in component reliability becomes apparent, what do we sacrifice in the area of software maintenance improvements and sustainment? Is unit quantity on the production contract impacted?**

A downward trend in component reliability may be tolerable in the short–term, if the overall system efficiency is not reduced below acceptable levels. Again, this can be accommodated with the model above by adding constraints on efficiency, η_t ,as shown in Equation 9.

$$S_t \geq \eta \quad \forall t \tag{9}$$

The objective function in this case can directly address the budget instead of targeting the minimum system efficiency.

As an example, if the drop in the efficiency rate of component 1 is assumed to be as shown in Figure 6, then the replacements recommended by solving the model and the budget requirements for the 10-year horizon are also as shown in Table 6.

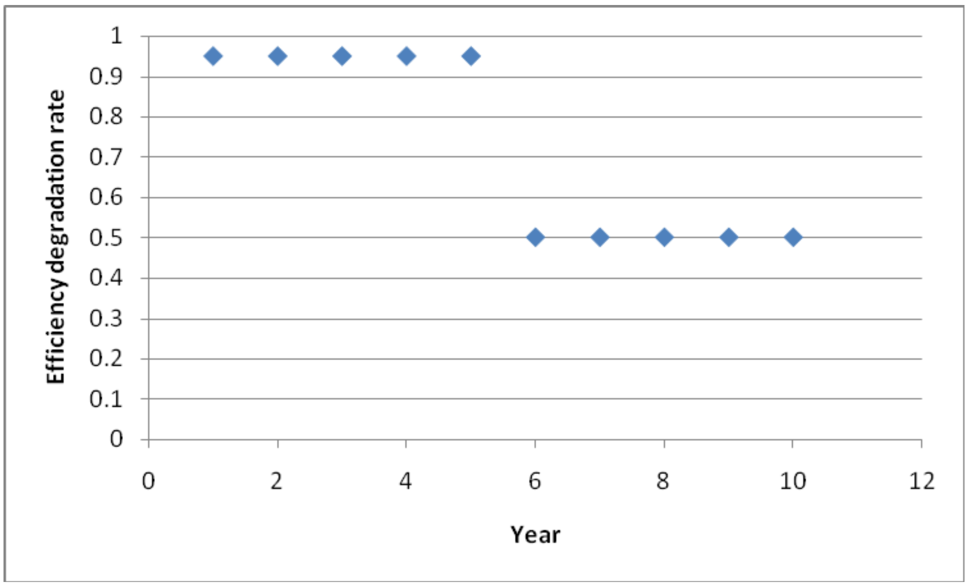

Figure 6. Drop in Efficiency of Component 1 in a 10-Year Horizon

Table 6. Upgrade Strategy and Budget Requirements Related to a Drop in the Efficiency of Component 1

Year	1	2	3	4	5	6	7	8	9	10
Budget $ (X1000)	515	75	340	125	245	220	275	295	220	225
Component Upgrades	All	5	1,3,6	4,5	2,3,5	1,6	1,2,4,5	1,5,6	1,3	1,2,6
System Effectiveness	1	0.78	0.82	0.76	0.76	0.77	0.78	0.76	0.76	0.76

4. **How should we allocate budgets between design upgrades and sustainment to maintain inventory at a minimum effectiveness level?**

Addressing budgets between design upgrades and sustainment to maintain inventory requires expansion of the model to include either/or choices for upgrades. This can be accommodated by adding binary choice variables and bringing these into the budget calculations appropriately. As an example, if there are several choices for upgrades (A_1, A_2, A_3, etc.) and the corresponding budgets for these are (B_1, B_2, B_3,etc.), then the choice can be enforced by imposing

$$A_1 + A_2 + A_3 ... \leq 1 \quad (10)$$

and the exact budget restriction is obtained by

$$B_1 A_1 + B_2 A_2 + B_3 A_3 ... \leq Total\,budget\,available. \quad (11)$$

5. **If we have fixed resource levels (other than budgets), what work can we accomplish given a minimum effectiveness level?**

The answer to this can be derived from the model by including additional constraints, limiting the use of various resources. Instead of the single constraint

$$\sum_{i=1}^{N} X_{it} * c_i \leq B \quad \forall t,$$

a set of constraints, identified by the index *m*, can be included as

$$\sum_{i=1}^{N} X_{it} * c_{im} \leq B_m \quad \forall m, t, \quad (12)$$

where B_m is the limit of resource type *m* available.

Multiple-product Evolutionary Design

Figure 7 illustrates a time-compressed representation of typical ongoing activities in progress in the Torpedo Enterprise. Three major acquisition projects, in different stages of realization, are shown simultaneously. In reality, the number of projects in play at the same time is in excess of a dozen.

