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Concept Exploration Lessons Learned

ABSTRACT

In the past, Concept Exploration was the first step in defining the properties of a ship. Of the many ships studied during Concept Exploration, one was to be further developed and refined by the government during preliminary and contract design. Following award of the detail design and construction contract, a shipyard would complete the design and construct the ship. With the advent of Acquisition Reform and industry taking on the responsibility for what was previously preliminary and contract design, the products of Concept Exploration have changed. Instead of the first draft of a ship design, Concept Exploration now results in a balanced set of Performance Requirements for the design and construction of the ship by the shipyards. The Government selects the Performance Requirements to achieve an affordable and operationally effective ship. Compared to internally Navy-controlled technical requirements, the performance goals are more difficult to change once competitive industry teams are under contract to produce a ship to the original goals. An effective design process must reflect this fundamental change in the desired product of Concept Exploration. This paper details the lessons learned by the authors while directing the JCC(X) Concept Exploration and offers recommendations on possible improvements for future ship concept studies.

INTRODUCTION

The Navy has four command ships (AGF 3, AGF 11, LCC 19 & 20) approaching forty years of age whose function must be replaced when the hulls wear out, but not necessarily by another ship. Furthermore, the functional replacement must accommodate a Joint Command structure that did not exist when the existing ships were designed or converted. This functional replacement is called the Joint Maritime Command and Control Capability (JCC(X)).

The authors were the Ship Design Manager (SDM) and Principle Naval Architect (PNA) in NAVSEA for the JCC(X) during its pre-Milestone 0 studies, Concept Exploration and Analysis of Alternatives (AOA). A Mission Area Analysis (MAA) was completed for JCC(X) in March 1999 followed by validation of a Mission Need Statement (MNS) in September 1999 and a Milestone 0 decision in November 1999. The AOA and Concept Exploration started immediately and completed in May 2001 in preparation for a Fiscal Year 2002 Decision Point. [1]

Under the current acquisition system that stresses the use of performance specifications, the primary activities that occur during Concept Exploration are:

- Conduct an Analysis of Alternatives (AOA)
- Develop Operational Requirements (ORD)
- Develop "Milestone" Documentation
- Develop System Requirements (P-SPEC) and procurement documents (RFP, SOW, Source Selection Plan, etc)
- Develop a cost estimate for design (RDT&E) and construction (SCN) in support of the Planning, Programming, and Budgeting System (PPBS)

[1] The former Milestone 0 (now Milestone A) is traditionally the boundary between "The Navy after Next" and "The Next Navy" for ship concepts. In SEA 05D, this is the point in which responsibility for the project transitions from SEA 05D1 (Advanced Concepts) to one of the other branches in SEA 05D. In actuality this transition was not at abrupt as one would think. Cdr Doerry was the JCC(X) Ship Design Manager before Milestone 0 although his billet was in SEA 05D4, which is responsible for all amphibious warfare ships and command ships. In April 2001, approaching the end of the AoA, he rotated to a PMS 377 billet in support of the LHD project and was replaced by a NAVSEA civilian SDM. The PNA remained part of SEA 05D1 for both phases.

Note that a "ship design" is not one of the products of Concept Exploration. This does not mean that ship studies are not done during Concept Exploration. On the contrary, JCC(X) developed over 60 ship concepts between December 1999 and February 2001. Unlike later stages of design, a ship study in Concept Exploration is merely a tool for understanding and developing the requirements. This is a fundamental change from the way the Navy did business ten years ago. Ten years ago, each stage of design (Feasibility Studies, Conceptual Design, Preliminary Design, Contract Design and Detail Design) added increasing levels of detail to the previous product definition (Engineering Duty Officer School 1979). The Government (or its agents) performed all design activity through Contract Design. Industry was only responsible for Detail Design and Construction. Now, Functional Design, which replaced Preliminary and Contract Design, is conducted by industry to a set of Performance Specifications whose development is the responsibility of the Government.

THE JCC(X) ANALYSIS OF ALTERNATIVES

Much of the ship design activity done during Concept Exploration supports the Analysis of Alternatives (formerly called the Cost and Operational Effectiveness Analysis (COEA) phase). The scope of the AOA is specified in written AOA guidance. For JCC(X) this guidance was a six page attachment to the Milestone 0 decision letter. It is not unusual for an AOA to consist of two or more phases, and in fact, the JCC(X) study guidance directed the AOA be conducted in two phases. The first phase was to determine whether a ship was needed or not. Advances in Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) systems were thought to enable the Joint Force Commander (JFC) in the near future to use land based facilities exclusively. The second part, if needed, would recommend the principal features of the solution determined in the first part.

A study director independent of the program office leads an AOA. In the recent past, senior Navy leadership has chosen the Center for Naval Analysis (CNA) to lead major ship acquisition program AOAs. Hence, the Ship Design Manager works for the AOA director, who belongs to a totally separate and independently funded organization, in conducting ship studies supporting the AOA. The SDM becomes the point of contact for ensuring the provision of other NAVSEA products, such as cost estimates, to the AOA Director. He does this while simultaneously working with a prospective program management team that, in accordance with DOD 5000.2R, is not to influence the results of the independent AOA. As a member of the NAVSEA Engineering Directorate, he also ensures good engineering practices are followed.

In conducting an AOA, the first step is defining the boundaries of the functional need. For JCC(X), the functional need consisted of all the systems and support required to support a 3 star Joint Force Commander, his staff, component commanders, and their staffs. In virtually every case, not all of the staffs were co-located. This meant that each single AOA alternative consisted of multiple systems such as dedicated JCC(X) ships of varying sizes, command spaces on aircraft carriers and amphibious warfare ships, and command elements ashore.

The Ship Design Manager was responsible for developing concepts for the ship "building blocks" that would be used in conjunction with other elements to form the JCC(X) alternatives. By its nature, an AOA is very high level and compares gross levels of performance to gross levels of cost. Early in the planning, the AOA study director and the SDM decided that the AOA would only be interested in design variables that resulted in changes on the order of $50M or more in acquisition cost. From that guidance the following list of key ship characteristics that are important to the AOA and were thought to have a significant cost impact were developed:

- Size of the Embarked Staff
- Survivability

- Speed
- Military Sealift Command (MSC) vs Navy manning

Additionally, incorporating improved habitability standards was also identified as likely coming close to the $50M threshold.

