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THE PROCESS OF NAVAL SHIP GENERAL ARRANGEMENT DESIGN AND ANALYSIS

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He was selected for the long-term training program at George Washington University in 1974 and completed the program in February 1976 with the degree of Master of Engineering Administration.

While at NAVSEC, Mr. Hope has been General Arrangement Task Leader on the AO 177, DDG 47, CSGN, CSGN (VSTOL), CGN 9 (AEGIS), CGN 42, and assisted in the landmark NAVSEA Civilian Professional Community Study. In 1978, he was selected as acting head of the Damage Control Section. From that position, he was selected as acting head of the Surface Ship Hydrodynamic Section. In February 1980, he was promoted to head of the Surface Combatant Arrangements Design Section.

In addition to numerous outstanding performance awards, Mr. Hope was nominated for the Commander, Naval Ship Engineering Center Professional Development Award in both 1978 and 1979.

In 1979, Mr. Hope was presented the National Capital Award for Professional Achievement (under age 36) by the District of Columbia Council of Engineering and Architectural Societies.

Mr. Hope has presented numerous professional papers at ASNE and ASE Technical Symposia. Three of these papers have been published in the ASNE Naval Engineers Journal, and his papers, Management of Research and Engineering: Selected Topics, *won the JOHN C. NIEDERMAIR Award for the best paper presented at the 13th ASE Symposium. His memberships in professional societies include ASNE, ASE, SNAME, ASME, and U.S. Naval Institute. He has served as an elected officer in ASE since 1978.*

ABSTRACT

This paper describes naval ship general arrangement design and analysis, a system engineering process that seeks the optimization of the ship as a total system. Through this system engineering process, the ship is geometrically defined by allocating scarce resources of area/volume and functional location.

The general arrangement design team synthesizes a design from subsystem requirements, system constraints, and policymaker influences through iteration and negotiation into the optimum general arrangement. The use of volumetric and area ratios and indices in this process are highlighted.

The paper concludes with a discussion of a new methodology now under development for analyzing and comparing general arrangement alternatives. This new general arrangement evaluation methodology links operational performance objectives to ship design philosophy and subsystem effectiveness.

INTRODUCTION

THE DESIGN OF SHIPS IS SIMILAR TO THE DESIGN OF OTHER SYSTEMS in that the total system, the ship, is an organized or complex whole made up of subsystems that contribute to the characteristics of the total system. The ship which contains these subsystems has a performance potential derived from the performance of the subsystems working in combination with each other. For example, the ship may have the performance potential to execute the Anti-Air Warfare mission derived not only from the performance of the combat system to detect, acquire, track, and engage air targets; but also the capability to steam with the task force provided by the propulsion system; power to operate combat systems provided by the electrical system; and even the crew's mental alertness and physiological readiness provided by the human support system.

It is performance as a total system that is the measure of effectiveness of the ship. The total system is an integrated group of subsystems, each providing its element of performance. The final system design, and thus performance potential, is bounded by naval architecture requirements applied in the integration of these subsystems and by overall system design constraints, such as cost and displacement limits.

In naval combatant ships, subsystems which form the whole include combat, propulsion, structure, human support, logistic support, life support, auxiliaries, electrical, aviation, damage control, and survivability systems. There are engineering design disciplines associated with the design and development of each of these systems. In addition, there are engineering disciplines associated with the integration of these subsystems into the total ship including general arrangement design, mass properties analysis, stability analysis, and hull form design — traditional areas of naval architecture. Furthermore, there are also system design constraints expressed in many areas but usually these are ultimately related to cost constraints, which in the design of U.S. naval ships are often expressed in terms of weight limits.

The nature of design constraints established for naval ships result in limited availability of principal resources in total ship system design including area/volume and weight. The nature of naval architectural design requirements for floating bodies moving through water are such that the area/volume resource is constrained to: (1) shape factors resulting from hull form and (2) weight location resulting from stability requirements. The result of these design constraints and naval architectural requirements is that, in the typical naval combatant ship design, subsystems are in competition for scarce resources which are insufficient to optimize each subsystem independently of the other subsystems. It is

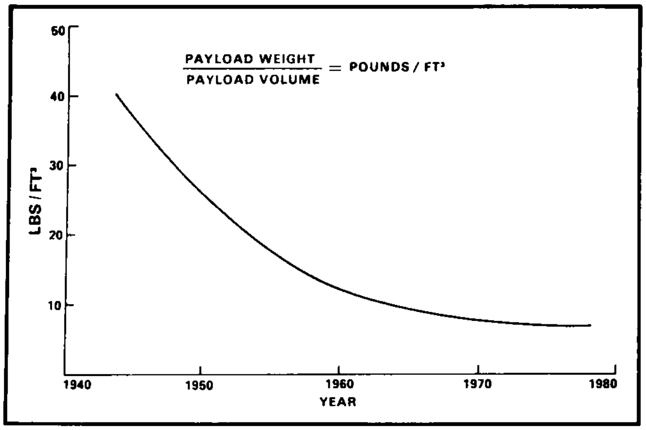

Figure 1. Payload Density Trend.

