# NAVAL SEA SYSTEMS COMMAND (NAVSEA) JULY 26, 1993

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## Background

Combat ships are probably the most complex things designed and built by man. They typically contain 10 million to 30 million parts and take 5 to 10 years to design. A single surface warship takes 2 to 3 years to build, while a nuclear submarine takes 5. Individual ships have service lives of 30 years or more, while a class of ships can be in service for more than 50. In current US Navy practice, concept, preliminary, and contract design are done by NAVSEA, while detail design is done by private shipyards with the aid of private naval architectural firms. (These terms are defined below.)

The Navy defends this division of labor, citing the complexity of the ships and its willingness to cut losses on an unsuccessful program. Contractors in other services are seen as using their allies in Congress to prolong programs that should be cut. The yards have countered with designs of their own for foreign markets and argue that producibility suffers under the present arrangement. Both the Navy and the Air Force buy aircraft designed by private contractors, reserving tight program management to themselves. But aircraft are much less complex than ships.

In the cases of both ships and planes, the government supplies all the weapon systems, sensors such as radar and sonar, and propulsion system components like engines and propellers. These are built by other private contractors, who design most of them in-house. These items are called government-furnished equipment, or GFE. The technology of these items evolves much more rapidly than does that of the basic "platform." Historically, platforms have been upgraded once or more with new weapons and sensors.

## Design Phases

Figure 1 shows the approximate time scale for designing a surface combat ship. The indicated phases are:

Feasibility studies: Often a much longer process than implied in the figure, this step comprises a wide variety of studies and debates concerning threats, missions, technological risk, and budget forecasts. Domestic and international politics are often involved. It is in this phase that the need for a particular type of ship must be formulated and "sold" within the Navy and Congress.

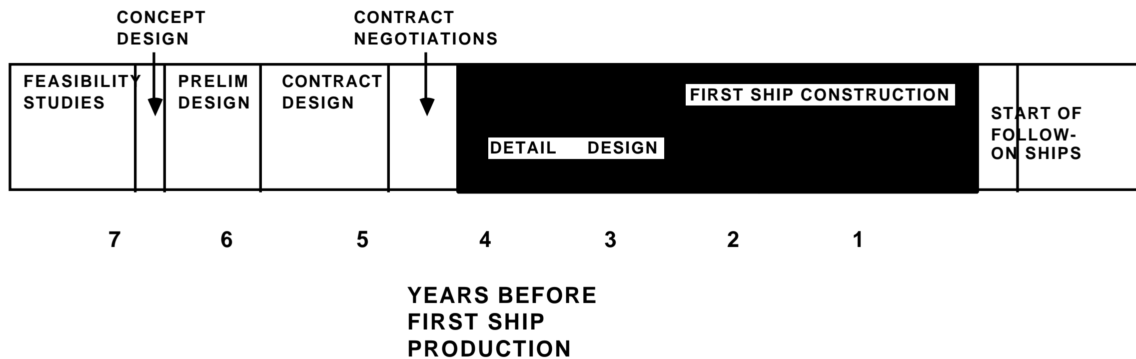


Figure 1. Approximate Design Cycle for a US Surface Warship (modified from Bosworth)

Concept design: In this phase, the debates over mission lessen but those over budgets and technological risk continue as the concept is refined to include basic capabilities, crew size, ship size, main propulsion and weapons complement, and class size (number of ships of this kind to be built).

Preliminary design: The basic hull shape plus the weights and locations of weapons equipment, machinery, auxiliary equipment, and crew must be estimated well enough that total weight can be estimated and the ship's seakeeping and fuel economy can be calculated. Approximate locations of interior decks and bulkheads are determined, as are the main structural breaks that define modular construction. (Modular construction is discussed below.) The main lines of the hull and superstructure are defined, as are the sizes and spacings of the main stiffeners.

Contract design: In this phase, the results of the prior phases are converted into a specification on which private shipyards can bid for the job of detail design and first ship construction as one package. This "lead shipyard" has the best chance of winning contracts to build follow-on ships but the Navy usually requires that a second or even third source be qualified. This requires a repeat of some of the detailed design steps to accommodate the different construction methods of the follow yard(s).

Detail design entails designing every structural plate and stiffener, every pipe and ventilation duct, every wire and wireway, placing each piece of equipment in every compartment, routing every pipe and wire to its destination, and so on. Each yard modifies the suggested module breakdown because each has different constraints on the size and weight of modules it can handle.

During the design of the DDG-51 (late 70s to mid 80s) the Navy encouraged the yards to contribute to the preliminary design process in the hope of improving the producibility of the ship. This was partially successful and many of the yards' suggestions were accepted. However, the effort was

limited by the need for each yard to keep its proprietary knowledge (mainly cost data) from the others and by the fact that the Navy did not wish to sacrifice performance for producibility to the degree required by many of the suggestions. The winning yard (Bath Iron Works) provided extensive producibility knowledge to its naval architect partner Gibbs and Cox during detail design. This knowledge was confined to design details and did not alter the major aspects of the ship, such as hull shape, deck separation, major bulkhead location, and main routes for pipes, wires, and vents.