A number of other requirements that had smaller cost impacts would not be addressed in the AOA, but would need to be addressed in the ORD and P-SPEC. These included:

- Number and type of aircraft to support: landing spots, hangar capacity, maintenance facilities
- Number and type of boats to support
- Seakeeping performance: (Because the embarked staff would include many non-Navy personnel not accustomed to sea motions, would JCC(X) be required to have less motions than typically accepted for a Naval Warship?)
- Degree of Reduced Manpower initiatives incorporated.

Another important activity supporting the AOA was the development of an Operational Architecture (OA) for the Joint Force Commander and associated staffs. The OA was developed by SPAWAR and detailed the Command and Control functional elements and Information Exchange Requirements (IER) for each of the elements of the JFC and staffs. The OA was used to develop bandwidth requirements and notional C4ISR system requirements that were incorporated into the ship studies.

A Technology Roadmapping effort for C4ISR systems was conducted to determine what major changes should be anticipated. In developing JCC(X) concepts, in accordance with the acquisition strategy, only existing C4ISR systems or systems currently fully funded and scheduled to be ready for fleet introduction in time for JCC(X) were used. The road mapping effort was intended to understand the robustness of the assumed C4ISR suite.

A Concept of Operations (CONOPS) was also developed to provide operational context for the definition of the JCC(X) systems. The CONOPS looked at three different levels of conflict from a humanitarian relief operation to a major theater conflict. It identified which staffs would be onboard, the time line for the deployment of JCC(X) and the physical location of JCC(X) with respect to friendly and hostile forces.

A summary of how these elements interacted in the Analysis of Alternatives is shown in Figure 1:

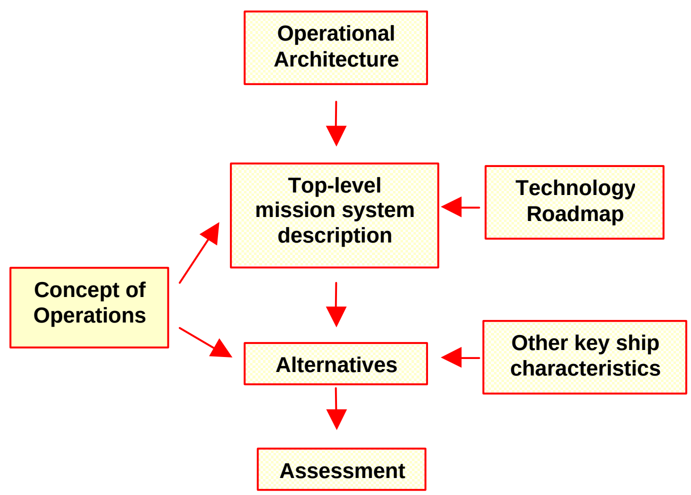

FIGURE 1: JCC(X) AOA Analysis Process

Phase 1 of the AOA completed in March 2000. It concluded that an afloat capability was required, but did not demonstrate sufficiently that a dedicated ship was required. Fully distributing the JCC(X) function by backfitting capability on LHD/LHA/CVN and building nodes into future large deck amphibious warfare ships and CVNX was still considered an option. In January 2001, the AOA demonstrated that the full distribution option was not affordable. In March 2001, the AOA demonstrated that extending the service life of the existing command ships, or converting other ships into command ships was not economically desirable. Modified repeat designs were shown to be not significantly cheaper, if at all, than a new design command ship. The final results of the AOA were presented in July 2001 and are detailed by Doerry, Austin and Strasel (2002).

MANAGING SHIP CONCEPT STUDIES

To support the Analysis of Alternatives, the SDM directed a series of Ship Concept studies to develop the "building blocks" for each JCC(X) alternative. These studies included clean sheet new designs, modified repeat designs, conversions, and service life extensions of the existing command ships. Doerry, Austin, and Strasel (2002) presented the results of these studies.

Each study, consisting of multiple ship concepts, was treated as an experiment or test. Before conducting each study, a study guide was created to document assumptions, tools, processes, responsibilities, and schedules. This study guide took the place of a test plan and test procedure. During the conduct of the study, additional assumptions or clarification of assumptions were documented in revisions to the study guide. The results of each concept were documented in a final report. At the end of the study, a consolidated final report and associated cost report were created to compare and contrast all of the concepts. Additionally, survivability analysis was conducted on a number of the concepts. This work was accomplished by a different team and managed independently.

To coordinate the multiple teams working on the Design Space Studies, weekly meetings were held to discuss progress and problems. As with any meeting, a well-defined agenda is necessary to keep the meeting short and focused. The AOA Director, program office personnel, and OPNAV personnel were invited to these meetings to ensure they knew what was being done and could provide timely feedback / redirection if necessary.

Internet/Web collaboration tools were tried with limited success. These studies occurred during the NAVSEA move from Crystal City in Arlington, Virginia to the Washington Navy Yard in the District of Columbia and obtaining specialized information technology (IT) support from NAVSEA was not possible. A Virtual Project Office (VPO) site at SPAWAR was tried, but for many of the supporting contractors, access was painfully slow. This prevented real time collaboration, but did allow for the publication of documentation such as the study guides. E-mail was also extensively used. The usual benefits (good records of what was sent) and drawbacks (a multiple addressed E-mail is effectively sent to no one since everyone figures “somebody else will do it”) of E-mail were apparent. Even with this low level use of online collaboration, the need for a co-located design site, with its considerable cost, was eliminated.

The biggest challenges in collaboration occurred with the survivability studies. These studies were mostly classified and precluded the use of the unclassified LANs/internet to share information. The inability to share updates to the Study Guide in a real time manner resulted in schedule slips, rework, and cost over-runs. Communication problems were compounded because survivability study participants were spread throughout the country. Individuals resorted to driving to the Naval Surface Warfare Center in Dahlgren, Virginia (NSWCDD) to courier disks because of the lack of classified network access at NAVSEA. In general, it was found that classified collaborative work without a classified network costs about 2 to 3 times more than what had been expected and generally took 2 to 3 times as long as expected. Hence, if a classified study without a secure network is required, it must be started early.

