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Systems Engineering and Zonal Ship Design

ABSTRACT

This paper relates the Defense Acquisition University defined systems engineering process to zonal ship design at the concept and feasibility design level. In particular, it describes an effective way of capturing a complete set of customer requirements based on the Universal Navy Task List (UNTL) and allocating these required functions to system packages comprised of hardware, software, and manpower elements. These system packages are allocated to ship zones such that loss of adjacent zones will result in the retention of sufficient system packages to meet survivability requirements. The allocated system packages also are used to establish zonal distribution system requirements to enable zonal distributed system design in a manner described in a previous paper presented at the ASNE Reconfiguration and Survivability Symposium in February 2005. System packages can also be used to develop skills based manpower requirements to determine required shipboard accommodations. The software element of the system packages can be used to estimate software development cost as well as Total Ship Computing Environment needs. The paper will also highlight ongoing efforts to incorporate this process into early stage ship design tools at NAVSEA.

INTRODUCTION

Naval architecture and ship design have relied heavily on systems engineering principles for many years. In fact naval architects practiced systems engineering considerably earlier than the post-World War II establishment of the systems engineering field. In designing ships however, Naval architects have viewed requirements in terms of what the ship has to do in terms of size, speed, payload, crew size, survivability features and so on. In the past fifteen years however, defense acquisition policy has shifted to requirements in the form of capabilities. Capabilities are expressed in terms of missions and mission effectiveness. This change in requirements language forced the ship designer to translate this new capabilities based requirement into the ship features based requirements that the available ship design processes and tools are capable of using. Unfortunately, this translation process has not been formalized, resulting in each ship design project conducting it in different non-repeatable ways.

Within the past 5 years, Navy decision makers have not been willing to wait more than a few months for the development of ship concepts. To be useful and relevant, ship studies must be completed quickly and accurately. Hence a need exists for a formalized method for defining capabilities and designing ship concepts to meet those capabilities in a timely manner. The ship concepts must be developed to a level of fidelity to enable comparisons with other ship concepts in terms of cost and capability.

This paper proposes a method for implementing the systems engineering process as currently taught at the Defense Acquisition University to zonal ship design for concept and feasibility design. The proposed process describes customer requirements based on the Universal Navy Task List (UNTL) and allocating those capabilities to mission system packages. These mission system packages are allocated to ship zones in a manner that satisfies survivability requirements. Derived Requirements from the collection of mission system packages are fulfilled with zonal distributed systems and other support systems. Manpower Requirements as well as non-recurring engineering requirements are also derived from the mission system packages and zonal distributed systems.

SYSTEMS ENGINEERING

Figure 1 shows the systems engineering process as taught by the Defense Acquisition University. (Defense Systems Management College 2001). This systems engineering model features three stages plus System Analysis and Control: Requirements Analysis, Functional Analysis/Allocation, and Systems Design. In Requirements Analysis, the systems engineer identifies and documents the customer's requirements and translates them into a set of technical requirements for the system. During Functional Analysis/Allocation, the systems engineer translates the requirements identified in Requirements Analysis 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. Configuration items can be hardware, software, or manpower. Finally, during Design Synthesis, specific hardware, software, & crew billets are defined that meet the requirements of the configuration items. Systems Analysis and Control provides the technical management activities to keep the entire process progressing on schedule, with acceptable performance, and within cost.

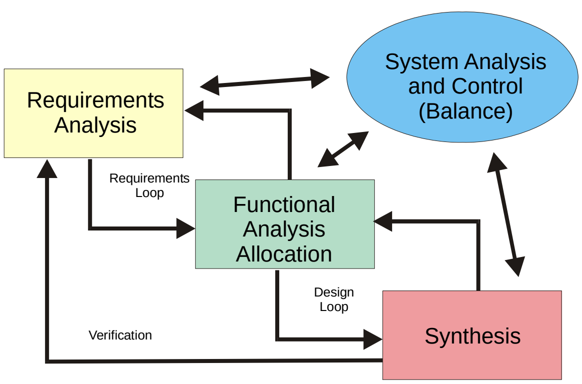

FIGURE 1 Systems Engineering Model

Often, the systems engineering process described in Figure 1 is viewed as a serial process. In reality, all stages are conducted concurrently. See Doerry and Sims (2002) for additional insight on the application of the DAU systems engineering model to Concept Design.