The DDG-51 was not the first design in which the Navy tried to obtain producibility input from the yards, and the effort continues on later ships. However, the whole process of naval ship design, not just in the area of producibility, has been undergoing revision or, in the words of Billingsley, a "revolution." But the current one is not the first.

**Prior Revolutions in Ship Design**

Prior to World War II, ships were designed from the point of view of performance and structure, but the construction process was conceived separately from design. Steel ships were built in much the same way as wooden ships before them: structural ribs and longitudinal stiffeners were assembled over a keel in a drydock. Individual hull, deck, and bulkhead sheets were brought to the dock and attached individually to the framework using rivets. Houses are built this way today.

It is possible to build a ship quickly by this method. A heroic effort by Britain's Portsmouth Navy Yard created the 17000 ton HMS Dreadnought in 366 calendar days (one 11.5 hour shift each day, 6 days per week by as many as 3000 men on site) following 7 weeks of concept and preliminary design (December 22, 1904 to February 22, 1905) and 7 months of detail design and ordering of material. It was the first battleship to use steam turbines and the first to be built of standard size plates ordered in advance. [Massie] Prior to Dreadnought, it took the British typically 31 months to build a battleship. No capital ship since has been built in such a short time.

Henry Kaiser improved on this method in the 1940s by prefabricating major pieces of structure and hauling them to the building ways to be assembled to other such pieces. He used heavy lift cranes that he had previously used on large dam construction projects in the 1930s. This process speeded construction because other areas besides the crowded building ways could be used in parallel. However, the rest of the ships' construction, such as installation of pipe and wireways, remained traditional and was done on board the ship.

In the 1950s and 60s, the Japanese improved on Kaiser's method by prefabricating entire finished sections of non-combat ships. These modules contained working lights, equipment, piping, and furnishings. Entire bays of machinery were built onto their foundations inside the construction shops

and tested there. The finished units were taken to the ship and dropped into place.

In some cases, these modules can be really huge, measuring 60 feet cube and weighing 50 to 100 tons. The New York Times for June 15, 1994 contains an article on page D1 about the recent boom in cruise ship design. A photo accompanying this article (Figure 2) shows an aft deckhouse comprising four decks and stretching the full width of the ship. This deckhouse is on the pier next to the ship ready to be lifted aboard. Interestingly, it appears to comprise only structure and possibly some pipe and vent, but little else. The Japanese refined statistical process control and repeatability processes to the point where a module of that size would fit its mates within 0.25" all the way around. This was accomplished by ruthlessly controlling the quality and uniformity of incoming material, especially welding rod, so that weld shrinkage could be predicted accurately. The prevailing American practice at the time of leaving 3" extra to be cut off at fitup time was called "planned rework" by Japanese shipbuilders. In the car industry, Toyota calls such things <u>muda</u>, Japanese for waste.

Figure 2. Cruise Ship Under Construction with Deckhouse Module at Upper Left

figure 2

More important than modularization of the ship was modularization of the design process. To take full advantage of the module method, the Japanese totally revised the design process. In the words of one observer, "Design became a subset of construction." [Chirillo] The module breaks were chosen to maximize ease of construction. Flat, simple hull shapes predominated, since these are the easiest to make. Module boundary choice was made easier by the fact that welded joints can be placed at the designer's convenience, unlike riveted joints. The yard and its personnel were similarly modularized, with separate areas assigned to do particular kinds of modules (simple flats in large quantity, simple flats in small quantity, single curved in small quantity, etc.) and given the appropriate machinery, skill levels, and training. By the late 1960s it was routine for Japanese yards to sign a contract for a 15000 ton bulk cargo carrier and have it on sea trials 7 months later.

Computers played little or no role in any of the above eras of shipbuilding, either for producing design drawings or controlling the

construction process. Instead, designers have relied on a variety of methods, some ancient, for creating fair hull shapes, plus many metrics that provide approximate answers. One of the most widely used metrics is based on weight classes. A structured bill of materials is drawn up during design in which each item is classified into weight classes. Typical classes include structure, pipe, vent, main machinery, weapons, auxiliary machinery, and so on. Interestingly, both the design offices and the ship's own management are divided into similar groups: there is an officer responsible for machinery, another for structure, another for weapons, and so on. NAVSEA is similarly divided.

In the car industry, pressed to reduce fuel consumption, it is known that the main factor raising fuel use is vehicle weight. A great deal of effort goes into reducing the car's weight. In ships, it is clear that to first order, more weight implies more cost, but one has to be careful to distinguish different kinds of costs incurred at different times in the ship's life cycle. The Navy's method of estimating cost during concept design apparently depends almost entirely on weight and it emphasizes basic acquisition cost, which depends mainly on materials costs. So far, so good, but this metric can lead to strange results. In the DDG-51 class of destroyers, application of this metric led to a reduction in the vertical space between decks. The discussion over this decision must have ranged far and wide in NAVSEA because I keep hearing about it 10 years after it was made. One downside is that it is much more difficult to fit the equipment inside the ship during construction. Repair and overhaul costs can be expected to be affected in similar ways for years to come. The problem of predicting cost during design is not unique to shipbuilding, of course, and this remains a major challenge to design theorists and practitioners.