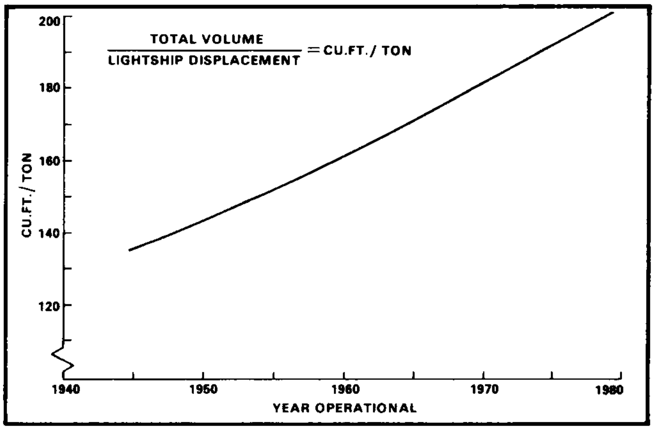

Figure 2. Total Specific Volume.

necessary that conflicting subsystem requirements and resource allocations are negotiated in an organized and rational approach that maximizes the performance of the ship as a total system.

Combined with system constraints is the trend in modern naval ships toward less dense payloads and, for the total ship, an increase of specific volume as shown in Figures 1 and 2. These trends have made modern naval ships volume limited. That is, the volume of ship required is more than the minimum necessary to float the ship's displacement. As more volume is added to satisfy volume demands; ship size, displacement, and cost increase. The need to reduce size and cost of naval ships has reduced the availability of this scarce system resource when trends are toward even more volumetrically demanding subsystems. Therefore, optimizing volume allocation to meet system performance objectives, as measured by performance analysis, has increased significantly in importance.

Not only is it necessary to optimize volume allocation in meeting conflicting subsystem demands and system constraints, the geometric definition of the ship is one of the most visible products of the overall design process. It is displayed, discussed, and reflected upon at many levels in the decision-making process. Within this diverse environment, it is the general arrangement design team that synthesizes the geometric design of the ship from subsystem requirements, system constraints, and policy-maker influences through a process of iteration and negotiation into the optimum general arrangement.

The general arrangement design team, and in particular, the leader of that team must have immediate command of a wide spectrum of knowledge that can only be gained through direct participation or observation in all aspects of the design and decision making process. By this direct involvement, the general arrangement design team can more effectively design and optimize the geometry of the ship. Effective arrangement design optimization demands that this team be knowledgeable in total ship performance requirements, subsystem performance requirements, physical interface requirements, design alternatives, design flexibility, and the goals and concerns of policy makers.

With this overview of the environment of designing the geometry of the ship, the focus now shifts to the process by which the general arrangement team designs and analyzes ship geometry.

Design and Analysis

General arrangement design is the process of geometrically defining the ship as a total system by: (1) locating all functional elements in the ship thereby establishing adjacency relationships, and (2) allocating area and volume to all functional elements. It is the purpose of general arrangement design to systematically attack the design problem with the objective of continuously optimizing the ship as a total system measured on system performance. The general arrangement design process that achieves geometric integration of the ship is a multistep process keyed to subsystem requirements, ship system resources, and conflict among subsystems for these resources.

These steps are:

(1) Establish mandatory and negotiable requirements for all subsystems of the baseline concept.
(2) Develop tentative design solutions satisfying these requirements.
(3) Identify areas of conflict among subsystem requirements.
(4) Negotiate resolution of these conflicts through continuous design iteration, performance analysis, and design decision.
(5) Formulate final optimum design for the given set of requirements and constraints.