New Ship Studies

Ship studies must be carefully planned to produce good results. The planning must clearly identify the questions that the study is intended to address. The planning must also address the likely source of errors and have mechanisms to reduce the error or, at least, understand their magnitude. For JCC(X) the principal ship synthesis tool used was the Naval Surface Warfare Center Carderock Division (NSWCCD) developed Advanced Surface Ship Evaluation Tool, Monohull Logistic and Amphibious version (ASSET MONOLA). An evolved LCC 19 was used as a baseline for the studies and a test case for debugging the synthesis model. An LCC 19 match run was updated to incorporate modern requirements, remove its 1000 tons of fixed sea water ballast, eliminate the boat sponsons, replace its single shaft steam plant with twin shaft electric drive, and incorporate a new superstructure to accommodate a flight deck and hangar. The LCC 19 was used as a parent for two main reasons:

1. LCC 19 was designed as a command ship (unlike the converted AGFs) and many relationships scale well.
2. Because LCC 19 has a 1960s vintage hull form, industry would likely not copy the concept designs in their proposals back to the Government for functional design.

The LCC 19 evolution studies were important because ASSET MONOLA depends much more on a having a valid parent ship than the surface combatant versions (MONOSC) which has many generic curves that cover warships from 700 to 17,000 tons. MONOLA had been used before for amphibious and logistics ships studies but never used for a command ship. Some of the logic, satisfactory for those ships, was not satisfactory for command ship studies. For example, if a Military Sealift Command (MSC) crew was requested, the program would not account for a command staff onboard since it was obvious to the original programmer that a MSC crew and a command staff would never be on the ship at the same time. Since an MSC crewed command ship was one of the primary alternatives considered by the AOA, the program had to be corrected. As studies continued, numerous "band-aids" and patches were used to adapt the program to cover command ships. This debugging-while-doing put a great deal of stress on the study workers since 'found problems' negate large blocks of previous work. The problem was exacerbated by the shift of naval architects from mission funded headquarters billets to project funded jobs at NSWCCD. This shift of personnel to the warfare centers where all work requires project funding prevented SEA 05D from customizing and debugging ship synthesis and other design tools prior to the start of the AOA. This need runs directly into the funding "catch-22" of no money for tool and model development unless you have a funded program, but once you have funding for a program, there is not enough time to do much meaningful tool development before study results are expected.

Developing and analyzing a ship concept required multiple individuals or teams. Before the ASSET modeling could start, NSWCCD and MSC developed ship manning estimates for each option while SPAWAR developed staff composition estimates. These estimates were based on the notional JCC(X) baseline modified by the assumptions in the study guide. The manning numbers and staff composition estimates were then documented in revisions to the study guide. SPAWAR also provided the required C4ISR areas and the direct cost of the electronic systems. As usual, estimation of electronics system weights in the early design stages was difficult – SPAWAR attempts to "build up" the weights by adding up the weights of black boxes resulted in numbers that were obviously too light. In electronics system weights the "add-ons" of cabling, cooling pipes, racks, furniture and everything else to make the system work are a major part of the Ship Work Breakdown System (SWBS) group. The naval architects looked at the SWBS weights of existing command-and-control-rich ships like LHDs and CVNs, and created a "best guess" of what a next generation of command ship should carry. The numbers, while not a result of sophisticated analysis, were good enough to size the ship and provide a budget for installation costs. The SDM developed a host of other assumptions needed to populate the ASSET databases. These included the propulsion plant, habitability standards, boats, aviation facilities, endurance requirements, etc.

The study assumed an Integrated Power System (IPS) on every new design option since the type of propulsion was not an important AOA issue. Using IPS simplified some elements of the design process since the IPS project had invested money in the ASSET ship synthesis model several years earlier to allow handling of modern electric drive propulsion. Unfortunately, the IPS model embedded in the computer model has components that had changed in weight and dimensions as the program matured. Thus, it became necessary to have an external hand scrub of the estimated machinery plant weights by a representative of the IPS program office for every major plant variation. This man-in-the-loop cycle slowed the process down. An area of weakness in the computer model was lack of data about the most modern cruise ships power plants that consist of propellers mounted on the rudders (Azipods or Mermaid brands). One interesting power excursion was a 35 knot sustained speed variant. With 4 screws and 8 gas turbines in a long hull, the hull resembled a modern version of the passenger liner *SS United States* which crossed the Atlantic at over 35 knots in the 1950s.

Once the ASSET models were completed, the PNA examined them to find potential discrepancies. Due to the large number of ships being compared, the SDM developed two programs for comparing the weight reports and space reports of two ASSET final reports. These programs identified possible discrepancies in the models. These discrepancies were then discussed with the ASSET modelers and, if necessary, the ASSET models were reworked. This served especially well in finding change as a result of built in ASSET "switches" making assumptions that were not intended.

Once the PNA and SDM found the ASSET models acceptable, the models were passed on to SEA 017 for costing. For acquisition cost estimation, SEA 017 used a combination of weight based cost estimating ratios (CERs), SPAWAR generated direct equipment costs, and programmatic cost estimates developed by PMS 377. For Operating and Support (O&S) cost estimates, SEA 017 developed a statistical based model using data from amphibious ships, command ships, and sealift ships.

In conducting ASSET studies that compare the results of two concepts, the JCC(X) study teams determined the principal sources of error to be:

- Changing Sets of Assumptions
- Naval Architects and the Learning Curve
- The "Artistic" component of Naval Architecture: Lack of reproducible results
- Synergistic Effects of different feature sets
- Operator Error
- ASSET bugs / undocumented "features"

To limit these errors, the JCC(X) study team did the following:

- Developed Study Guides to document how studies were to be conducted and all requisite assumptions.
- Conducted studies in Blocks (Called Design Space Studies or DSS) to limit the effects of the learning curve on the results.
- Used the same individuals to conduct all of the studies within a DSS.
- Used "Design of Experiments" techniques to determine the impact of different features on acquisition cost and performance.
- Developed computer tools to compare the results of two ASSET runs to identify significant differences in weights, areas, and Centers of Gravity.
- Used Regression Analysis to determine potential discontinuities.