**A Short Comparison of Industries with Similar Design Problems**

Consider cameras, cars, planes, ships, and nuclear power stations. These have many common elements, such as dense packing of many arbitrarily-shaped parts, many different technologies working together in one or more interconnected systems, lots of "distributive systems" (pipes, ducts, and wires), lots of power being generated and used (except cameras), and complex interactions with human operators (the operators are <u>inside</u> the object except in the case of cameras). Production volume is almost exactly the inverse of size, with the smallest being the most numerous. In terms of maturity of design methods, cars are clearly in the lead, with ships probably next, then cameras and planes, and last power stations.

Computers were being used to design aircraft wing sections during World War II when "computer" meant "person who computes." Real computers were being used to design car bodies in the 1960s before there was a CAD industry. By the 1980s, digital definition of car outer body panels was well developed in many companies, and drawings with ANSI Y 14.5 tolerances were being used to define many of the mechanical parts. This was

also true in the military aircraft industry. The commercial aircraft industry remained surprisingly backward computationally (except for airfoil shapes) until very recently, with many parts being defined by computer-drawn mylar patterns that were in turn used by tracer mills to cut out complex shapes. As noted below, several shipbuilders were able to represent huge sections of a ship before most aircraft companies could.[1]

The shipbuilding industry has pioneered modular construction and carried it to a degree not found in any other major industry. Neither cars, nor planes, nor power stations (in spite of the latter's similarity to ships in terms of steel structure, wires, and pipes) are built with significant use of pre-outfitted modules. Additionally, none of these industries has made systematic use of modular thinking in conceiving its designs. Commercial aircraft construction stands today about where Kaiser stood with shipbuilding: main structure subassemblies are made as whole units by subcontractors and shipped hundreds or thousands of miles to the final assembly plant. But the internals are mainly installed after the whole structure is finished.

Current car design does not permit an entire interior (comprising the dashboard, steering wheel, seats, radio, inner soft trim, etc.) to be preassembled and dropped into the car through a hole in the roof. The car is a unified sheet metal shell for the purposes of reduced weight and increased crash resistance. It is also painted before the interior is installed, so it is not possible to install the interior in a split body and then weld the halves together. A sufficiently strong room temperature alternative to welding as a joining method has not been found. Instead of such modules, cars are made with the aid of a variety of mechanical subassemblies such as engine, transmission, body, and so on, often made in separate factories. The interiors are installed piece by piece in a very awkward and lengthy manual process.

Power stations, in spite of their superficial similarity to ships, are hardly made in modules at all, except (no surprise) in Japan, where shipyards are major reactor vendors. Japanese reactors are built at the seacoast to be near cooling water supplies, permitting huge modules to be built at far-away yards and sent by barge to the construction site. US reactors are spread out over the continent and are usually built using local labor and subcontractors. The prime contractor usually faces a huge cultural gap in such circumstances and is hard pressed even to obtain individual pieces of pipe in run-length sequence, much less entire modules with sufficient dimensional accuracy. [Reinschmidt]

This comparison is intended to show that even when the technical aspects of a product's design may be similar at some level, there are many

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[1]Note that rubber mallets can be used to address fitup problems on planes and cars where the metal is thin. This is still common in the aircraft industry. But it is impractical on ships where the material can range from an inch to a foot thick.

aspects that are different, including history, which cause the design methods and applied computer technology to be very different.

**Modern Computerized Warship Design**

Modern warships are so complex that it is difficult to see how they could be designed without the aid of computers. Ordinary computer-aided design (CAD) as sold and used in commercial industry is sorely tested by shipbuilding. Automobiles have about 10000 parts, and while some of these are quite complex and require special software to design them and their fabrication tools, the scale of ship design is at least two and possibly three orders of magnitude greater. While the CAD industry sold most of its early software to the automobile industry, it was shipbuilders who taught the CAD vendors what a complex design really is. At Ingalls Shipbuilding Company in 1986 I was taken to the CAD area: "Here," said my host, pointing to over a dozen huge disk drives, "is the data store, and there," pointing to four consoles, "are our workstations." At that time, Ingalls could store, display, and modify the main deckhouse of a CG-47 missile cruiser. By 1993 it could provide "walk-throughs" of entire surface-modeled sections of the ship in color. Over that same time period, Boeing acomplished essentially the same things in aircraft design.

The character of shipbuilding is also unlike conventional manufacturing, being more like construction. One of my NAVSEA hosts put the contrast this way: in ordinary mechanical CAD, one creates and controls the specifications for one part and then makes hundreds or thousands; in shipbuilding one has to control the specifications for thousands of parts that come together to make one thing. In today's environment, a production run of 50 ships is very large. By contrast, Boeing has made a hundred or more 737s each year for many years.

Moreover, both ships and cars (also airplanes) comprise two quite different kinds of parts: mechanical things made up of complex combinations of typically simple shapes like cylinders and blocks; and free-form surfaces that make up car bodies, ship hulls, and aircraft wings. No commercially available CAD software is totally satisfactory at handling both kinds, although several airframe companies and one auto company feel that CATIA does both better than its competitors at present.[2] The Navy has given Intergraph a long term contract to support ship design. Its software was originally aimed at mechanical design. The Navy's needs in scale, complexity, and freeform surfaces are requiring Intergraph to upgrade its software.

