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CONTROLLING THE COST OF C4I UPGRADES ON NAVAL SHIPS

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Summary

The U.S. Navy spends more than $100 million annually on labor to install C4I system upgrades. C4I systems are widely deployed throughout the Navy to gather and process information for decisionmaking and to facilitate communication throughout the ship, among ships and naval bases, and between the ship's company and their families. Expenses associated with installing C4I systems include not only the purchase of new hardware and software but also the labor and material required to install new systems and replace existing systems.

COTS systems allow the Navy to take advantage of investments made in computing technologies by the civilian marketplace, and the Navy has embraced COTS technologies for C4I systems to the extent that the majority of the information technology on naval ships uses commercial hardware, software, and networks. However, it is difficult for the Navy to ensure that naval ships have the most up-to-date systems for computational processing and information sharing because COTS technologies for C4I systems refresh at a rapid pace. COTS systems may change multiple times during the years it takes to build a complex naval warship, and they may also change while in-service ships due for upgrades are unavailable to receive such upgrades because of operational demands.

Research Objectives and Approach

Recognizing the need to control and reduce the costs of C4I system upgrades, PEO C4I asked RAND to examine the factors that influ-

ence C4I-upgrade costs and identify what might be done to help reduce those costs. Specifically, we addressed the following questions:

- What actions during the design and construction of naval ships could help reduce the time and cost required to implement future C4I system upgrades?
- What factors contribute to the cost of installing C4I system upgrades on in-service ships, and how well are future C4I system-installation costs estimated?

To understand the challenges and constraints that program offices face when installing C4I systems as they design and build ships and to identify options for reducing C4I installation costs, we interviewed a number of program officials who were involved in the process of building new ships. These programs included *Zumwalt* destroyers, *Ford*-class aircraft carriers, and the next-generation cruiser. We also conducted interviews with program officials associated with ships currently in the active fleet, including *Nimitz*-class aircraft carriers; *Arleigh Burke*–class destroyers; *San Antonio*–class amphibious ships; and *Ohio*-, *Los Angeles*–, and *Virginia*-class submarines. To obtain the shipbuilders' perspective on these challenges and to gather suggestions for reducing costs, we interviewed General Dynamics Electric Boat and Northrop Grumman Newport News.

To analyze cost drivers, variability within costs, and the accuracy of the Navy's cost estimates, we obtained data from PEO C4I, which maintains a database that collects information on C4I-upgrade installations. The data set we obtained contained information on nearly 12,000 system upgrades that took place sometime in 2000–2008. We used techniques from statistics and data mining to look for significant patterns and correlations in the data set, and we tested the significance of potentially significant relationships using statistical analyses that primarily involved correlations, regression, t-tests, and analysis of variance. To assess estimate accuracy, we performed analyses using five error metrics.

Ship-Design and Ship-Construction Initiatives to Reduce C4I-Upgrade Costs

Both the various problems faced when upgrading C4I systems and the actions being taken to overcome those problems can be grouped into three categories: those that arise or apply during new ship construction, those that arise or apply to in-service ships, and those that are common to both new-construction and in-service ships. We address each of these categories below.

C4I-Upgrade Issues Specific to the Design and Construction of New Ships

During the design and construction of new ships, there are four major issues related to the installation costs of C4I systems.

Adopting commercially available systems versus special-built systems. The Navy faces a few disadvantages when it exploits the declining costs and increasing capabilities of the commercial marketplace. COTS equipment is designed for commercial or home use, not for a shipboard operating environment. Peacetime naval operations subject the equipment to salt air and the pitching and rolling of the ship, and even-more-taxing demands occur in wartime environments, which require the equipment to operate successfully after sustaining significant shocks. Military specifications for shock, quieting, and maritime operations can result in the addition of significant modification costs to the otherwise inexpensive commercial equipment. The submarine community has overcome these problems by isolating the equipment from the source of the potential shock. The "rafting" approach it uses for the design and build of the *Virginia* class basically "floats" the equipment above the outside structure of the submarine.

Deciding which C4I systems will be government furnished-equipment (GFE) and which will be contractor-furnished equipment (CFE). There are advantages and disadvantages to both GFE and CFE systems. GFE equipment allows standardization across the fleet, and such equipment is easier to support once a ship enters the fleet. Complete standardization across the fleet of even one C4I system is probably an unattainable goal, however, because of the high refresh rates of commercial technologies. Moreover, ship program managers (PMs) argue that PEO C4I systems are often a generation behind what is available in the open market and that ship designers can provide equal or better capability at lower costs.