Requirements Development

One goal at the outset of any design is for the design team to reach a stable consensus on requirements, not only total ship and subsystem performance requirements, but also subsystem design requirements. Of course, while a stable consensus is sought, requirements will not remain completely stable during design. Indeed, some dynamic evolution is desirable because the lengthy time required to design a ship demands flexibility to exploit new opportunities and to meet unforeseen problems. The design challenge is to create the means to make orderly progress toward design objectives while maintaining flexibility to meet new requirements as they emerge. This challenge can be met in part by partitioning requirements and through the traditional iterative approach to ship design. Partitioning of requirements is part of the first phase of general arrangement design and analysis.

Subsystem requirements are of two general types, mandatory requirements and negotiable requirements. Mandatory subsystem requirements are those that must be met, and in ship design there are few of these. Usually, these mandatory requirements are related to subsystems that are designed and developed separately from the ship design and are used in the ship design without custom-fitting the subsystem to the ship. Typical examples of mandatory requirements are length of the MK 26 guided missile launching system magazines, dimensions of the snowplow configuration of an AEGIS radar room, hangar clearances for specific aircraft, and working circles for sensors and weapons.

Most subsystem requirements are negotiable in that certain design solutions are established as baseline; however, subsystem performance can be maintained with variation of this baseline or performance can be traded-off (either enhanced or degraded) with variation in the baseline). These variations and performance trade-offs become the basis for negotiating allocations of system resources of the ship which include space, both area/volume and location, and weight. Typical examples of negotiable requirements, among many that could be cited, are area allocated to Combat Information Center (CIC), location of CIC, area allocated to human support, location of berthing spaces relative to battle stations, area and shape allocated to the communications center, and others.

In the first phase of general arrangement design, requirements are established for all subsystems through a variety of methods. One primary method is the application of historical data from previous ship designs. Most new ship designs are similar in some respects, and often in many respects, to recent previous ship designs. Many of the issues raised and resolved in the general arrangement design of the previous ship will still apply to the new ship. Further, fleet feedback on a particular aspect of the previous design may be available which can validate previous design decisions for use in the new design.

However, judgment must be used in applying historical data because all systems are designed to meet requirements within constraints established during design. Requirements and constraints that applied to the previous design may be different from those that now apply to the new design with the result that the previous design solution may be inappropriate to the new design. The engineer experienced in general arrangement design through a succession of ship designs will be in the best position to apply these judgments of historical data to the new ship design.

A second major source of subsystem requirements is from design documentation of the subsystem including system descriptions, specifications, and drawings. There is documentation for each subsystem that can be searched for general arrangement design requirements. A particularly useful source document that is used in the AEGIS program is the Combat System Ship Interface Criteria Manual (COMSSIC) which contains a wealth of information on many aspects of the combat system for AEGIS ships. Other sources of useful information on subsystem requirements include General Specifications for Ships, Vulnerability Reports, Technical Practices Manuals, Top Level Specifications, and Design Criteria Manuals.

There is a significant distinction between collection of historical data and review of subsystem source documentation. In collection of historical data, the general arrangement team works independently while in review of subsystem source documentation, subsystem engineers work with general arrangement engineers. It is through these initial intergroup working sessions that requirements are identified and also separated into mandatory and negotiable requirements.

Iterative Approach

While requirements development is the first phase, the next steps in design and analysis form the heart of the traditional iterative approach to ship design. After mandatory and negotiable requirements are established, the general arrangement design team synthesizes a tentative design solution that satisfies mandatory requirements and accommodates negotiable requirements to the greatest extent practicable within the system constraints. In developing this tentative solution, experience and judgment of general arrangement and subsystem engineers are important in assigning degradation to subsystems. Usually, there are no "cookbook" rules for assigning degradation — it is through experienced judgment of all factors that bear on the design problem including past designs, theoretical optimum solutions, current requirements, and design constraints that the initial balancing of the design is achieved.

This initial balancing of the ship represented by the tentative design solution, and depicted on general arrangement drawings, provides a focus for continuing design activity. Areas of conflict among subsystem requirements are identified and the drawings are circulated to the entire design team. These drawings are then used as a basis for analyzing performance and negotiating the allocation of system area/volume resources. Utilization of weight resources are tabulated in the mass properties report and most of the significant changes in weight distribution are initiated through changes in the general arrangement of the ship. Thus, the arrangement drawing becomes a principal vehicle for negotiating requirements among competing subsystems.