Computers help the Navy and its contractors with an almost unbelievably complex space definition and allocation problem, since ships are very crowded inside. (Only the engine compartment of a car seems more

[2] See the report on the auto industry for a description of Chrysler's strategy for adopting CATIA.

crowded, and it is much smaller than a ship.) Ships are designed from the outside in, starting with a seaworthy hull, and everything else must either fit inside the hull or ride on top of it. As technology advances during the long service life of ships, space must be found for new equipment. Placing it inside finally becomes impossible, and lengthening the hull is too costly. So new equipment is put above decks. Here it contributes to making the ship less stable, so ultimately the class of ships becomes obsolete for this reason, if not for others.

Computation has also helped refine structural design. Designers provide structural strength and stability against buckling either by thickening the skin or adjusting the size of stiffeners and the spacing of a rectangular grid of them. Optimization studies have revealed that a lighter hull is obtained (other factors remaining the same) if the skin is thinned and the stiffeners put closer together. This trend has been aided by development of higher stiffness steels. There are thus more stiffeners in modern ships than in the past, making construction more costly: more stiffeners means more runlength of weld and more hand-made structural intersections. More stiffeners also can mean more penetrations or detours being needed for distributive systems. Finally, since module breaks should be kept away from stiffeners, a denser array of stiffeners provides less freedom to choose module breaks, or requires that module decisions and structural detail design be coordinated earlier in the design process than used to be necessary.

**Challenges to Ship Design CAD**

Computers have clearly made ship design easier but at the same time have encouraged more refined and complex designs. These and other trends have caused the Navy, like commercial industry, to discover that "design" means more than creating drawings of parts. In fact, the data required to describe a complex product probably consists of more non-geometric data than of geometric. This surprising fact is emerging from studies of how the design process should work when hundreds or thousands of people in many organizations must work together quickly to design something. This is true in all industries, not just shipbuilding. An enormous amount of information is required to keep track of cost and schedule, coordinate the work of people, pass information between them, and be sure all the parts fit during assembly.

In the past, these problems were often solved by building mockups or by trial and error during construction of the first ship. This practice is costly enough in car or airplane production where the first unit is not intended for actual use. But the first ship is delivered to the Navy for regular fleet use, and using it for both prototype and production has become too costly, time-consuming, and risky. Mockups can be made of small things like car interiors but are impractical for large objects or for those that are designed as separate elements at dispersed locations. (In the case of jet engines, it takes so long to create a hard mockup that it seriously delays the design process. Since many

versions of the same engine are designed, confusion often occurs because only one mockup can be made and the designer has to imagine what it is like in different versions.)[3]

"Electronic pre-assembly" is the name used by Boeing to describe how CATIA is helping to solve some of these problems. All the parts and assemblies of the new 777 are being designed by computer so that digital data definitions of their shapes are available. These can be assembled in the computer and viewed on the screen so that interferences can be detected. Shipbuilders are using similar methods.[4]

Ideally, the data definitions to support such activities should identify individual parts or related groups of parts. Intergraph stores files, not models of parts, just as most other CAD systems do. Files correspond to drawings, but drawings can have more than one part on them, or several drawings may be required to describe one part. As a result, NAVSEA personnel are adapting their file definitions in anticipation of the need to separate information required in different phases of the design process.

Boeing can put up on the screen an entire section of the fuselage fully surfaced in color and see if it interferes with another section. To assemble such models from individual designs of small parts, Boeing had to write data management software that could find all the parts within some specified distance of a given coordinate location in the aircraft. Since the tens of thousands of part data models are stored by part number or name rather than by coordinate location, this seemingly trivial piece of software was very hard to write so that it could find all the parts quickly; it is a vital piece of Boeing's design process.

An example of non-geometric data vital for design is versioning and change notification. Design is an iterative process, and designs evolve over time. Different versions of the same item or set of items emerge and must be kept track of. Intergraph and other CAD systems support tracking of different versions of drawings. These often co-exist in the database so that a record of the design's evolution can be kept and backtracking is possible. Keeping all the versions straight and controlling the release of new versions is complex, and there are many opportunities for error.

Change notification is another difficult area. When a designer changes a design, the change usually affects other designers' work. Unigraphics, for example, has a facility whereby <u>notice</u> of design changes can be propagated

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[3]See the report on Rolls-Royce.

[4] Boeing has invested an enormous amount of time and money in enhancements to CATIA. By one estimate, the original 2 million lines of code obtained by Boeing in 1986 is now 6 to 8 million, created at a cost of over $1 billion. A Boeing source told me that the company has more mainframe computing power than anyone outside of the National Security Agency.

from one drawing to another. This procedure is set up manually; a person must designate which other drawings to "notify" if a change occurs. People must pick up these notifications and find out what changes have been made, usually by inspecting the drawing visually. ProEngineer contains a feature called "associativity" in which dimensions on one part can be hot-linked to corresponding dimensions on related parts. If one changes, the other will change automatically. These changes can ripple through a design in unplanned ways, and some ProEngineer users have turned this capability off. Learning how to use automatic change propagation properly will be one of the main tasks involved in spreading Concurrent Engineering throughout industry.