CFE systems can leverage the broader commercial marketplace and provide multiple technology options, hopefully at a lower cost. However, CFE systems may be proprietary, and sufficient documentation on the systems may not be available to PEO C4I to support the systems one they enter the fleet. Furthermore, CFE systems can present a problem to PEO C4I once a ship enters the fleet and responsibility for system support transitions to the Navy, which may not have complete knowledge of the systems. Finally, CFE systems may create a unique logistics tail, requiring a separate spare-parts pool and system-unique training for the sailors who operate and maintain the system. The issue of whether PEO C4I should be the preferred provider for new-ship programs warrants further study, especially in terms of the total life-cycle cost impact of choosing either GFE or CFE.

Delivering ships to the fleet with the most-up-to-date systems. One of the biggest problems facing ship PMs during new-ship construction is ensuring that the most-up-to-date C4I technologies are incorporated in a new ship at delivery. C4I technologies can refresh multiple times during the several years it takes to build a ship. Thus, when C4I systems are identified too early in the ship-construction process, they may need to be removed and replaced with the latest upgrade as soon as the ship is delivered to the Navy. On the other hand, ship designers and builders need to lock in both the dimensions and foundations required for the C4I systems and the systems' power and cooling requirements as early as possible in the design and construction process; otherwise, there may not be sufficient space, power, and cooling to support the equipment.

Ship PMs have developed a strategy to overcome the problem of obsolescence in C4I equipment at ship delivery. The strategy—termed *design budget*, *technology insertion*, or *turnkey*, depending on the program—basically provides ship designers and builders the broad specifications of the C4I equipment in terms of space, power, and cooling requirements without identifying the specific equipment that will be installed. Not-to-exceed values for space, power, and cooling are defined, and ship managers must stay within these parameters to ensure that there are no problems installing the equipment when it is finally specified.

Incorporating adequate design margins for weight, power, cooling, and bandwidth into the ship design. The majority of the ships in the Navy fleet have little extra capacity to meet increased demand for weight, power, cooling, and bandwidth because the initial design margins are typically consumed very early in a ship's life. This lack of extra capacity results in difficulties in finding ship services to support the new equipment and in additional costs when upgrading C4I capabilities, especially when adding new capabilities to a ship. Workarounds, including the addition of new power and cooling plants, are often needed to provide the additional ship services required to accommodate C4I upgrades. Existing systems may have to be downgraded, or ship operations may need to be constrained (e.g., by not operating certain systems while others are being operated). Some ship classes have become so constrained that a new system or capability cannot be added without an existing system being removed.

The issue of adequate design margins is being addressed in the design of new classes of ships. For example, the design for the new *Ford* class of aircraft carriers includes both extra cabling in various spaces and extra bandwidth. The design also features a zonal electricity grid that allows power to be directed throughout the ship where and when it is needed.

C4I-Upgrade Issues for In-Service Ships

Many of the issues that arise during ship design and construction also arise when upgrading C4I systems for ships that are in the operational fleet. There are, however, two problems that are unique to in-service ships.

Various ship configurations make the planning of upgrades difficult. The cost of specific upgrades to C4I systems could be reduced if the installation details were the same across all ships in a given class. This uniformity would permit both the creation of just one set of design drawings for the upgrade and the implementation of a repetitive approach to installing the upgrades. Unfortunately, the C4I systems of various ships in a given class feature different configurations, and the areas where C4I systems are installed may be differently laid out. Nonstandard configurations across ships in a single class mean that each installation requires a check of the ship's configuration, the development of a unique set of design drawings, and an almost-unique process for installing the upgrade. These requirements contribute to increased cost and time to accomplish the upgrade. The biggest contributor to different configurations is the high refresh rate of the technology used in the C4I systems. For example, the C4I configurations in DDG-51–class ships currently in construction will differ from those in DDG-51–class ships delivered only a few years ago. The submarine community appears to do the best job of maintaining similar C4I configurations across all of the submarines within a class and even across various classes. Part of this success is due to adapting an open-architecture design philosophy and business model for C4I and combat systems.

Navigating the ship maintenance (SHIPMAIN) process. The SHIPMAIN process was initiated in November 2002 to identify and eliminate redundancies in maintenance processes so that the right maintenance is done at the right time, at the right place, and at the right cost. It also seeks, through a common planning process for ship maintenance and modernization, to maintain configuration control of the various changes made to ship systems and equipment over the life of a ship. SHIPMAIN has been successful in reducing the churn in maintenance and modernization planning and in reducing maintenance costs while providing ready ships to the fleet. It has also been successful in establishing and sustaining configuration control across the ships in a given class for hull, mechanical, and electrical equipment and systems. However, because C4I technologies can change one or two times during the three-year planning and implementation period, SHIPMAIN is typically viewed as too difficult and too time-consuming to implement during C4I upgrades. The process—and the time required to approve and implement changes—is the same regardless of the magnitude of the change. For example, software upgrades go through the same SHIPMAIN process as major hardware changes.