Understanding the "Learning Curve" as it applies to Naval Architects is very important. In conducting multiple similar ship studies, a Naval Architect will learn how to optimize the design as he/she does more and more of the designs. Hence the last concept of a study will likely be much more optimized than the first concept. There is a risk that differences calculated between two options are more a function of a Naval Architect getting smarter than of the real differences between the two options. Using relatively small blocks reduces the cost of redoing the earlier concepts to reflect the lessons learned in the following concepts. A block size of 24 ships was used for the first Design Space Study (DSS I) which turned out to be too large a block – the rework in getting all 24 consistent was expensive. In subsequent new ship concept studies, block sizes were on the order of 10 to 15 ships.

In DSS I, it was intended that two different organizations (NSWCCD and CSC Advanced

Marine) split the workload for conducting the studies. Initial results showed a considerable error component in the comparison of two options if the two options were accomplished by different organizations. This forced assignment of all the New Design work to one organization (NSWCCD). The other organization was then employed to conduct all of the Modified Repeat and Conversion studies.

It's well known that the order in which features are added to a baseline concept impact the incremental cost of each feature (Sims 1993). For this reason, the average incremental cost of a feature over multiple sets of features was calculated. In DSS I, the entire design space was explored (3 staff sizes x 2 speeds x 4 survivability/manning options = 24 options) to determine the impact of each variable. This method helped ensure that a robust answer of the impact of a given feature was created.

The manner in which the results are presented is also very important. During the AOA, the study is interested in developing relationships between specific requirements and changes in overall ship performance. The relationship is usually more important than specific performance of any one option. Hence average values, cost – capability curves and contour charts, such as Figure 2, are useful.

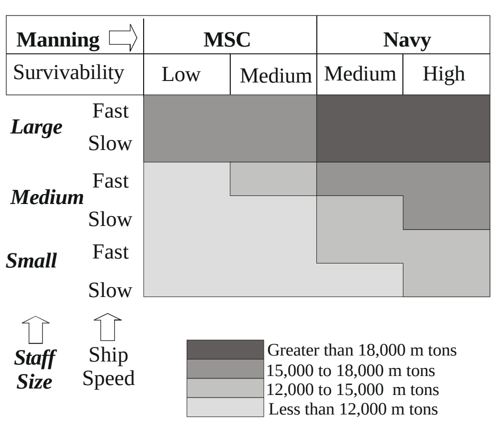

FIGURE 2: Example of Design Space Study results – Light Ship Displacement

Modified-Repeat Studies

Performing Modified Repeat Studies is actually more difficult and expensive than developing a new design in Concept Exploration. In a modified repeat study, one has to spend a considerable amount of time studying the parent to determine what should be kept and what should be removed. For non-Navy ships, or ships that have not yet been constructed, obtaining accurate technical and cost data can be challenging. Even if an ASSET model of the parent ship exists, it probably requires updating and validation to ensure it reflects the current configuration of the parent ship. Modifying the ASSET model to fulfill the new mission must also be done with great care to avoid making inappropriate changes. In some cases, enough technical data may not exist and feasibility must be determined by creating 2D arrangement drawings and approximating weights and other naval architectural properties. To keep concept exploration costs down, one should minimize the number of modified repeat studies performed. If possible, use compelling arguments other than modeling to eliminate modified-repeat candidates.

Ships that were considered candidates as hull parents for a dedicated command ship modified-repeat design were T-ADC(X) [now T-AKE], LMSR, LPD 17 and LHD 8. Modified-repeat studies showed the usual virtues: reuse of existing design segments, shared production lines and shared logistics support. They also showed the usual problems: baseline hull is either too large or too small for the desired mission payload, and it locks in elderly HM&E technology and associated manning levels. The T-ADC(X) study was conducted over the summer by three student interns. The study results were not so favorable as to mandate a mod-repeat JCC(X) hull nor so bad as to forbid consideration of them. The results of this study led to the recommendation that industry be allowed to propose modified-repeats, once a specific mission package was defined. These results were not surprising as past history has shown that modified repeat designs are generally not cost effective if significant changes or three or more vessels are required (Covich and Hammes 1983).

Future ships that were considered as possibly being fitted with command nodes, in addition to their main mission, were CVNX and LHA(R). It is always a touchy situation when you tell another program manager (PM) that the AOA will consider grafting another mission onto his program. The other PM's first reaction is to forbid such a study as an unwanted complication to his program plan. It has to be pointed out that an AOA director has a wide charter to study anything of interest regardless of the desires of other programs. Normally a mutually beneficial relationship can be worked out where the other PM contributes study resources and, in return, the people conducting the AOA will ensure that the PM's opinions on cost, schedule and performance risks of such a change to an on-going program are incorporated into the study results. In fact only a limited amount of feasibility engineering was done on CVNX and LHA(R) since the major issue of those ships was schedule: New CVNX and LHA(R) assets would enter the fleet only every 4-5 years, requiring many years to replace the existing command ships. Generally the long replacement interval, typically several decades, required an interim solution for JCC(X) that would have to be paid for. The combination of the interim solution and the modification of a large number of ships resulted in Total Ownership Costs rivaling new construction, but with considerable loss of operational flexibility.

Conversion of Existing Ships

Conversion studies are conducted in a similar manner as modified repeat studies. As with modified repeat studies, it is often cheaper to argue against a conversion on a basis other than the creation and analysis of a model. For JCC(X), existing ships that were considered candidates for complete conversion were laid up submarine and destroyer tender, and cruise ships. The submarine tender study is discussed in Appendix I. The problem with cruise ships was that, in spite of low prices of used ones, the low prices reflected that they were designed for 20 years service life. Incorporating cruise ships into the Navy would involve a new European base logistics train and, since it was unlikely that 4 sister ships would be available, each different class ship would have it own logistic train. Given the fact that all the rip-out and installation would be inefficient afloat waterfront work, there was not a major SCN savings.

Ships that were considered candidates for "node" ships were LHA/LHDs, CVNs and the first five CG 47s with their early Aegis and MK 26 launchers. The existing LHA/LHDs and CVNs are internally filled up with their current mission needs and, with the flight deck occupying most of the topsides, not suitable candidates for major addition of new antennas. A study on retaining Aegis and forward missile capability of the CGs, while adding hull and deckhouse volume aft to fit a maritime component commander, was judged infeasible due to lack of topside space for new antennas. Removal of all missile capability (hence topside illuminators) provided enough antenna space and additional command volume forward. A full conversion was feasible but unless other node ships for the other component commanders were bought at the same time, it was only a partial solution and would be on 20 year old ships, with half their service lives already consumed.