An essential element in this process of negotiation is communication among the subsystem engineers and the general arrangement team. When it becomes apparent that it will be necessary to increase the area allocation of one subsystem, other affected subsystems are identified, and subsystem engineers are brought together with the general arrangement team to develop a new solution through performance analysis and face-to-face negotiation. In these negotiations, the effects of changes in volume/area allocations on the performance of individual subsystems are assessed along with the change in total system performance that will result from these changes in subsystem performance. While these changes in performance can sometimes be measured quantitatively, particularly for subsystems, overall performance is often assessed qualitatively through experience and engineering judgment of the people involved. Because it is necessary to rely on experience and judgment of engineers involved in the design, the importance of enhanced inter-team communication is emphasized in the development of new design solutions. These new solutions, which often have ripple effects throughout a number of subsystems, are reflected on the general arrangement drawings. These drawings are circulated periodically to continue the design iteration process by maintaining communications within the design team. Design iteration continues throughout all design phases, and as more definition is gained in subsystem design, the general arrangement design is further refined.

The general arrangement design process, described here in a few words, in reality requires a long time to execute. For a new ship, 3 years could be consumed in going through concept, preliminary, and finally contract design. A conversion or modified repeat design could be completed in less time, but time is essential to obtain convergence to an optimum system design that meets given requirements and constraints, regardless of

APPENDIX A

GENERAL ARRANGEMENT DESIGN RATIOS AND INDICES

Function	Volume Ratio*	Area Ratio*	Specific Index
Command Control	X	X	
CIC	X	X	
DPC	X	X	
ExComm	X	X	
Flag	X	X	
Sensors	X	X	
Radar	X	X	
Sonar	X	X	
Electronic Warfare	X	X	
Weapons	X	X	
Guns (each type)	X	X	V&A/No. of rounds
Missile Launcher	X	X	V&A/No. of missiles
Torpedoes	X	X	V&A/No. of torpedoes
Small Arms	X	X	
Directors	X	X	V&A/No. of directors
Handling	X	X	V&A/No. of weapons
Special Mission (Specify Type)	X	X	
Aviation	X	X	V&A/No. of aircraft
Hangar	X	X	V&A/No. of aircraft
Maintenance	X	X	V&A/No. of aircraft
Administration	X	X	V&A/No. of aircraft
Stores	X	X	V&A/No. of aircraft
Ship Control	X	X	
Damage Control	X	X	
Interior Communication	X	X	
Propulsion Plant	X		V/Shaft hp
Electrical Plant	X	X	V&A/Kw
Auxiliary Machinery	X	X	V&A/Weight Aux
Fan Rooms	X	X	
Logistics Support	X	X	
Repair Parts			
Stowage	X	X	
Workshops	X	X	
Replenishment-at-sea	X	X	
Stores Handling	X	X	
Elevators/Conveyors	X	X	
Provisions	X	X	V&A/No. of accom.
Human Support	X	X	V&A/No. of accom.
Berthing	X	X	V&A/No. of accom.
Recreation	X	X	V&A/No. of accom.
Sanitary	X	X	V&A/No. of accom.
Food Service	X	X	V&A/No. of accom.
Messing	X	X	V&A/No. of accom.
Laundry	X	X	V&A/No. of accom.
Medical	X	X	V&A/No. of accom.
Boats	X	X	
Anchoring	X	X	
Pollution	X	X	
Passages/Access	X	X	
Offices/Admin.	X	X	V&A/No. of accom.
Liquids	X		
Fuel	X		V/range
Potable Water	X		V/No. of accom.
Feedwater	X		

*Volume or area of that function as a fraction of the total internal volume or area of the ship.

whether the design is for a new ship, a conversion, or a modified repeat design.

The final step of the general arrangement design process is formulation of the final optimum design. As the design evolves through intensive negotiations, the optimum design solution becomes more and more apparent. It is this final optimum solution that is reflected in the general arrangement drawings at contract design signature. While general arrangement drawings are the final result of this design and analysis process, the true products represented by the drawings are engineering and policy decisions made during the design. Not only is this product representative of design decisions; it also serves, in interim issues, as a focal point for establishing an effective dialogue between the fleet, the design community, and the office of the Chief of Naval Operations. In the design of CGN 42, the most recently completed surface combatant design, particularly effective use was made of the general arrangement design process as a means of stimulating and incorporating the results of operational community review. The approach used and results achieved in the design of CGN 42 are described more fully in reference [2].

From this overview of the general arrangement design and analysis process, focus now shifts to analytical techniques used to assess the general arrangement design.

Analysis Techniques

Ratios and Indices

Powerful tools for analyzing space allocation are volumetric ratios and volumetrically based specific indices. Volumetric ratios have been used in general arrangement design over the years. In addition, landmark work in the use of ratios and indices for comparative analysis has been done by Commander Clark Graham, USN. These ratios are of two basic types.