Software upgrades are also more difficult than hardware changes to certify in the SHIPMAIN process because it is difficult to specify the impact of a software change from an operational perspective.

In interviews, various organizations noted that, with waivers, an alteration can be approved within 90 days under SHIPMAIN. However, the approval process itself takes time and resources. Because quick approvals are typically required for C4I upgrades, this shorter alternative should be streamlined and made easier to navigate.

General C4I-Upgrade Issues

A few factors influence C4I installation costs during both new-ship construction and when upgrading in-service ships: the need to integrate and test the new systems installed in the ship, the amount of "hot work" (as welding and the installation of foundations and structures are known) and changes to ship services (i.e., space, power, and cooling) required, and the need to integrate the antennas on the topside of the ship. There are factors specific to ship design and construction and factors specific to in-service ships.

Integrating and testing the new systems installed in the ship. The proliferation of C4I systems on naval ships has complicated the process of integrating the various systems into an overall ship C4I architecture and testing the overall C4I package to ensure that all functions are working correctly. How systems integration will occur is a key decision in the C4I design process. The federated approach decentralizes the hardware and software functions of the various C4I systems while allowing all systems to share data and information through a common network. Under this decentralized approach, the hardware or software problems of one C4I system, or of an upgrade to a system, can be isolated and addressed without affecting the performance of other C4I systems. One downside of using a federated approach is that doing so involves some level of redundancy in C4I hardware and software, which results in increased costs and increased demands on ship services.

An integrated architecture reduces hardware and software redundancies by using both a shared network and shared computing hardware and system software. C4I functions in integrated systems are typically supplied by software programs that use common system-hardware processing and the common network to share data and information. The disadvantages of integrated systems are (1) the potential loss of all C4I functions when a problem with the common hardware or system software arises and (2) the fact that there are few suppliers capable of delivering the more-complex hardware and software systems involved in this type of architecture.

Regardless of the overall architecture chosen for C4I systems, a consolidated testing plan is needed to ensure that all C4I systems are working correctly in both a stand-alone mode and as part of the overall C4I architecture. A consolidated testing plan should reduce redundant activities, thus saving money, and allow testing to occur later in the build process. However, a consolidated testing plan typically requires that a facility perform the testing of the overall C4I system, and constructing and operating such a facility entail monetary, schedule, and opportunity costs. The *Virginia* program has successfully implemented a consolidated testing plan in which the electronic components of the C4I weapon systems are assembled and tested at the Command and Control System Module Off-Hull Assembly and Test Site facility at Electric Boat before they are inserted into the submarine.

The need for both hot work and changes to ship services drives the costs of C4I upgrades. If adding a new capability to or upgrading an existing capability on a ship were as easily accomplished as upgrades to home computers or audio-visual systems, C4I-upgrade costs would not be an issue for the Navy. However, the complexity of integrating C4I systems, the limited supply of ship services, and the density of modern ships require a significant amount of labor to remove and replace equipment. The Navy is employing several initiatives to reduce the required amount of hot work and changes to ship services. For example, the CVN-21 aircraft-carrier program[1] is incorporating a flexible infrastructure into various C4I spaces on the *Ford* class, and changes since the last design include a raised deck with ventilation running underneath and movable vents on the deck to direct the cooling where it is needed. New-ship designs are also incorporat-

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[1] A CVN is an aircraft carrier, nuclear.

ing features to allow for easier access to C4I systems during upgrade installations. For example, wider passageways and less-dense placement of C4I equipment allow for the removal and installation of new equipment without affecting existing equipment.

Integrating antennas for the various C4I systems on the topside of the ship is often more difficult than integrating C4I systems within the ship structure. Each antenna must have a clear field of view to receive signals, and it cannot cause electronic interference with other antennas. Topside space, from both the horizontal and vertical perspectives, is limited and must be carefully managed. There are efforts under way to consolidate various antennas, but these efforts have not yet led to an acceptable solution. The submarine community has made progress with the topside integration problem by adopting a universal modular mast that allows antennas to be changed more easily. Table S.1 summarizes these various upgrade problems and displays options aimed at lessening their impact during C4I upgrades. As the table shows, single management decisions and design options are typically aimed at solving multiple upgrade problems.

Factors That Influence C4I Installation Costs and the Accuracy of Estimates

Through our analyses of historical data on the cost of installation labor, we sought to better understand the factors that influenced the labor costs of installing certain prior C4I upgrades, the variability within those costs, the extent to which cost improvement occurred, and the accuracy of cost estimates. Table S.2 shows the labor costs of the six types of upgrades that were the focus of our analyses.