Intergraph CAD is presently most applicable to detail design, and to a lesser degree to preliminary design. The shipyards are being encouraged to use it, but several have advanced CAD capabilities of their own based on other commercial software. For this and other reasons, NAVSEA and several partners have been developing an advanced data exchange capability called NIDDESC (Navy-Industry Digital Data Exchange Standard Committee). The work of this committee extends far beyond data exchange, however, and its work is described in a later section of this report.

**Computer Support of Ship Design**

At this point, it is appropriate to discuss briefly some of NAVSEA's efforts in computer aids for ship design. A concept evaluation program called ASSET, originally developed at MIT, has been extended by NAVSEA. It operates independently from the Intergraph system, passing its results on but presently unable to take data back. ASSET is a parametric design system that uses historical data to help a designer predict sizes, weights, and other ship characteristics while exploring a design. Another tool helps designers place equipment in compartments, keeping track of weights, utility needs, and space requirements. Work is under way to create software that will help designers assign module breaks so that equipment locations and associated utilities can be planned to avoid the breaks. Another effort focuses on making a bill of materials early in the process[5] and identifying long lead items. These items will be associated with their modules as well as with the modules' build schedule, so that they can be ordered at the right time. Yet another program keeps track of catalog items like pumps and valves, indicating which types have been approved for use on the current ship.

Much of this software has been written either by Intergraph or by contract programmers in India and the Far East. The contractors cannot visit

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[5] In the auto industry it was considered revolutionary to have a bill of materials during concept design. Now, fuel economy regulations are forcing car designers to be careful of weight, which cannot be estimated without a bill of materials and associated weights of each item. The earlier such information is available the easier it is to modify the design to meet such constraints.

NAVSEA to fix a number of serious bugs, a disadvantage incurred when NAVSEA decided to contract out software instead of keeping the skill in-house. The advantage sought was more professional software, better user interfaces, use of more advanced hardware technology, and so on. A choice like this is one of many that organizations have to make as they decide what their core competencies should be. Another report in this series discusses the core competence choices of companies in product design methods, production equipment, and software.

Thought is also being given at NAVSEA to the flow of information during design. While this activity has yet to result in software, it is making the designers more aware of information structuring in the service of design. Information is being broken down into smaller packages so that portions can be released earlier and used by others. For example, structural analysis can begin before every compartment has been located. Only the main decks and bulkheads need to be defined. As a result, each of these is being kept in a different Intergraph file. No formal methods of structuring design information flow are in use at this time.

The infrastructure that supports these activities and the ship design process itself includes about 4500 personal computers and several hundred workstations. These are linked by a Novell local area network.

These tools are helping to make the technical aspects of design more effective, and are bringing non-technical aspects into the computer as well. However, much deeper changes are being proposed, and these are discussed next.

**The "Revolution" at NAVSEA**

A recent paper [Billingsley et al] called "Revolution at NAVSEA: Managing Design and Engineering Information" makes the case that modern shipbuilding is essentially an information management problem and that computers capable of managing that revolution are just now becoming available. What is needed is a complete restructuring of the ship design and construction process. Ships last a very long time and the process of creating and operating them over that time involves a huge number of people and organizations. Under current methods the information is too easily confused, lost, or distorted over time and place, and people work very hard to hold the process together.

It is not enough to take the existing process and "automate" or "computerize" it. The existing process is based on too limited a notion of what information is or what can be represented in a computer. As stated above, only a small part of the information describing a ship is geometric. Much of the rest is in other categories:

• interconnection logic related to distributive systems (which points are connected, what is at each of the points, what flows between them, etc.)

• decision logic describing how a design is done, how a physical system works or should be turned on or off, how to find things in the ship or in the supply system

• hierarchical system descriptions saying what something consists of or is part of

• data from a variety of sources including both analyses and experiments

Naval ship design has been taught for years as a "spiral" in which broad categories of physical requirements are gradually given more detail, revisited and revised iteratively until finally everything falls into place. Such a process produces a thing that sails, so to speak. The Japanese revolutionized shipbuilding by thinking of a ship as something to be built. The modern technique approaches a ship as something that performs a mission, and thus must sail, and thus must be built.

In commercial ships and aircraft, design consists of two nested loops, the inner one physical and the outer one economic. (See Figure 3.) Buoyancy is the nexus of the inner loop: the ship must float while carrying a payload, fuel for range and engines for speed; the airplane must take off fully loaded with fuel, payload, and engines. Economic payback over time is the nexus of the outer loop: enough payloads must be carried over the economic life of the vessel to return the owner its purchase and operating cost plus a profit. If the range is too short, or the speed too low, or the ticket/freight cost too high, the owner will not get business and he will lose his investment. There are many examples of planes with such range and payload that they could not take off.