SHIP DESIGN PROCESS

The previous section describes a general model for systems engineering that can be applied to any product to develop varying degrees of product definition. Another way to look at the ship design process is by the establishment of configuration baselines. In this view, ship design can be considered to consist of three largely sequential stages: Early Stage Design, Preliminary & Contract Design, and Detail Design & Construction.

Early Stage Design (ROM and Concept Studies)

The purpose of early stage design (ROM and Concept Studies) is to provide Navy leadership insight with respect to cost versus capability for the purpose of establishing the Functional Baseline and associated budget for a ship acquisition program. The Functional Baseline describes the capabilities that the ship must have to fulfill its mission requirements. In the past, the Functional Baseline took the form of Top Level Requirements (TLR) or an Operational Requirements Document (ORD). Under the current Joint Capability Integration and Development System (JCIDS) defined in CJCSI 3170.01E, the Functional Baseline is initially captured in the Initial Capabilities Document (ICD) based on analysis conducted in early stage design and refined in Preliminary Design as the Capability Development Document (CDD).

It is important to remember that while the goal of the later stages of design is synthesizing a ship design to meet requirements, the goal of early stage design is to synthesize requirements based on insight gained from developing multiple concept designs and performing other analysis. Early stage design studies can last in duration anywhere from 1 day to 1+ year, depending on the nature of the questions the studies are meant to answer and the required fidelity of the answer. Table 1 shows the current categorization of early stage studies used by the Future Concepts and Surface Ship Design Group (SEA 05D) in NAVSEA. (NAVSEA 31 JAN 2005) Typically, most of the early stage design effort is spent on Study Level 3 ROM studies of 1.5 to 6 weeks in duration.

TABLE 1 NAVSEA Categorization of Concept and Feasibility Studies

Study Level	Description	Duration	Typical Product
1	Quick ROM	0.5 weeks	Email
2	Fast ROM	1.4 weeks	Letter Report
3	ROM	1.5 - 6 weeks	Letter Report
4	Extended ROM	4.5 - 12 weeks	Letter Report
5	Concept Studies	3 months	Letter Report
6	Concept Studies	4-5 months	Letter Report
7	Feasibility Studies	6 months	Design Report
8	Feasibility Studies	8 months	Design Report
9	Feasibility Studies	1 year	Design Report
10	Pre-Preliminary Design	1+ years	Design Report

Early Stage Design ends with the attainment of an Acquisition Milestone A decision. At Milestone A, the basic capability requirements for the ship are established. Additionally, the projected cost of the ship acquisition program is integrated within the Navy's overall budget.

Preliminary and Contract Design

The major goal of Preliminary Design is stabilizing the Functional Baseline and cost estimates. During Preliminary Design, the Functional Baseline is captured in the CDD. For many ships, Preliminary Design is normally of about 1 year in duration and consists of multiple 2 to 3 month design iterations. During these iterations, the design team identifies critical system interfaces, Government Furnished Equipment (GFE), Government Furnished Information (GFI) and Class Standard Equipment (CSE). Essentially, Preliminary Design establishes the Operational and Systems architectures for the ship.

During Preliminary Design, many cost versus capability decisions will be made based on a series of trade-studies. These decisions will be reflected in both the evolving configuration of the Preliminary Design and in the evolving CDD. Additionally, Preliminary Design will begin to identify specific technical and programmatic risks

Often, there is not a clear boundary between Preliminary and Contract Design. Contract Design begins when the Functional Baseline is stable enough so that remaining anticipated changes will not cause significant rework in the definition of the Allocated Baseline. The end of Preliminary Design occurs at the successful completion of a Preliminary Design Review (PDR). In some cases, Contract Design can start before Preliminary Design finishes.