Our analyses found inconsistent trends across the types of installations. Although there were significant differences within an installation type (e.g., installation on one coast was more expensive than on the other), there were no consistent trends associated with factors, such as age and size of ship, that would be useful in adjusting future estimates. This variability is a reflection of both the quality of the data and the diversity of the installations, which ranged from

Table S.1
Actions Taken to Solve Various C4I-Upgrade Problems

Action Taken	Cost of Hot Work	Ship Service Modifications	Military Specifications	Systems Integration or Testing	High Tech Refresh Rate	Requirements Growth
Create a flexible infrastructure	X	X			X	X
Employ standard racks or enclosures	X	X			X	X
Employ modular isolation			X			
Improve access to C4I-system spaces	X	X			X	
Use the design-budget process during construction					X	X
Incorporate adequate design margins					X	X
Decide on federated vs. integrated systems			X	X		
Employ consolidated testing				X	X	
Use COTS, SOA, and/or OA					X	X

Table S.2
Labor Costs of Analyzed Upgrades

Upgrade Type	Number of Installations Examined	Labor Cost (FY09$)		
		25th Percentile	Average	75th Percentile
GCCS-M GENSER 4.X (V) 1–4	31	158,121	283,651	459,345
ISNS Embarkable Drops	34	55,016	186,600	188,751
ISNS LAN GIG-E	54	1,029,918	1,577,444	1,624,571
ISNS COMPOSE 3.0 Software	82	27,947	43,303	51,617
EBEMs for WSC-6 Variants	48	32,212	42,929	50,682
SSEE Increment E	24	545,300	734,060	918,195

software upgrades to major system replacements. For example, ship size and age frequently had a significant impact on the cost of installation related to Ships Signal Exploitation Equipment (SSEE), super-high frequency radios, the Integrated Shipboard Networking System (ISNS), and the Global Command and Control System–Maritime. In some cases, the costs varied significantly by installation location. Also, for some specific installations, the variability in actual labor cost, even within a ship class, was quite high (i.e., the high-to-low value was different by an order of magnitude). Early adopters of the Consolidated Afloat Networks and Enterprise Services system tended to exhibit higher installation costs than did similar ships that were not selected as early adopters.

There was some evidence of cost improvement but it was weak and inconsistent across upgrade types. In many industrial and manufacturing situations, costs decrease as an activity is accomplished more frequently. Our analyses of the different upgrades suggest that there was a decrease in installation costs associated with both the Enhanced Bandwidth-Efficient Modem for WSC-6 Variants and the ISNS Embarkable Drops upgrades. For these upgrades, costs decreased as successive installations were accomplished. However, there was negative learning (i.e., an increase in costs for successive upgrades) for the ISNS Common PC Operating System Environment and SSEE Increment E upgrades. This finding is troublesome because it suggests that teams required more hours to complete each successive installation of these upgrades—a trend exactly the opposite of what we expected.

We used several metrics to assess the accuracy of the estimates of C4I-upgrade costs. The mean bias across all the installations in the database was over $7,000, suggesting that installation costs were typically overestimated. Overestimating was a particular problem for installations on larger ships, such as aircraft carriers and amphibious ships. Also, overestimates were especially large for installations that had low actual costs. Furthermore, we found that cost estimations tended to overestimate the cost of upgrades. Additionally, the relative error was quite high, particularly for aircraft carriers, nuclear; guided missile frigates; and attack submarines, nuclear. Many of the factors that were found to influence cost variability, such as hull type, ship age, and installation coast, also affected estimation accuracy.

Recommendations

Several recommendations flow from these findings. Although our first few recommendations are not new, they are not being considered consistently across ship types and classes. From the perspective of designing and building naval ships to facilitate C4I upgrades, the Navy should

- ensure that adequate design margins for power, cooling, and space are incorporated into the design of a ship and that adequate margins are sustained during the operational life of a ship
- include adequate access paths when designing a ship, especially a surface combatant
- use standard racks and fixtures and flexible infrastructures to help reduce the amount of hot work required to remove old fixtures and install new ones when upgrading C4I systems

- conduct additional analyses comparing the advantages and disadvantages of using (1) GFE versus CFE, (2) federated versus integrated systems, and (3) service-oriented architectures versus open architectures
- include in the Space and Naval Warfare Systems Center/PEO Integrated Data Environment and Repository database both information about the facility where an installation was performed (i.e., private shipyard, public shipyard, or operating base) and an identifier for the organization or team that accomplished the installation
- develop after-action reports for each installation or, if that is not feasible, for at least those installations during which actual costs significantly differed from estimated costs.