Service Life Extension Studies

The existing ships, two AGFs and two LCCs, were evaluated to see if extending their service life was warranted. Using aircraft carrier Service Life Extension Program (SLEP) experiences, a rough cost for an additional 10 or 15 years of life for the existing ships was estimated. Even after a SLEP, the ships would not have the capability to fulfill all the functions needed to support the JFC. An additional problem was one of schedule since each SLEP would require an 18-24 month yard period during which an alternative solution, such as a shore based facility, would be required. Furthermore, since the expected service life of the SLEPed ships was so short, the cost per year rivaled new construction. The only justification for a SLEP program would be as an interim solution based on an expectation that in 10 - 15 years other solutions, not currently available, could materialize or that reach-back technology could place all the staffs ashore.

DEVELOPMENT OF OPERATIONAL REQUIREMENTS

The Operational Requirements Document (ORD) is the responsibility of the OPNAV sponsor. Typically the Program Office and SDM will support the OPNAV sponsor in developing the ORD and should consider the following points:

- One should be able to acquire a ship meeting all of the threshold requirements with the funding available in the Future Year Defense Plan (FYDP). A program that does not have enough funds budgeted to meet the threshold requirements is not executable and will likely be cancelled.
- Unless the contracts with industry have appropriate performance incentives, objective values in the ORD have no meaning. No one has any incentive to greatly exceed threshold values of the ORD because increased performance typically costs additional funds, and cost is typically incentivized.
- In selecting Key Performance Parameters, try to select operationally significant parameters that predictive tools can accurately predict early in the design process. In this manner you can limit your technical, cost and schedule risk. Do not pick Key Performance Parameters that you won't know if you have met them until the first product is delivered.
- Make sure the ORD language is testable.
- Make sure the ORD language is unambiguous as to whether you pass or fail the criteria. Avoid specifying values that are a function more of analysis assumptions than of properties of the delivered product. A particular problem area is specifying numbers such as Operational Availability, Probability of Raid Annihilation, and Total Ownership Cost. This does not imply that these metrics are not important, rather the desired end state is to optimize their values (independent of the actual value calculated) within available R&D and SCN funds. This assumes that the analysis assumptions will not radically affect the optimal ship configuration, but will have significant impact on the calculated value.
- Avoid ORD language that places arbitrary limits on the design and do not have direct operational significance. This includes use of arbitrary limits on length, beam, displacement, crew size, etc. in an attempt to limit program cost.
- If possible, limit the requirements stated in the ORD to just those of the greatest significance. Put less significant requirements in the P-SPEC (hence, it's a good idea to have a draft P-SPEC while developing the ORD). The program office has change control over the P-SPEC while the Milestone Decision Authority has change control over the ORD. If a change is necessary, it is a lot faster and cheaper to implement a change in the P-SPEC than in the ORD.

It should be remembered that the ORD is the contract between the Program Office and the Milestone Decision Authority. In theory, it doesn't have to limit what is put under contract with industry. As long as the final product meets the ORD requirements, the project team has done its job.

THE SYSTEMS ENGINEERING PROCESS

Figure 3 shows the classical systems engineering process (DOD 2001) (DSMC 1999) featuring three stages plus System Analysis and Control: Requirements Analysis, Functional Analysis/Allocation, and Systems Design. The purpose of the Requirements Analysis block is to properly identify and document the user's requirements and translate those requirements into a set of technical requirements for the system. During Functional Analysis/Allocation the requirements identified in Requirements Analysis are translated into a functional decomposition that describes the product in terms of an assembly of configuration items where each configuration item is defined by what it must do, its required performance, and its interfaces. In a generalized sense, human operators can be considered configuration items or humanware during the Functional Analysis/Allocation process. Finally, during Design Synthesis, specific hardware, software, & humanware are defined that meet the requirements of the configuration items. Systems Analysis and Control provides the technical management activities to keep the entire process moving along on schedule, with acceptable performance, and within cost.

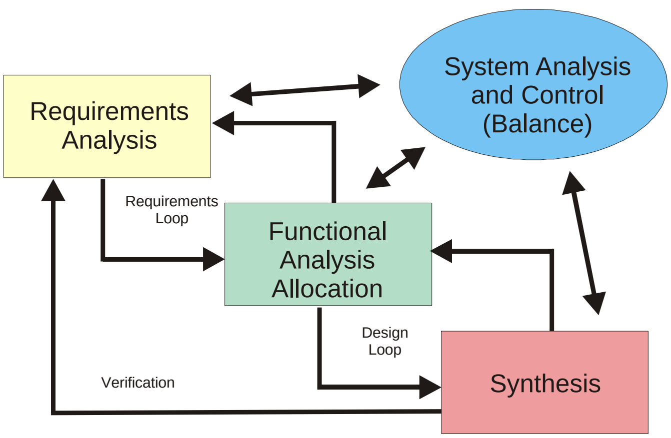

FIGURE 3: The Classic Systems Engineering Process

The problem with Figure 3 is that it is typically interpreted to be serial and iterative. This interpretation unfortunately, is simply wrong. In reality, all of the components occur concurrently. Additionally, the feedback loop from Synthesis-to-Requirements Analysis is more than just Verification. In actual practice, the systems engineering process works in the following manner:

- The Operational Requirements, Policy, Practices, Customs, and Imposed Requirements are analyzed and allocated to functional components (to include humans). These functional components become configuration items. In supporting the Functional Analysis and Allocation, the requirements should be analyzed to determine the probability that each requirement will change over the life cycle of the product. The allocation of functions should attempt to isolate the impact of likely changing requirements.
- The configuration items are synthesized by selecting / designing system architectures and associated hardware / software / humanware system elements.
- The selection of hardware / software / humanware system elements during synthesis results in the creation of derived requirements. Typically these derived requirements include many of the distributed systems onboard ship such as electrical power, compressed air, sewage, potable water, etc.
- These derived requirements generated during synthesis feed back to the Requirements Analysis Block (In addition to verification that the design and the developed product meet the requirements) which in turn feed into functional analysis and allocation to develop additional configuration items (or change existing configuration items) that fulfill the derived requirements. These new configuration items are then synthesized which in turn may create even more derived requirements. The process continues until the Synthesis loop does not create any additional derived requirements and the design is verified to satisfy all direct, derived, and imposed requirements.