The first type are fractions of volume and arrangeable area allocated to major subsystems as a proportion of the total volume and area of the ship. The second type are specific indices that relate volume and area of major subsystems to specified characteristics. Appendix A is a listing of the primary ratios and indices that can be used in volumetic analysis of general arrangement designs. Appendix A includes both those ratios used traditionally in general arrangement design as well as those developed and used by Commander Clark Graham, USN, at the Massachusetts Institute of Technology and described in reference [3].

The first step in using these ratios is to compile a data base of the ratios and indices for different ship designs. For example, analysis of new surface combatant designs would include a data base consisting of the following classes: CGN 42, CGN 38, CGN 36, CG 26, CG 16, DDG 47, DDG 993, DDG 37, DDG 31, DDG 2, DD 963, FFG 7, FFG 1, FF 1052, and FF 1040; which are drawn from a larger data base that includes all major classes of naval ships. By comparing data for new design alternatives against the data base, differences in ratios and indices may be found.

These differences will be caused by many factors such as advanced design practices, new technology, different design philosophies, and different payload characteristics to cite only a few. The key point however, is to identify where diferences exist and then explain the reason for the difference. By reviewing these reasons, those things that improve the general arrangement design can be highlighted and emphasized in subsystem design development. Those things that tend to degrade the general arrangement design can likewise be highlighted for continued design development with the objective of reversing negative effects.

Another use of ratios and indices is in identifying areas that would benefit from innovative approaches. For example, if a ratio or index has remained relatively constant over a large number of classes for an extensive period of time, that subsystem may have reached an optimum state within established policy or existing technology constraints. Highlighting such plateaus can stimulate possible innovation in policy constraints or an advance in the state of the technology.

As seen in appendix A, volumetric ratios and indices are grouped by subsystems, and are used in evaluating subsystems as related to volume allocation of the total ship. Some indices are currently related to performance levels, such as the volume allocated to main propulsion compared to shaft horsepower of the propulsion system. One objective of general arrangement design is to link all subsystem allocations to performance levels or performance indicators. Developing appropriate performance indicators is a continuing task for both general arrangement and subsystem engineers.

Another objective of general arrangement design is to link subsystem effectiveness as measured by performance indicators to a ship design philosophy that reflects operational performance objectives. New efforts in this exciting and challenging area are now underway in ship general arrangement design and analysis.

General Arrangement Evaluation Technique

BACKGROUND—Before describing current developments in general arrangement evaluation, the background for this effort will be briefly highlighted. The evaluation approach currently envisioned is a derivation of the system design philosophy or criterion for optimization as presented in the landmark paper by Leopold and Reuter [4]. The evaluation method includes a prioritized design philosophy represented by weighting factors applied in relative importance of ship subsystems. Each subsystem is measured to the extent possible on performance criteria. Weighting factors and subsystem evaluations are combined to aid the judgment of the design team in optimizing the ship as a total system. The first use of quantitative general arrangement evaluation was by Mr. Lloyd Wood in the early phases of the CSGN design in 1975–1976. These results, which were not formally documented in the literature, combined judgmental measures of effectiveness with derived weighting factors and were used by Mr. Wood for comparing alternative general arrangement concepts. From these early beginnings, a new methodology is now emerging.

There are efforts now underway that will lead to the formulation of a new methodology to systematically evaluate, compare, and analyze alternative general arrangement designs. The basis for this methodology is performance assessment of design alternatives linked to ship design philosophy. The derived general arrangement figure of merit is an indicator of the ability of that alternative to achieve operational performance objectives as measured by subsystem effectiveness and relative priority in the total ship design philosophy.

FIGURE OF MERIT FORMULATION—The general arrangement design figure of merit could be formulated generally as follows:

$$FOM = \sum_i W_i \times E_i$$

Where W_i = the weighting factor of a subsystem derived from the ship design philosophy

$\sum_i W_i = 1.00$

E_i = the subsystem effectiveness as determined using performance assessment and judgmental factors

i = major subsystems of the ship (as listed in Appendix B)

$O \leq W_i \leq 1.00$

$O \leq E_i \leq 1.00$

Maximum FOM = 1.00

APPENDIX B

GENERAL ARRANGEMENT EVALUATION MAJOR SUBSYSTEMS

Anti-Air Warfare
Anti-Submarine Warfare
Surface Warfare
Strike Warfare
Electronic Warfare
Amphibious Warfare
Mine Warfare
Special Mission
Structures
Total Ship Survivability
Command and Control
Exterior Communication
Aviation Support
Ship Control
Damage Control
Propulsion
Electrical Generation
Auxiliary Machinery
Heating, Ventilation, Air Conditioning
Interior Communication
Logistics Support
Human Support
Access
Shipboard Administration
Pollution Control
Boats
Anchoring
Replenishment
Repair
Salvage