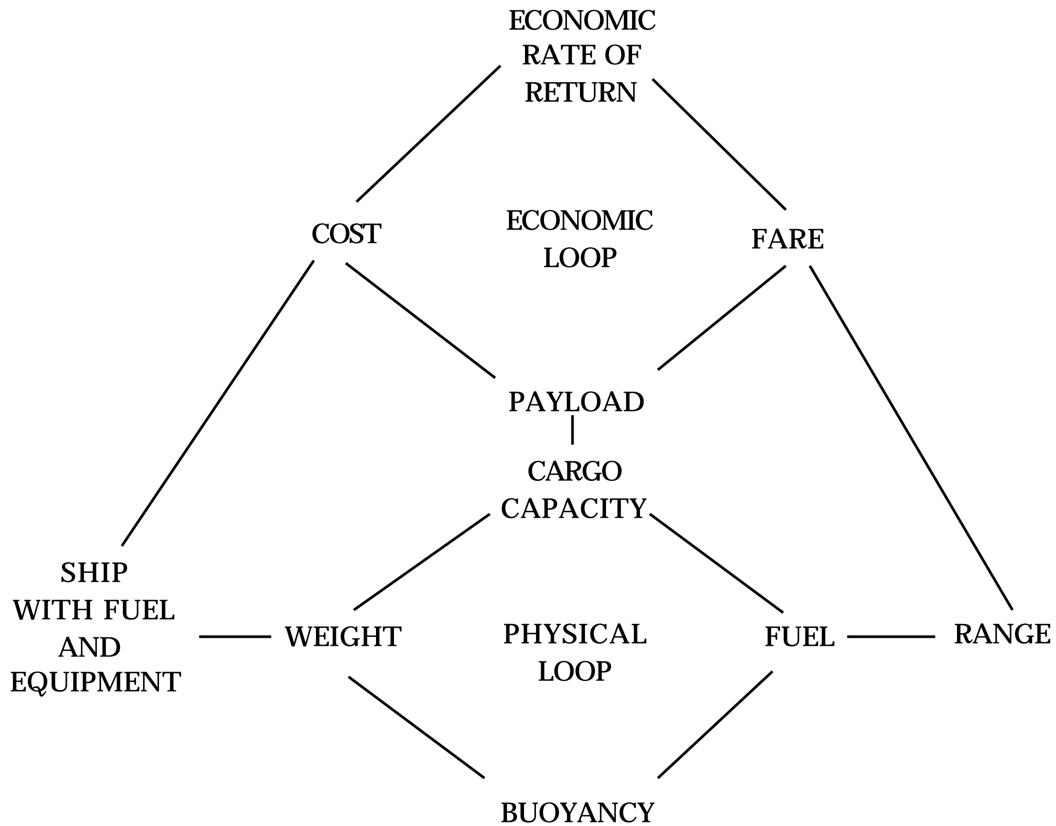


Figure 3. The Nested Loops of Ship Design

In military ships the economic nexus has been missing in the past but it is here with a vengeance in the post Cold War era where "affordability" is the new requirement. The old way of organizing NAVSEA into weight classes does not provide enough information early in the design process to address these loops adequately. Similarly, the traditional naval architect's approach of starting with the skin and working in via the ribs to the compartments to the components will not work either. (See Figure 4.) This again divides decision-making into the wrong categories and prevents the designers from seeing how combinations of decisions in the traditional areas impact the larger issues. This separation of decision and effect prevents important tradeoffs from being recognized and addressed when they can be dealt with most effectively.

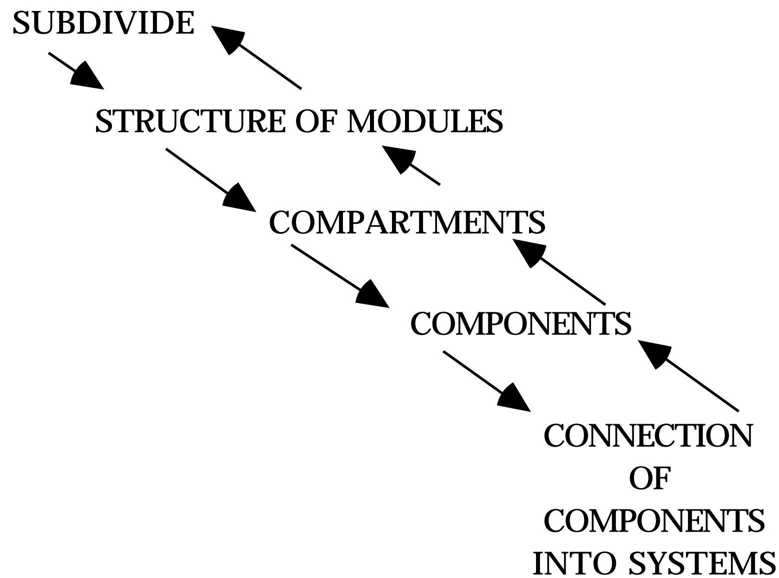


Figure 4. Traditional Ship Design Sequence

For example, in the traditional organization, many of the separate groups did their own structural, stability, or distributive analyses. Each operated on its own engineering or geometric models of its aspect of the ship. Coordinating all these analyses and seeing what they mean to the whole ship was difficult. Currently a lot of effort is going into unifying the underlying data so that analytical models will operate from the same set of assumptions or be at the same level of revision. This will make comparisons between different disciplines' results easier and make tradeoff analysis more confident.