The Primary goal of Contract Design is the establishment of the Allocated Baseline in the form of Ship Specifications, Project Peculiar Documents (PPDs), Contract Drawings, and Statement of Work (SOW) language. Contract Design normally takes about one year to accomplish. The major design activities that take place are

- Engineering Development of the Preliminary Design
- Risk Reduction
- Refined Cost Estimation
- Translation of the completed design into a technical package consisting of specifications, PPDs, Contract Drawings, and other data.
- Extensive review and certification of the technical package by Technical Authorities.

During Contract Design, the Functional Baseline in the form of the CDD may be refined, but should largely remain stable. The end of Contract Design occurs with the successful completion of a Critical Design Review (CDR) and the certification of the Allocated Baseline. (NAVSEA 2004)

Detail Design and Construction

Detail Design and Construction, performed by the Shipbuilder with oversight by the Government, commences with the award of the Detail Design and Construction contract following the Milestone B acquisition decision.

During Detail Design, the Allocated Baseline defined in the contract package is implemented and documented in the Product Baseline consisting of Detail Drawings and other engineering and production planning products.

EARLY STAGE ZONAL SHIP DESIGN

The previous section described the generic ship design process as currently practiced in the U.S. Navy. The following sections describe how Zonal Ship Design can be implemented to improve the ship design process, particularly during early stage design when many important decisions are made.

Concept Capabilities

As stated earlier, the purpose of early stage design (ROM and Concept Studies) is to provide Navy leadership insight with respect to cost vs capability for the purpose of establishing the Functional Baseline and associated budget for a ship acquisition program. To provide the requisite insight, it is not unusual to develop hundreds of ship concepts to systematically explore the design space using Design of Experiments and Response Surface Methodologies.

The input to an individual concept design consists of the desired capabilities and concept of operations for the concept. Currently, the capabilities under study are documented in a Study Guide (NAVSEA 14 OCT 2005). Many more ship capabilities that are not of interest are assumed. Currently these assumptions are at best documented in the synthesis tool model. The danger in this practice is that differences between concepts may be influenced by unintentional differences in assumptions. This error in calculating differences between concepts can lead to wrong conclusions with respect to cost versus capability.

What is needed is a comprehensive list of tasks that a generic Naval Warship can be expected to fulfill as well as the level of performance expected for these tasks. By using such a comprehensive list to describe the desired capabilities of a ship concept, and deriving the ship configuration from the comprehensive list, then the chance for unintentional differing assumptions between two concepts can be minimized. Holding all capabilities but those under study constant will improve the comparison of cost and capabilities between the concepts.

While such a comprehensive list of tasks has not previously been used in ship concept studies, such a list has been created to assist the operational fleet in battle force planning and training. The Universal Navy Task List (UNTL) as defined in OPNAVINST 3500.38A provides a master menu of tasks, conditions, and measures to establish a common language and structure for Navy Mission Essential Task Lists (NMETLs). The UNTL combines Strategic and Operational level of war tasks from the Universal Joint Task List (UJTL) with the Navy Tactical Task List (NTTL). Within the UNTL, a task is defined as "actions or processes performed as part of an operation." Tasks are defined to describe a discreet activity visible outside the command. Tasks do not define who, or how the activities are accomplished. As such specific equipment or environmental issues are not included in the task definition.

As defined in the UJTL "Conditions are variables of the environment that affect the performance of tasks in the context of the assigned mission. They are categorized by conditions of the physical environment (e.g., sea state, terrain, or weather), military environment (e.g., forces assigned, threat, command relationships), and civil environment (e.g., political, cultural, and economic factors). Some conditions are designed to help describe the theater of operations (e.g., hostnation support), others describe the immediate operational area (e.g., maritime superiority), while still others describe the battlefield conditions (e.g., littoral composition). When linked to tasks, conditions help frame the differences or similarities between assigned missions."