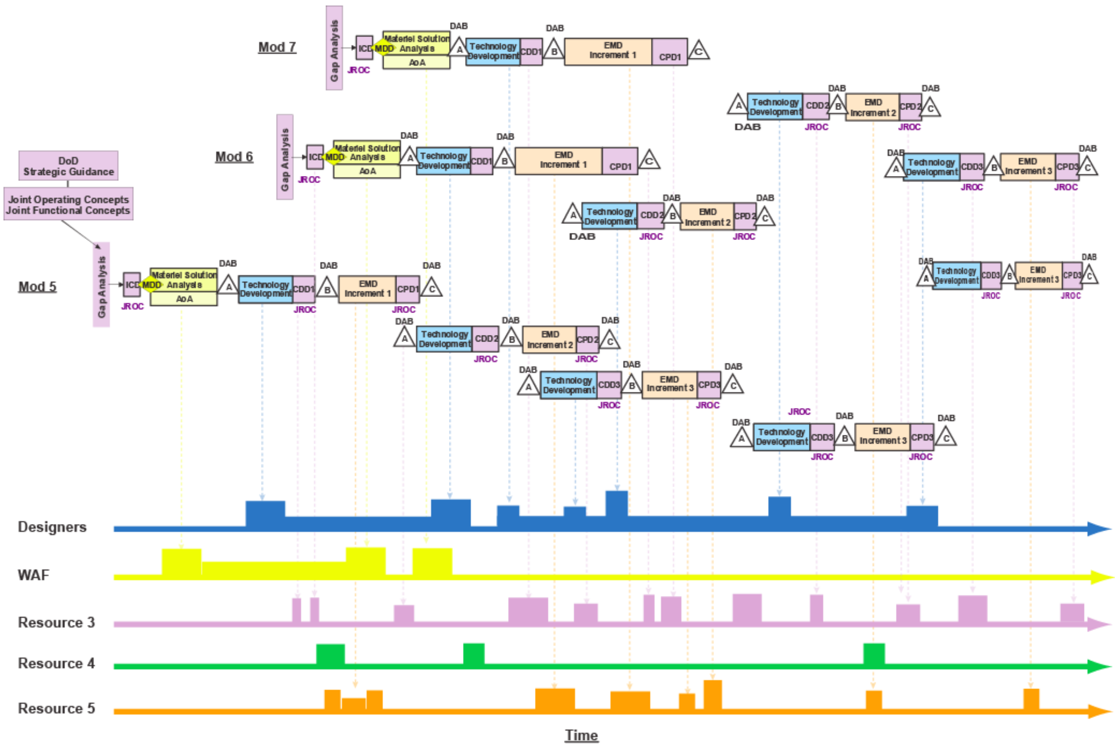

Figure 7. Multiple Cycles of the Torpedo Enterprise

As mentioned in the historical overview, as a result of emergent threats and technology upgrades, several designs of the torpedo are in service in the Fleet at any given point in time. In addition, because overall torpedo inventories are fixed, the upgrade process involves coordination of Fleet exercises, depot workloads, transportation times between locations, spares' availability and several resource considerations. Based on the depiction in Figure 7, the planning task involves determining not only the levels of effectiveness obtained by upgrading existing inventory, but also the scheduling of different design and maintenance activities over an extended-time horizon. Models 2-7 can be extended to include these considerations, but the resultant model is a large, mixed-integer programming formulation. Although this model has been solved for test cases using commercial mathematical-programming software, the solution times are considerable, and work on improving the solution efficiency is ongoing.

Conclusion

Planning in the Torpedo Enterprise is difficult because of various unique constraints. One of these is that the Torpedo Enterprise has not been procuring new torpedoes for the past two decades. New upgrades are introduced into the Fleet by taking existing inventory offline and updating specific hardware and software components. As discussed in the historical background section, changes in threats and new technology opportunities have resulted in multiple torpedo configurations concurrently in the Fleet. This compounds the planning problem. When budget decisions have to be made, torpedo effectiveness, inventory effectiveness, software capability upgrades, and technology insertions and refreshes must all be taken into consideration. To assist the decision-makers, a mathematical model has been developed that enables satisfaction of system-effectiveness requirements while meeting budgetary and programmatic constraints. This model is a linear, mixed-integer model, and it can be solved for problem sizes matching those corresponding to the decisions typically encountered in the torpedo domain within reasonable computation time. This model can be extended to answer typical programmatic questions such as the budget required to meet prescribed levels of system effectiveness, planned obsolescence upgrades, and tradeoff decisions between software upgrades, reliability improvements, or sustainment planning. The use of this model for multiple-project planning with several resource types is also presented. Program management, using the *DODI 5000.02*-prescribed framework (DoD, 2008, December 8), may reduce some uncertainties in resource utilization, but it does not eliminate them. The uncertainty remnants include reliability failures, resource reduction, component obsolescence, technology upgrades, and threat changes. The task of managing multiple projects and optimizing project resources remains a complicated endeavor.

List of References

Blanchard, B.S. (2003). *Logistics engineering and management* (6th ed.). Upper Saddle River, NJ: Prentice Hall.

Brown, G.W., Lu, J.Y., & Wolfson, R.J. (1994). Dynamic modeling of inventories subject to obsolescence. *Management Science*, *11*(1), 51-63.

DoD. (2008, December 8). *Operation of the defense acquisition system* (DoD Instruction 5000.02). Washington, DC: Author.