Weighting factors and effectiveness evaluations must have the property that numerical values indicate relative priority or achievement. That is, if $W_x = 0.50$ and $W_y = 0.25$, then subsystem X is considered to have twice the priority of subsystem Y. Similarly, if $E_x = 0.60$ for design alternative 1 and $E_x = 0.30$ for design alternative 2, then alternative 1 is judged only 60 percent as effective as its hypothetical maximum potential but is twice as effective as alternative 2 for that subsystem.

Combining weighting factors and evaluation scores established in this way yields figures of merit that likewise have the property of indicating relative effectiveness of the total ship system as reflected by the general arrangement design. For example, if alternative 1 has a combined figure of merit of 0.77 and alternative 2 has a combined figure of merit of 0.70, then alternative 1 could be judged to be 10 percent more effective, as a total system general arrangement than alternative 2.

Of course, as with all complex formulae that compare dissimilar attributes, the figures of merit are a tool or guide for design engineers to use in optimizing the design and should not be considered as strict decision parameters. The design engineer's experience and judgment of design parameters continue to be the dominant factors in design decision; however, the general arrangement evaluation technique can be an important tool to aid the engineer's judgment. First, this technique makes customer requirements, as expressed in the ship design philosophy, more explicit. This philosophy, which must be developed jointly between the design community and the operational community, helps both communities understand better what is truly operationally required, what can be technically delivered, and what the tradeoffs are. Second, subsystem evaluations indicate how well a subsystem has been integrated into the ship design. A low score indicates an area to concentrate on for improvements. Also, the process of evaluation will indicate sensitivity to design changes. Factors used in determining subsystem scores will have sensitivity to increases or decreases in volume allocations or change in functional location. Those sensitivities are highlighted by rigorous evaluation and serve as guides for the design engineer in optimizing the general arrangement design.

DERIVATION OF WEIGHTING FACTORS — Weighting factors used in this evaluation technique are derived jointly by the general arrangement design team and the ship design manager and imply that a ship design philosophy is developed between the technical community and the operational community. Such a ship design philosophy has not always been developed in the past, but will increase in importance in the future when designs become more and more constrained by cost and tough choices will have to be made among performance requirements.

General arrangement weighting factors must flow from an expressed or derived ship design philosophy, and a ship design philosophy is a necessary element of the system engineering approach. As expressed by Commander Clark Graham, USN:

> "It is absolutely imperative that all of the participants in the design process work with

the same selection and optimization criteria. That is, the designers of each and every subsystem and the overall ship designer should be approaching their design tasks with consistent design philosophies." [5]

Priorities established in a ship design philosophy will guide the definition of weighting factors used in general arrangement evaluation. Where a ship design philosophy has not been expressed, general arrangement weighting factors may be derived jointly by the design team from their experience and judgment of important features from previous designs and the objectives and constraints defined for the new design. Not only is design team experience and judgment important in deriving weighting factors, it is also important in assessing the effectiveness of ship subsystems as will be seen in the following section.

SUBSYSTEM EFFECTIVENESS—The Second major element of the general arrangement evaluation technique is assessing the effectiveness of ship subsystems as these relate to general arrangement design. General arrangement design is the process of geometrically defining the ship as a total system through: (1) locating all functional elements in the ship thereby establishing adjacency relationships, and (2) allocating area and volume of all functional elements. The ability of a subsystem to perform its basic mission within its allocated volume is bounded by the amount of equipment and manned operating stations that can be packaged within that volume. Also, the performance of a subsystem may be affected by its location on or within the ship. Other subsystem attributes are also affected by volume allocation and location such as motion effects, survivability, maintainability, producibility, and others as listed in Appendix C.

APPENDIX C

SUBSYSTEM EFFECTIVENESS FACTORS

Basic Mission Performance
Motion Effects
Structural Integrity/Flexure
Human Factors
Subsystem Survivability
Redundancy/Availability
Battle Spares Location
Maintain Accessibility
Equipment Replacement
Future Growth
Producibility
Subsystem Cost
Installation Cost

These factors are judged as related to volume allocation and location, i.e., the design parameters of general arrangement design, and not as related to other system design parameters. For example, installation cost or subsystem cost is influenced by many factors that do not relate at all to volume allocation or location, such as material selection, source availability, etc. Only its relationship to volume allocation and location are judged in this evaluation criteria.