Measures describe how well an organization or force must perform a task under a specific set of conditions for a specific mission. Within the operational forces, the list of tasks that are essential to successfully complete an assigned mission under the specific conditions and to the assigned measures is called the Naval Mission Essential Task List (NMETL). (Naval Warfare Development Command 2000)

The author proposes that an analogous list, the Naval Concept Essential Task List (NCETL) be defined as the cumulative list of tasks that a concept is designed to accomplish under the specific set of conditions and to the assigned measures. The NCETL should employ the tasks, conditions, and measures defined in the UNTL to the greatest extent practical. This should not be difficult with respect to tasks and conditions. However, the measures defined in the UNTL may not be sufficient to characterize a ship concept and may require augmentation.

Ideally, a software tool would exist to enable the Naval Architect to rapidly create an NCETL and compare the NCETLs of different concepts. In such a way, the design capabilities of two concepts can be quickly compared. The NCETL would also provide a way to systematically vary capabilities in Design of Experiments based studies.

System Packages

Once the capabilities for a ship concept are defined in a NCETL, these capabilities must be allocated to systems, software, and manpower as part of the "requirements loop" of the systems engineering process shown in figure 1.

Many capabilities can be fulfilled in an "open loop" fashion by including specific systems, software, and manpower independent of other ship characteristics. In other words, before beginning the design effort, the naval architect can predict what is needed to achieve the capability. Other capabilities, such as "sortie generation rate" and "probability of raid annihilation" are a function of the overall ship design and are achieved by iterating the design in a "closed loop" manner as shown in figure 2. These iterations comprise the "Design Loop" of figure 1.

Because Open-Loop Design only requires one iteration, it can be accomplished much faster and cheaper (Design costs only) than Closed-Loop Design. To reduce the design effort and associated design costs, as much of the ship design should be accomplished using Open-Loop Design. Unfortunately, this is not always possible or desirable. In a number of technical disciplines, the predictive abilities of our tools are not sufficiently accurate to perform Open-Loop Design without significant design margins that negatively impact the acquisition cost of the ship. Closed Loop Design is desirable when there is enough time and the cost of additional design iterations is offset by reductions in acquisition costs across the production run of ships.

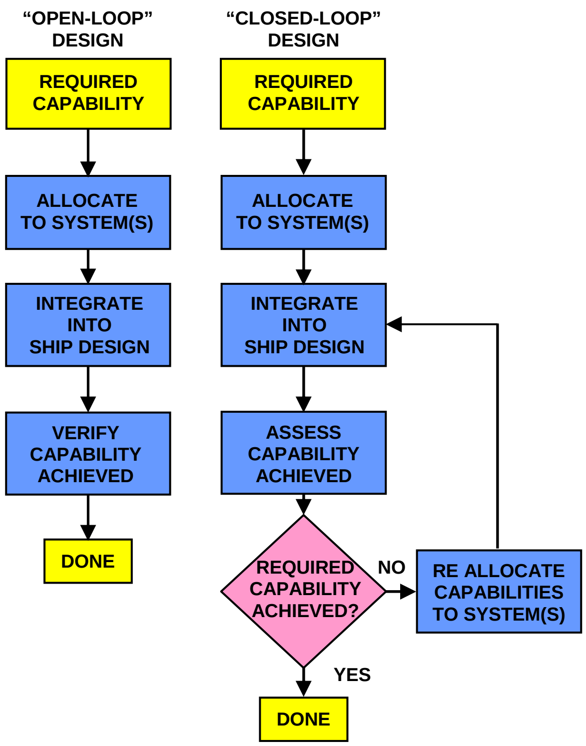

FIGURE 2 Open Loop versus Closed Loop Design

In early stage design, time is often in short supply. Consequently, the use of Closed Loop Design should only be used for capabilities that have a large acquisition or life cycle cost impact.

Even when Closed Loop design is used, the goal should be to minimize the number of design iterations.