Based on the above analysis, here are a few observations:

- There are three types of requirements: Direct, Derived and Imposed.
- Direct requirements are “owned” by the customer. To change a direct requirement you have to go back to the customer for approval.
- Not all direct requirements are specified in the ORD. Many direct requirements are in policy, practices, and customs.
- The designer controls derived requirements. The customer does not have to approve changes to derived requirements.

- Imposed requirements come from external bodies such as federal law or other federal agencies such as EPA or the US Coast Guard. Even helicopter certification by NAVAIR can be considered such an external requirement. Theoretically, a program or the customer can negotiate exemptions or waivers to imposed requirements but the track record of doing so at reasonable time and costs for the value of the change is not good.
- Trying to use requirements traceability tools to trace every requirement to the ORD is a waste of time and money. Traceability tools should be used to
    1. Identify Direct, Derived, and Imposed Requirements (Which requirements require customer approval for changes?)
    2. For Direct Requirements, it should determine which are traceable to the ORD and which to policy, practices, and customs. (Hence, which customer do I go to for approval for changes?)
    3. For Derived Requirements, it should determine what other configuration items are the source of this derived requirement. (What other components impact this requirement?)
    4. For Imposed Requirements, the source of the imposed standards should be traced.

As the current tools and models were being used, areas for creation of future improvements were identified and are presented in Appendix II.

COMMERCIAL STANDARDS

A command ship, unlike most naval vessels, has a ship-level commercial equivalent that appears to be very relevant – the ships of the cruising industry. While most programs have to deal with the Commercial Off The Shelf (COTS) issues at the component or system level, the JCC(X) studies had to do it at the platform level. The question had several variants: 1) should a used cruise ship be purchased and converted, 2) should an existing cruise ship design be used as a modified-repeat parent for a new ship or 3) should cruise ship systems be fitted to a new hull?

The SDM and PNA had to learn about the commercial ships by reading the literature, talking to organization familiar with commercial ships (such as the American Bureau of Shipping) and visiting an existing ship during its port layover. In fact, the cruise ship industry has developed items of direct value to any future command ship such as close alongside maneuvering systems and procedures / compartment layouts for quick on-and-off loading of large numbers of people and their bags. The cruise ship construction practice of using totally outfitted berthing compartments (built ashore in factories with complete units being lifted onto the ship and just connected up) is of direct relevance. The existing ship design models, including MONOLA, has some ability to do commercial-like ships but it is not very strong nor does it cover all the aspects of a truly commercial design.

PERFORMANCE SPECIFICATION AND ACQUISITION STRATEGY

DOD currently favors the use of Performance Specifications for the acquisition of Defense systems. This is a departure from how business was done 10 years ago and has an impact on the work accomplished during Concept Exploration. Here are some points to consider:

- Performance Specifications can and should contain detailed requirements for interfaces. These interface requirements also require specific validation requirements to prove that they are met with the delivered system.
- The Performance Specification (P-SPEC) should include in section 3 only the properties of the delivered product. Requirements for how the design should be accomplished belong in the Statement of Work. Requirements for how the contractor demonstrates that the design meets the

requirements of section 3 of the P-SPEC should be in section 4 of the P-SPEC.

- Section 4 of the P-SPEC should include verification methods for all stages of ship design, construction, and delivery.
- The contractor should be able to meet the threshold requirements of the P-SPEC with available funds.
- The contractor doesn't have any incentive to exceed threshold requirements unless the contract includes incentives to do so.
- The P-SPEC thresholds do not have to match the ORD thresholds. In general, they should at least meet the ORD thresholds, but you may want to set them higher to reduce risk.
- The P-SPEC should ideally be less than 100 pages long. This figure is roughly the size of a document that one person can completely understand. If the document gets much larger, then coordination between multiple people interpreting the P-SPEC will likely result in lots of confusion, miscoordination, misunderstandings, and rework.

Typically, most programs start the development of the P-SPEC 4 to 6 months before the RFP is released. While it is possible to write a specification in this short period of time, the resulting specification often is not well written with many internal inconsistencies. In particular, a proven example of a good Performance Specification for a large complex system does not exist. Hence the SDM had a strong desire to start much earlier than normal. In fact, the work started on the P-SPEC over 2 years before its anticipated need. Initially, the low level P-SPEC work was used as a way to identify potential problem areas and the need for future studies. For the initial effort, only two people worked on it part time. In February 2001 the development was ramped up in order to have a P-SPEC in reasonable shape for review by industry after the award of "Early Industry Involvement" contracts awarded in September 2001.

Under a normal P-SPEC development process, one would appoint multiple Systems Engineering Managers (SEMs) for a number of ship systems who would lead working groups that would develop the applicable P-SPEC sections. Because work on the P-SPEC was starting much earlier and there was not much in the way of additional funds to do the work, that approach could not be afforded. Instead a small team of engineers (between 4 and 6 at any one time) was assigned to develop the draft Performance Specification. Any problems or possible alternative ways of writing P-SPEC language were documented in "Technical Issues". The Acquisition Manager and the SDM reviewed these "Technical Issues" to determine a resolution. The SDM could arbitrarily direct a solution or initiate a study. To fund these studies, "charge accounts" at various contractors and government labs were created ahead of time. As a study was identified, a study guide was created and negotiated with the appropriate organization to identify who would conduct the study and the fixed price for the study. In this manner, technical expertise was paid for only when needed. The drawback is that it requires very precise study guide development and strong oversight of the study to ensure a good product. It is important to insist on a written report (not just a Powerpoint presentation) detailing the work of the study.

One of the challenges experienced in developing the P-SPEC is how to deal with Derived Requirements. Ideally one shouldn't have to even mention derived requirements in a P-SPEC, but in the real world this isn't practical. Industry is not likely to produce a product with which the Fleet customer is completely satisfied, without derived requirement guidance. The P-SPEC should provide sufficient guidance to keep the contractor from needlessly deviating from good naval ship design practices. For example, the requirement for an electrical system is usually a derived requirement. One wants 60 Hz power at the electrical outlets, even if everything will work with 55 Hz. Hence, one wants to place some restrictions on the electrical distribution system, even if it is a derived requirement. The problem is that there does not exist a conceptual framework for incorporating derived requirements into the P-SPEC that provides sufficient, but not over restrictive, guidance for determining what types of P-SPEC language are appropriate and what types are not appropriate.