The tasks of general arrangement and subsystem design engineers are to formulate methods for assessing subsystem effectiveness that relate functional location and volume allocation to performance levels and then scoring subsystem effectiveness for various alternative general arrangement designs that are being compared. For some subsystems, powerful tools exist to perform quantitative assessment, such as Combat Capability Assessment, Ship Vulnerability Model, and Personnel Flow Simulation. [6][7][8] In other areas such tools do not exist and qualitative judgments are used. In fact, even with the tools cited, some qualitative assessment of the numerical results is needed to determine the subsystem score.

For example, the Personnel Flow Simulation, as described by J.P. Hope and C. Carlson, measures quantitatively the amount of time required for ship's company to go from one condition of readiness to another. This attribute is but one element of access design; two others are equipment removal and stores strikedown. [8] Thus, in evaluating access design, the quantitative results measured by the personnel flow simulation must be combined with a more qualitative assessment of equipment removal and stores strikedown.

SUBSYSTEM EVALUATION EXAMPLE—As an example of how this combined assessment could work, consider the following. An operational performance objective of going to battle stations (Condition I) from wartime steaming (Condition III) in 3 minutes could be hypothesized. In formulating the access evaluation criteria, the access design engineer could consider personnel movement access worth 80 percent, equipment removal 10 percent, and stores strikedown 10 percent. This priority within access design would indicate that the access engineer judges movement of people in emergency conditions to be eight times more important than either of the other two major elements of access design. Now consider general arrangement alternative 1 in which the personnel flow simulation indicates that all hands could move to battle stations in 3 minutes 30 seconds.

In order to judge the merit of this numerical value, the access engineer could postulate a rating system that would give a 100 percent score to a design that met the operational objective of 3 minutes, and it could further be postulated that 5 minutes is unsatisfactory and worth a 0 percent score. Scores between 3-5 minutes could be determined by linear proportion of the value between 100 percent and 0 percent. The simulated numerical value of 3-½ minutes on this rating system would score 75 percent.

Furthermore, using qualitative judgment, equipment removal access was determined to be approximately 80 percent of optimum and stores strikedown access approximately 60 percent of optimum. Thus, the combined access score would be:

$$E_A = 0.8 \times 0.75 + 0.1 \times 0.80 + 0.1 \times 0.60$$
$$E_A = 0.74$$

Now consider general arrangement alternative 2 in which a new athwartship passage has been added that relieved a traffic bottleneck. Personnel movement to battle stations is simulated to be completed in 2 minutes 56 seconds. In addition, this new passage also improves stores strikedown routes but has no effect on equipment removal. The operational objective has been achieved and this score is now 100 percent. Qualitative judgment of the stores strikedown improvement raises this score from 60 percent to 80 percent. The new combined access score would be:

$$E_A = 0.8 \times 1.00 + 0.1 \times 0.80 + 0.1 \times 0.80$$
$$E_A = 0.96$$

General arrangement alternative 2 is judged to be a significant improvement in access. However, it must be remembered that this improvement was achieved by adding an athwartship passage that used some of the system resources in volume. Reallocating this volume to access comes at the expense of some other subsystem.

GENERAL ARRANGEMENT EVALUATION EXAMPLE—Now, the broader content can be postulated. Assume that the athwartship passage was added in a subdivision that was previously dedicated to Anti-Air Warfare (AAW) spaces. Further assume that no growth is possible because subdivision and hull boundaries are fixed and all the affected AAW functions require adjacency and must remain as located in alternative 1. The volume applied to access in alternative 2 is taken from the AAW spaçes, thus, the arrangement evaluation of AAW will be degraded in alternative 2. The AAW design engineer redesigns his spaces for alternative 2 and finds that basic mission is unaffected but some volume for maintenance access has been lost and all future growth capability has been eliminated. A hypothetical AAW subsystem evaluation and rating scale might appear as follows:

Design Element	Weight	Alt. 1		Alt. 2	
Mission Performance	0.90	100%	.90	100%	.90
Maintenance access	0.05	100%	.05	80%	.04
Future growth	0.05	80%	.04	0	0
			.99		.94

This assessment must now be combined with the access assessment in the general arrangement evaluation technique. Assume, in a simplistic example for illustration only, that in the derivation of general arrangement weighting factors from the ship design philosophy, AAW warfare is worth 0.4, Anti-Submarine Warfare 0.2, Propulsion 0.2, Access 0.1, and all other factors combined 0.1. Only AAW and Access were affected by the postulated new alternative and a general arrangement evaluation of these two alternatives might appear as:

Design Element	Weight	Alt. 1		Alt. 2	
AAW	.4	.99	.40	.94	.38
ASW	.2	.80	.16	.80	.16
Propulsion	.2	.84	.17	.84	.17
Access	.1	.74	.07	.96	.10
All other	.1	.65	.07	.65	.07
			.87		.88

In this case, the combined evaluations for both alternatives are almost identical and the decision to adopt alternative 2 or remain with alternative 1 will be made on the combined judgment of the design team.