Fabrycky, W., & Blanchard, B.S. (1991). *Life-cycle costs and economic analysis*. Upper Saddle River, NJ: Prentice Hall.

Persona, A., Grassi, A., & Catena, M. (2005, December). Consignment stock of inventories in the presence of obsolescence. *International Journal of Production Research*, *43*(23), 4969–4988.

Porter, G. (1998). *An economic method for evaluating electronic component obsolescence solutions.* Boeing Corporation White Paper.

Rabideau, G., Knight, R., Chien, S., Fukunagava, T., & Govindjee, A. (1999, June). Iterative repair planning for spacecraft operations using the ASPEN system. In *Proceedings of 5th International Symposium on Artificial Intelligence, Robotics and Automation in Space*. Noordijk, The Netherlands: ESTEC.

Rajagopalan, S. (1992). Deterministic capacity expansion with deterioration. *Management Science 38*, 525-539.

Rajagopalan, S., Singh, M., & Morton, M. (1998, January). Capacity expansion and replacement in growing markets with uncertain breakthroughs. *Management Science*, *44*(1), 12-30.

Singh, P., & Sandborn, P. (2006, April-June). Obsolescence driven design refresh planning for sustainment dominated systems. *The Engineering Economist*, *51*(2), 115-139.

THIS PAGE INTENTIONALLY LEFT BLANK

2003 - 2009 Sponsored Research Topics

Acquisition Management

- Acquiring Combat Capability via Public-Private Partnerships (PPPs)
- BCA: Contractor vs. Organic Growth
- Defense Industry Consolidation
- EU-US Defense Industrial Relationships
- Knowledge Value Added (KVA) + Real Options (RO) Applied to Shipyard Planning Processes
- Managing Services Supply Chain
- MOSA Contracting Implications
- Portfolio Optimization via KVA + RO
- Private Military Sector
- Software Requirements for OA
- Spiral Development
- Strategy for Defense Acquisition Research
- The Software, Hardware Asset Reuse Enterprise (SHARE) repository

Contract Management

- Commodity Sourcing Strategies
- Contracting Government Procurement Functions
- Contractors in 21st Century Combat Zone
- Joint Contingency Contracting
- Model for Optimizing Contingency Contracting Planning and Execution
- Navy Contract Writing Guide
- Past Performance in Source Selection
- Strategic Contingency Contracting
- Transforming DoD Contract Closeout
- USAF Energy Savings Performance Contracts
- USAF IT Commodity Council
- USMC Contingency Contracting

Financial Management

- Acquisitions via leasing: MPS case
- Budget Scoring
- Budgeting for Capabilities-based Planning
- Capital Budgeting for DoD

- Energy Saving Contracts/DoD Mobile Assets
- Financing DoD Budget via PPPs
- Lessons from Private Sector Capital Budgeting for DoD Acquisition Budgeting Reform
- PPPs and Government Financing
- ROI of Information Warfare Systems
- Special Termination Liability in MDAPs
- Strategic Sourcing
- Transaction Cost Economics (TCE) to Improve Cost Estimates

Human Resources

- Indefinite Reenlistment
- Individual Augmentation
- Learning Management Systems
- Moral Conduct Waivers and First-tem Attrition
- Retention
- The Navy's Selective Reenlistment Bonus (SRB) Management System
- Tuition Assistance

Logistics Management

- Analysis of LAV Depot Maintenance
- Army LOG MOD
- ASDS Product Support Analysis
- Cold-chain Logistics
- Contractors Supporting Military Operations
- Diffusion/Variability on Vendor Performance Evaluation
- Evolutionary Acquisition
- Lean Six Sigma to Reduce Costs and Improve Readiness
- Naval Aviation Maintenance and Process Improvement (2)
- Optimizing CIWS Lifecycle Support (LCS)
- Outsourcing the Pearl Harbor MK-48 Intermediate Maintenance Activity
- Pallet Management System
- PBL (4)
- Privatization-NOSL/NAWCI
- RFID (6)
- Risk Analysis for Performance-based Logistics
- R-TOC Aegis Microwave Power Tubes

- Sense-and-Respond Logistics Network
- Strategic Sourcing

Program Management

- Building Collaborative Capacity
- Business Process Reengineering (BPR) for LCS Mission Module Acquisition
- Collaborative IT Tools Leveraging Competence
- Contractor vs. Organic Support
- Knowledge, Responsibilities and Decision Rights in MDAPs
- KVA Applied to Aegis and SSDS
- Managing the Service Supply Chain
- Measuring Uncertainty in Earned Value
- Organizational Modeling and Simulation
- Public-Private Partnership
- Terminating Your Own Program
- Utilizing Collaborative and Three-dimensional Imaging Technology

A complete listing and electronic copies of published research are available on our website: www.acquisitionresearch.org

THIS PAGE INTENTIONALLY LEFT BLANK

ACQUISITION RESEARCH PROGRAM
GRADUATE SCHOOL OF BUSINESS & PUBLIC POLICY
NAVAL POSTGRADUATE SCHOOL
555 DYER ROAD, INGERSOLL HALL
MONTEREY, CALIFORNIA 93943

www.acquisitionresearch.org