CUSTOMER FEEDBACK – DECISION SUPPORT

Although desirable, Decision Support tools were not employed to understand the preferences of the customer to develop the Operational Requirements Document because of program timing. Using such tools to support the development of the P-SPEC and procurement documentation was considered. The Design Space Studies have identified the ship impact and cost associated with many different features. Many of the features are desirable, but budgetary constraints will preclude the incorporation of all of them. Decision support tools enable the customers to evaluate the utility of the different features. These utility curves help establish the threshold and objective values in the P-SPEC and help the program office develop incentives for the contractor to produce a design that exceeds the thresholds.

In a previous tour of duty, the SDM had participated in decision support sessions and used lessons learned from those sessions in developing the plan for JCC(X). In particular the JCC(X) plan included:

- Only comparing options that are true design options. Facts of life such as those things required by law (Imposed requirements) shouldn't be evaluated.
- Participants must be suitably educated before the voting starts. In particular, each option must be explained, including its operational significance. The participants should be voting on the utility of the operational significance, not on their perceived analysis of the feature.
- Ensuring the correct formatting of the question. If the question is "what does a good warship need?", the answer will usually be more weapons and sensors. If the question is "what about your ship makes you or your sailors want to quit the Navy?" the priority of investments in reliable machinery, habitability, air conditioning, and pollution control will rise considerably.
- In keeping with an acquisition strategy stressing performance specifications, participants should be voting on capabilities and not systems.

SUPPORTING THE RESOURCE SPONSOR

The OPNAV Resource Sponsors play an important role in moving a program forward. Their major areas of interest are in the development of Operational Requirements (discussed previously) that match their direct inputs to the Planning, Programming, and Budgeting System (PPBS). In order to support the Sponsor with the PPBS process, the SDM and Program Office develop acquisition strategies and funding profiles. As a tool to translate the acquisition strategy into funding profiles, an Engineering Management Plan (EMP) was created. Most people are familiar with a SEMP or Systems Engineering Management Plan. A SEMP describes how a contractor intends to conduct its systems engineering activities. The EMP compliments the SEMP in that it describes how the government intends on accomplishing its engineering responsibilities. In today's environment where virtually everyone working on the program must be funded by the program, the SDM must have a clear understanding of all personnel requirements over the life of the program. The EMP is a tool for estimating the amount of support (and associated funds) that are needed to fulfill the responsibilities of a ship design manager. The EMP has been in constant flux as the acquisition strategy evolves, and as the P-SPEC, RFP and SOW evolve. Note that for each element of section 4 of the P-SPEC, the EMP should identify the government effort required to validate the requirement.

CONCLUSIONS

Most previous Analysis of Alternatives were conducted for planes, ships or systems to replace ones already under production using an established construction infrastructure. This meant that there was also a large user community who already had ideas about where technology was going and what the next generation of requirements should be. This large community, by sheer gravitational pull of existing infrastructure and R&D programs, moves an AOA in a certain direction. This is not the case with command ships. The last command ship was delivered in 1971 and was not designed for a Joint role, so there is no existing production infrastructure and there is not a large existing joint command ship community. Thus, the JCC(X) was a relatively pure clean-sheet-of-paper AOA. It was not even certain if the function required a ship at first. The eventual decision that a forward deployed ship was necessary required an unusually wide range of staff sizes and ship possibilities to be evaluated. The answer could have been multiple interconnected ships with different primary missions or dedicated command ships. The existence of multiple options required novel approaches to designing the concept studies and evaluating the results. The many possible hull options (such as conversions, modified-repeat designs or Service Life Extensions) meant that just-good-enough-to-do-the-job engineering approaches had to be customized for those concepts. With the existing ship approaching 40 years of age, the schedule of when replacements could be made available was as important an issue as cost and performance. The AOA was different from most previous ship ones because the end products were to be consistent with acquisition reform instead of the traditional Navy controlled design. Since future ship programs will also likely incorporate acquisition reform, the lessons learned and successful methods used by the Navy community to support the completion of this complex AOA should be studied for application to future AOAs.

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Philip Sims graduated from Webb Institute in 1971 and went to work for the Advanced Design Branch of the Naval Ship Engineering Center (now NAVSEA). He was part of the FFG 7 design team in 1972. From 1973 to 1975 he was involved in creating automated early stage aircraft carrier design procedures and performing carrier design studies as part of the Sea Based Air Study and CVV design. He returned to school in 1976 for a master’s degree

at MIT. The 1977-80 period was spent in updating in the Navy's destroyer-cruiser early stage design procedures and conducting design studies for the CGN 41, the reserve FFX, and the DDX (later DDG 51) projects. During this period he was also team leader on concept formulation (CONFORM) studies of new ships such as a heavy combatant and a survivable cruiser. From 1981-83 he was the naval architect on the BB 62 modernization/ reactivation and Ship Design Manager for the BB 61 and CA 134. He was member of the NATO Staff Requirements Working Group for the NATO Frigate Replacement for the 1990s (NFR 90) and the principle naval architect on NFR 90 at NAVSEA. The early 1990s were spent on CGN, DDG 993 and CG 47 modernization studies. He conducted Navy studies of the Arsenal Ship, prior to the award to industry teams, followed by review of the industry ships. He prepared destroyer/frigate studies as part of the Force Architecture phase of SC 21. In 1999, he started conducting the first pre-milestone A studies of JCC(X).

APPENDIX I – SUB TENDER CONVERSION STUDY

Two Submarine Tenders (AS 33 and 41; sister ship is shown in Figure I-1) and two Destroyer Tenders (AD 38 and 42), currently in the Ready Reserve Fleet, were considered candidates for conversion given their large size and volume.