To reduce the time required to allocate capabilities to systems and then synthesize system solution in both Open-Loop and Closed-Loop Design, the author proposes the creation of a library of "System Packages" to map tasks from the UNTL to existing mission system solutions. These "System Packages" would consist of:

- Capability Performance
    - UNTL Capabilities satisfied by this System Package
    - Measures the System Package can achieve for specific Conditions
- Hardware Descriptions
    - Expanded Ship Work Breakdown System (ESWBS) code + Nomenclature
    - Geometric + Mass Properties for the entire package or for each of several sub-packages (if needed)
    - Distributed Systems Needs
    - Ship Arrangement Considerations
    - Integrated Logistics Support (ILS) Needs
- Software
    - Amount of Total Ship Computing Environment (TSCE) Re-use code required
    - Amount of TSCE New code required
    - Other TSCE requirements
- Manpower
    - Watch-standing Skill-Objects and Manhours
    - Maintenance (Preventative (PM) and Corrective (CM)) Skill Objects and Manhours

For capabilities that can be satisfied with Open-Loop Design, incorporation of the applicable System Package from the library of Packages into a design would be sufficient to ensure all requisite mission equipment are included. Of course, the distributed system needs of the System Packages levy additional Derived Requirements that must in turn be allocated and synthesized.[1]

Capabilities requiring Closed-Loop Design, generally are a function of multiple System Packages and the manner in which they are integrated to form a total ship solution. The library of packages can help in managing the collection and configuration of the multiple packages for each iteration, but the library does not address how to integrate the packages to achieve the desired capabilities. To simplify integration, zonal design offers opportunities to the naval architect.

Design Complexity

Zonal Design is a technique for reducing design complexity. Design Complexity is hard to define, but its impact is well known. Bob Colwell claims complexity lead to fragile designs that are very sensitive to small perturbations. (Colwell 2005) It also complicates design management because few engineers understand the whole design. This can lead to sub-optimal design or different design teams working to cross-purposes.

Colwell does not attempt to quantify complexity, but states it is a function of:

- "Number of ideas you must hold in your head simultaneously;
- Duration of each of those ideas; and
- Cross product of those two things, times the severity of the interactions between them."

While a generalized complexity metric is likely not achievable, in the context of ship design, it

[1] In the DAU Systems Engineering Model, the loop from "Synthesis" to "Requirements Analysis" is labeled "verification." The author contends that this loop would better be titled "Derived Requirements" to indicate the process of integrating mission systems with the distributed systems supporting them.

may be possible to calculate an indicator for complexity. The author proposes the following metrics

$$SCF_i = \sqrt{\frac{1}{2}\left(\left(\frac{m_{systems\_touching}}{n_{3\_digit\_NTT}}\right)^2 + \left(\frac{m_{spaces\_impacting}}{n_{spaces} - 1}\right)^2\right)}$$

$$SCM = \sum_{i=1}^{n_{spaces}} SCF_i$$

Where:

SCF_i	Space Complexity Factor
SCM	Ship Complexity Metric
$m_{systems\_touching}$	Number of Systems touching a space
$n_{3\_digit\_NTT}$	Number of 3 digit Tasks in the NCETL
$m_{space\_impacting}$	Number of other Spaces, which if modified within limits, will impact a system within this space
n_{spaces}	Number of spaces in the ship

The complexity factors recognize that later stages of ship design currently are centered on the arrangement of spaces and groups of spaces that form construction modules. The number of systems touching a space is an indirect measure of the number of design teams that must coordinate their activities to design the space. The complexity metrics are also intended to capture the sensitivity of the overall design to small perturbations that typically occur during the design process. In other words, a less complex design will prevent design perturbations in one space from propagating through-out the ship.

Please note that the Ship Complexity Metric addresses complexity of design integration. It does not measure the complexity of individual systems. In fact a less complex ship design may be composed of very complex systems.

Zonal Design

Zonal Design enables the naval architect to assign mission functions to specific zones of the ship in a manner that can reduce ship complexity, enhance survivability, and reduce the amount of closed-loop design required to integrate a ship.

A zone is a geographic region of ship. The boundaries of the zone can be arbitrary, but to maximize survivability, the zones of multiple distributed systems as well as damage control zones should be aligned. For shipboard distributed systems, this typically means the zone boundaries are the exterior skin of the ship and selected transverse watertight bulkheads. The zone boundaries may rise above the watertight bulkheads into the superstructure, or the superstructure may be composed of one or more zones independent of the zones within the hull.