A more sophisticated revision of the process proposed by Billingsley sees the design process as formally starting with a statement of requirements and proceeding by stages to a definition of a candidate design, analysis of its capabilities, and finally comparing those capabilities to the requirements. (See Figure 5.) "This process scales fractally," he says, meaning that it can be applied to the whole ship, to major systems within the ship, to subsystems, and so on. In the aerospace industry this is sometimes called "requirements flowdown" in the sense that each level below takes a portion of the requirements from above and seeks to satisfy them.[6]

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[6]Software explicitly designed to manage requirements flowdown is starting to appear. A system called RDD has been in use for several years in military programs as a program manager's tool to see that no requirement is forgotten, as well as to ensure that all requirements are met in time to finish the design on schedule. Other software currently being developed permits the manager to look into the data being created by designers at remote locations to see directly how the work is proceeding.

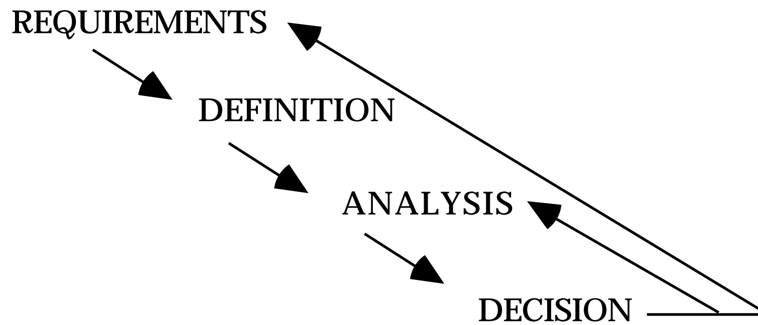


Figure 5. Iterative Design Loop for a Ship or Subset of One

The most sophisticated version of this vision dates from about 1992 and includes mission requirements (not unlike what commercial industry calls customer requirements or market analyses) as well as funding cycles in Congress and the Office of Management and Budget. Moreover, it includes both the design process and the process of planning how NAVSEA will muster its resources. (See Figure 6.)

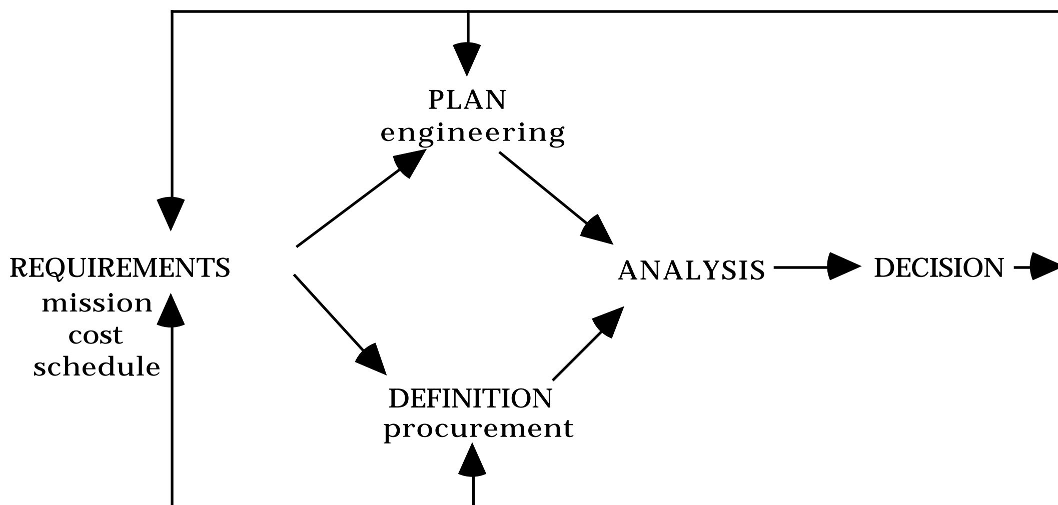


Figure 6. Full Information Flow Model of Ship Design

This is a generic iteration loop not unlike what might be found in many industries. It is quite unlike the traditional design spiral. It clearly defines five types of information that the design process must support: *requirements*, *planning*, *definition*, *analysis*, and *decision*, together with the data models and algorithms required to create, structure, and use the information. To make it work will require, in particular, much better cost models early in the process.

Cost prediction has been a particularly difficult area for the military. The contractors jealously guard their cost data even as the Navy tries to compile approximations of it from their bids. It is now recognized that the government's procurement policies add overhead costs that sometimes

dominate the total. Finally, only commercial industry really understands how to give cost issues equal standing with performance issues, and it will take some time before the military attains similar sophistication.[7]

The vision in Figure 6 is currently in the process of being put into place; it is by no means complete and may not have the complete agreement of everyone involved. It also deals most effectively with those phases of design that come after the concept is finished. Past concept designs were often driven by personalities and political issues, and they will continue to be driven by changing foreign policy and assessments of foreign threats. It may be difficult to systematize the concept stage of the process very much.

One ambitious step in implementing the current vision has been completed, called information engineering. What this means in practice is creating specific data models of ships and their main components so that unambiguous product definitions can be transmitted between design groups or between the Navy and its suppliers and their sub-suppliers. The NIDDESC was set up to generate these models, and it has been working for over 7 years investing roughly 50 man-years of effort. The basis for these models is the Nijssen Information Analysis Method (NIAM) which is a structured graphical representation method for recording relationships between things at a variety of levels of abstraction. The NIAM models are used as the basis for STEP/PDES application protocols (APs) and have been coded in EXPRESS, the standard data representation language of STEP/PDES. NIAM models have been made for ship structure and many important ship engineering systems such as pipe and vent duct.