FIGURE I-1: Submarine Tender AS-36

Converting the laid-up tender type ships to a JCC(X) that accommodated an approximately 450 man joint staff was feasible based on a overall size/volume comparison with the LCC 19 class. However, the study did not proceed to produce internal layout or topside drawings and weights for a JCC(X) configured tender. It was conducted at a much higher level. A short survey of a tenders weight estimate showed that about 27% of the light ship would have to be scrapped to make room for command facilities. Figure I-2 is a typical new JCC(X) light ship weight fraction pie chart while Figure I-3 is typical new JCC(X) cost fraction pie chart. The weights saved by converting a tender were primarily SWBS groups 1 (structure), 2 (machinery) and 3 (electrical plant) which make up about 68% of the light ship. However, those groups only make up 26% of a new ship cost. The first penalty of saving those groups is the cost of precision scrapping of the 27% of the sub tender to be removed. Precision scrapping, unlike regular scrapping where whole hunks of a ship can be dragged into a field to be easily disassembled, required careful tagging of items to be kept and cutting around them. It was estimated that it took 1/2 the man-hours of installing new systems to precision scrap old systems. This is why, normally, the preferred hulls for major conversion of merchant ships to naval uses are container ships or tankers – being full of air, they do not come with a large precision scrapping bill. For the tender conversion, the new JCC(X) electronics, mission systems support auxiliaries and new living spaces would have to be installed on the ship but it would not be shop work or open assembly field work but the most inefficient type of shipyard work which is afloat modifications to the ship. Thus the new parts of a ship would come with a significant man-hour installation penalty compared to putting those same systems on a new hull. The summary of the precision scrapping bill and the penalized new installation rate was a ship whose cost rivaled that of a new ship.

The tenders have unusual features such as bilge keels hanging down from the flat of bottom instead of the turn of the bilge in order to avoid stabbing alongside customers. They have a relatively full waterplane hull so, when lifting heavy weight with cranes, there would be little list. The power plant design was predicated on occasional movements from port-to-port rather than continuous deployments. The steam plant’s higher fuel use and manning would mean that Operating and Support Costs would be significantly greater than for an equivalent new ship design. Thus the tender hull steel and machinery saved by conversion of the ships would be hull steel and machinery that didn’t match the mission in the first place.

The study results given to the AOA director was not a traditional naval architectural design study but more of industrial efficiency and comparative naval architectural analysis. It was “good enough” to convince the study director that further engineering effort was not needed. Many of the studies in an AOA are like that – the first cycle must evaluate risk, cost, schedule and suitability of the basic concept. If a convincing case that it is fatally flawed in any of those areas can be prepared, an extensive engineering effort is not warranted.

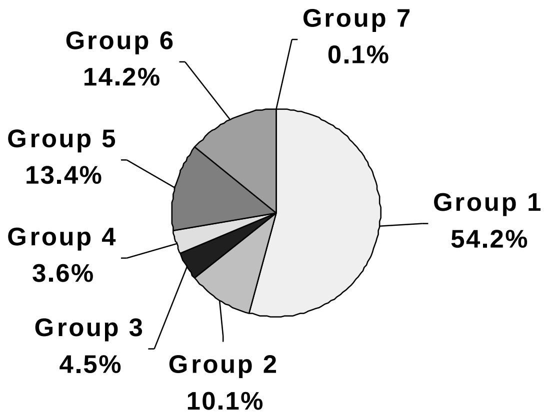

FIGURE I-2: Typical JCC(X) SWBS Weight Fractions

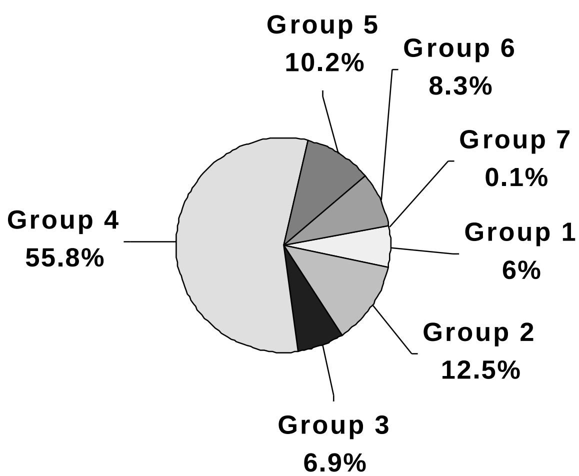

FIGURE I- 3 Typical JCC(X) Procurement Cost by SWBS

APPENDIX II – FUTURE RESEARCH OPPORTUNITIES

Genetic Algorithms

It may be possible to eliminate some of the errors associated with the "learning curve" and the "Art of Naval Architecture" by employing genetic algorithms to obtain something close to an optimum solution for each concept. The metrics for optimization should include those elements one is trying to measure. Hopefully the errors associated with differences in concepts will be more randomly distributed.

Error Analysis Tools and Procedures

Many of the Navy's analysis tools are deterministic and provide answers that may include a considerable amount of error. It is not clear if the sources or the magnitude of these errors are well understood. As long as the errors do not lead us to an incorrect decision, the value of the analysis is retained; the errors are small enough to be considered minor static on a solid carrier wave. Unfortunately, the only current way of knowing whether the tools are lying or not is the experienced engineers intuitive sense of "something not being right". The next stage of improving our models it to have more error analysis incorporated into the design tools.

Experimental Design Tools

A lot of effort has been expended in being able to link different computer tools together to address complex problems. Not much effort has been expended in determining which computer tools are required to address a problem and what assumptions are required to drive the computer tools. In many of the large studies, this effort was largely done by hand and documented in Study Guides. Tools to help develop Study Guides would be beneficial.

Requirements Risk Analysis

Typically Risk Analysis is used to control Schedule, Cost, and Performance Risk. Requirements Risk Analysis should also be performed to anticipate and mitigate the cost of changes in customer or derived requirements. Requirements Risk Analysis is a means for applying well known risk management techniques to identify requirements that are likely to change over the service life of the ship and to develop mitigation plans for dealing with these changing requirements. Typically an engineer desires to develop systems that meet a specific set of requirements. In reality, the requirements are not always that firm and change over time. To date, the approaches for dealing with uncertainty in requirements has been ad hoc such as using margins based on past performance problems, and indiscriminately mandating open systems architectures or modularity (whether or not they are warranted). This had led to many missed opportunities for building flexibility into the design where they can have significant payoff.

The requirements analysis block of the systems engineering process should incorporate a risk analysis. In this manner, the functional allocation block can help mitigate high-risk requirements by partitioning them into their own configuration items. Likewise, the synthesis block can incorporate systems that in turn create derived requirements with low requirements risk. In this manner, Requirements Risk Analysis becomes an integral part of the systems engineering process and should result in robust systems capable of quickly adapting to changing requirements.