However, if the addition of the new athwartship passage had a more severe degradation on the AAW subsystem, the choice might be more clearcut. For example, if the volume deleted from AAW spaces impacted not only maintenance access and future growth, but also reduced basic mission capability then a Combat Capability Assessment and qualitative judgment might yield an AAW assessment as follows:

Design Element	Weight	Alt. 1		Alt. 2	
Mission Performance	.90	100%	.90	60%	.54
Maintenance access	.05	100%	.05	0	0
Future growth	.05	80%	.04	0	0
			.99		.54

The combined general arrangement evaluation would be:

Design Element	Weight	Alt. 1		Alt. 2	
AAW	.4	.99	.40	.54	.22
ASW	.2	.80	.16	.80	.16
Propulsion	.2	.84	.17	.84	.17
Access	.1	.74	.07	.96	.10
All other	.1	.65	.07	.65	.07
			.87		.72

In this case, the general arrangement evaluation for alternative 2 is significantly lower, and alternative 1 is a clear choice in optimizing the ship as a total system.

These hypothetical and simplistic examples are presented to show the spirit and intent of the general arrangement evaluation technique. In actual practice, the considerations, effects, and their interactions are much more complex. In fact, these factors are so complex that in past designs these judgments have often been made intuitively based on the collective experience and knowledge of the design team. As the system engineering problem becomes more difficult in the future, as it will with the simultaneous demand for both increased capability and reduced cost, it is imperative that the transition continue from a strictly intuitive approach to a more rational approach that links the evaluation of design alternatives to performance measures. The general arrangement evaluation technique is a step in that transition that makes use of rational tools that exist; such as the Combat Capability Assessment, Ship Vulnerability Model, Seakeeping Performance Index, and Personnel Flow Simulation; and combines these with a continued necessary reliance on experience and judgment where such analytical tools do not yet exist. And while still relying on experience and judgment, the general arrangement evaluation technique brings the assumptions and considerations used in judgments into a sharper focus that will be necessary to optimize future ship designs to meet more demanding threats in more highly constrained environments than have been seen before.

CONCLUSION

General arrangement design, as a system engineering process, is a unique blend of experience and judgment combined with the systematic evaluation performance. Its objective is to optimize the ship as a total system by continuously attacking the design problem as described in the five step general arrangement process. The product of the process not only is a representation of design decisions, it also serves as a focal point for establishing an effective dialogue within the design community and also with the operational community. A vital part of this dialogue is the ship design philosophy prioritizes operational performance objectives.

New and exciting efforts are now underway in general arrangement design to develop a method that measures the achievement of operational performance objectives by combining the ship design philosophy with subsystem performance evaluation. This new method is a significant step in the transition from intuitive design approaches of the past to the new design approaches of today which meld experience and judgment with powerful analytic techniques. These new approaches are needed to meet the more demanding systems engineering problems that can be expected with the simultaneous demands for ever-increasing performance delivered to the fleet for less cost.

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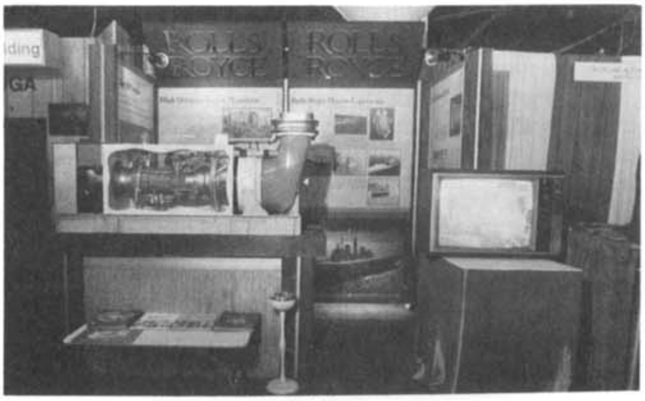

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