The size of a zone is a compromise between increased survivability and cost. In general, damage from threats that are not over-matching should be limited to one or two adjacent zones. However, zones should not be so large that a significant amount of mission system equipment will remain undamaged but inoperative due to a lack of required services from damaged distributed systems. For most combatants, about 6 or 7 zones is a good starting point, resulting in each zone being roughly 15% of the length of the ship.

For mission systems, Zonal survivability is the ability of a mission system, when experiencing internal faults due to damage or equipment failure confined to adjacent zones, to continue its function, perhaps at a somewhat lower level of performance, with the surviving equipment in undamaged zones. Zonal Survivability assures the impact of damage does not propagate outside the adjacent zones in which damage is experienced. Zonal survivability requires sufficient damage control features to prevent the spreading of damage via fire or flooding to zones that were not initially damaged.

To implement zonal design, the Naval Architect starts with the NCETL and chooses mission system packages to achieve the NCETL capabilities. These packages, or elements of the packages, are assigned to different zones of the ship. For the capabilities that are required to have zonal survivability, redundant packages, or redundant elements of the packages, must be assigned to different non-adjacent zones. This assignment of functions and associated equipment to different zones at the earliest stages of design is the key feature of zonal ship design.

When combined with zonal distributed systems design, this consistent approach to mission system design assures a minimum level of zonal survivability using an open-loop design methodology in the earliest stages of design. Contrast zonal design with the current closed-loop design methodology with its iterative synthesize, analyze, and correct design process.

Zonal Distributed Systems

As described earlier, the distributed system needs of the mission system packages are derived requirements that must in turn be analyzed, allocated, and synthesized. The use of zonal distributed systems as described in (Doerry 2005) ensures the zonal survivability of the mission systems is not compromised by un-survivable supporting systems.

Zonal distributed systems also help reduce ship design complexity by limiting the number of distribution elements that cross a space without servicing the space. In zonal distribution systems, only longitudinal mains run for fore and aft. Feeders generally run port or starboard and up or down. By careful location of the longitudinal mains, perhaps even using dedicated utility trunks, the number of spaces that must be "crossed" to reach the end user can be minimized.

Manpower Estimation

In early stage design, the size of the crew is usually estimated based on analogy to similar ships. Often, this estimate is crudely performed before the start of the study and documented as an assumption in the Study Guide for the concept study. Where a higher fidelity manpower estimate is required, tools such as the Manpower Analysis and Prediction System (MAPS) are employed. MAPS enables the naval architect to develop a crew size estimate by applying workload analogies at the Department or even Division level. MAPS has embedded within it the Ship Manning Document (SMD) data from many existing classes of ships. MAPS enables the user to systematically use the collective data from the multiple existing ships to develop a reasonable estimate for a new concept. New technologies, processes, and procedures can be modeled with additional effort.

Using System Packages offers an opportunity to trace manpower requirements to the NCETL which the current process does not explicitly do. In early stage design where developing insight is of high value, being able to see the impact of changing concept capabilities on ship manpower can contribute significantly to developing such insight. For example, assuring that the level of ship system automation and the manpower requirements are aligned is currently a manual process. It's now too easy to claim that a concept has a small crew because of automation, but not provide sufficient design information to ensure the cost estimate includes sufficient development and equipment costs to implement that level of automation. Because System Packages link hardware, software, and manpower, these elements should be properly aligned and costed.

Total Ship Synthesis

The final steps in zonal ship design are wrapping a ship hull around all of the zones, analyzing the total ship to ensure the concept "balances" and all concept capabilities are achieved, and executing one or more "closed loop" iterations if needed. Figure 3 graphically depicts the process starting with defining the desired concept capabilities in the NCETL, allocating these capabilities to System Packages, assigning the system packages to zones, identifying derived requirements for distributed support systems, synthesizing the distributed support systems, analyzing the total ship performance, and making any needed adjustments to the zonal system packages (closed-loop design).

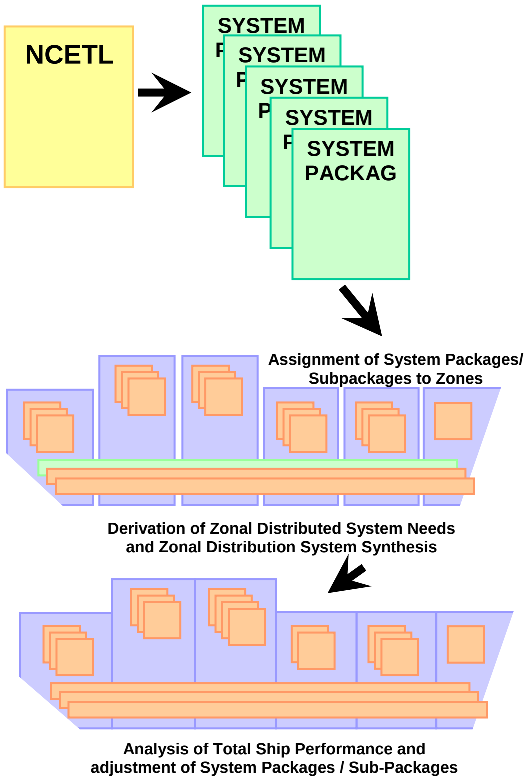

FIGURE 3 Zonal Ship Design Process

In balancing the ship, system packages / sub-packages and/or distributed system elements may have to be moved from zones with volume and/or area deficits to zones with available volume or area. When relocating packages, the Naval Architect must ensure that zonal survivability is considered.

FUTURE EFFORTS

Before Zonal Design can be incorporated into the standard business process for concept design in NAVSEA, a number of tasks still remain. These tasks include applying zonal design techniques to actual concept designs to gain a better understanding of the benefits and weaknesses of the method as well as to identify improvements in the zonal design process. Tools development is also needed. The current ship synthesis tool, the Advanced Surface ship and Submarine Evaluation Tool (ASSET) is not currently capable of directly performing zonal design; all of its algorithms are based on total ship calculations. Within the year however, ASSET will fully integrate with the Leading Edge Architecture for Prototyping Systems (LEAPS), which will enable it to more easily evolve within an open-architecture framework. Once fully integrated with LEAPS, ASSET users will be able to substitute existing modules in ASSET with replacement modules at run-time. This will enable rapid prototyping and evolution of zonal design tools by not tying the zonal design tool development schedule to the ASSET development schedule.

The Early Manpower Assessment Tool (EMAT), currently under development, is the first design tool designed to implement a portion of zonal design methodology. Its goal is to predict the crew size of a ship concept based on the required concept capabilities and the systems allocated to fulfill those capabilities. Much of EMAT will likely be based on MAPS, but the user will interact with program from a NCETL like interface.

Additional tools and processes will be required to fully implement Zonal Design. The concept of a System Package and its associated data structure must be formally defined and incorporated into LEAPS. A process must be established for maintaining the library of System Packages to ensure they are accurate for use by the concept designer. Design tools are needed to facilitate assigning packages / sub-packages to zones and verifying that the zone has sufficient area and volume to hold the allocated packages. Zonal Distributed System design tools are needed. Design Tools are required to quickly assess the survivability of a concept, the total amount of engineering effort required to integrate a design, the total amount of software development needed, and the complexity of a design.

CONCLUSION

Zonal Design offers the Naval Architect a design process for implementing the DAU Systems Engineering Process in a deliberate manner.

Zonal Design enables the linking of concept capability requirements to design solutions in a traceable manner not currently possible in early stage design. Zonal Survivability can be designed into the concept in a simpler and less costly, open-loop design process, than the current closed-loop design, analyze, fix process currently used. Zonal Design also offers the naval architect the opportunity to reduce design complexity and reduce the Non-recurring engineering effort in later stages of design.

Implementing Zonal Design will require an investment of resources to develop the necessary tools and processes. The impending integration of ASSET with LEAPS and the development of EMAT are the initial steps towards implementing a design environment suitable for conducting zonal design.

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