An example is the AP for piping [NIDDESC] which is over a half inch thick and consists of careful definitions of the data required to be provided for contract design, detailed design, production engineering, and support engineering. Data for contract design comprises equipment arrangement, flow analysis, piping system test definition, and connectivity checks. For detailed design one has, in addition to an enriched connectivity check, an interference analysis, bill of material, pipe stress analysis, and a graphic representation. For production engineering one has pipe fabrication and assembly definition, and pipe installation definition. For support engineering one has documentation.

For example, here is a fragment of the data model representing a piece of equipment attached to one or more pipes: (See Figure 7.)

(Figure 7 is at the end of this paper)

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[7] I recently visited a primarily military U. S. aircraft company that was working for the first time with a Japanese subcontractor on a commercial airplane. The subcontractor's on-site representatives constantly challenged costly items like tolerances, which drive military aircraft design and manufacturing cost. The U. S. program manager told me, "We have realized that these people are not amateurs."

Figure 7. Fragment of NIAM Model of Piping System Equipment

An example fragment of EXPRESS code defining the entity flanged pipe port reads as follows:

```
ENTITY np_flanged_pipe_port
	SUBTYPE OF (np_specific_pipe_port_implementation)
	bolt_hole_orientation_type_value
	bolt_hole_circle_diameter_value
	flange_type_name
	bolt_hole_diameter_value
	bolt_hole_count
	flange_face_type
	flange_thickness
END_ENTITY
```

The main accomplishment of this effort so far has apparently been to get basic agreement as to what data should be in such models as well as to establish a vocabulary. The model also has captured important relationships between things, not only at a given level but up and down several levels of detail. This is a considerable accomplishment, though it remains to be tested extensively in use by many designers. Revision is likely but the stable nature of EXPRESS and the uniformity of the approach taken should make the revision process easy unless it requires a complete redesign of the hierarchy. It also represents a large effort and indicates how much work will be needed to capture designs in general.

It is also clear that it is a method of describing a finished thing, such as a pipe system. It is not yet a description of a thing in the process of being designed or a description of the design process. It is not clear what else would be needed, but some likely candidates include links to the required analyses of vibration or heat dissipation, or stress on the bolts in the flange joint. Other obvious candidates are assembly instructions for connecting flanged joints and testing them.

Not shown in these examples, but an integral part of the NIDDESC documents, are graphics of the entities themselves such as pumps and valves, including carefully defined coordinate frames for mounting equipment to the ship and connecting it to pipes. See Figure 8 for an example. Such data permit items to be ordered or specified in terms of their envelopes only when dealing with vendors, but in more specific detail when making training documents for operators of the equipment.

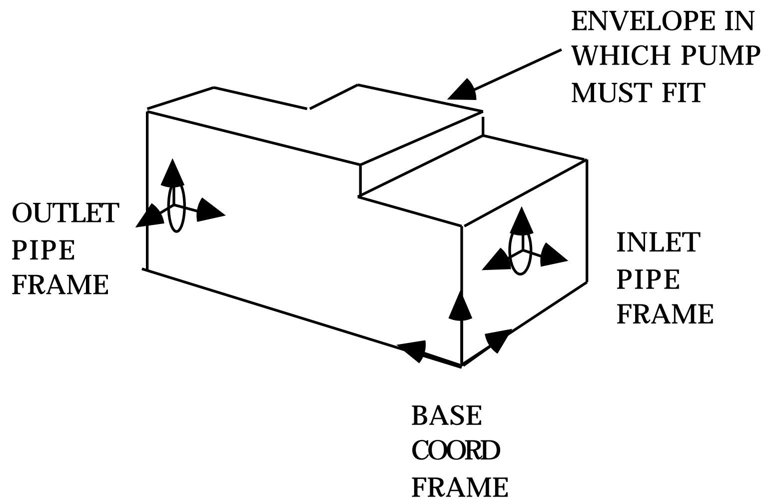


Figure 8. Example Envelope Specification for a Pump

The result of all this careful work is that the Navy will have an easier time dealing with the industrial base of the future, in which there will not be a separate set of contractors that do purely military work. Instead the Navy will have to work with a primarily civilian industrial base and may have to buy equipment that was designed for civilian use. Dealing with contractors just in terms of specifications and envelopes is called "black box procurement" in the civilian world, and is actively practiced by Japanese car makers, among others. Specifications like that in Figure 8 will form the basis for standardized procurement, possibly including the objective of creating stand-by manufacturing capability that can be called forth in time of an emergency.

The pipe system data model was tested by loading it with all the pipes in the DDG 51 destroyer. The system was able to retrieve answers to such requests as "list all the pipes in linear order from bow to stern in system X," or "list all the valves of type Y," or "list all the revisions to the design of system Z since date D."

The AP for ship structure is three times larger and more complex. This partly reflects NAVSEA's high expertise in structure as well as the fact that this AP contains some design-related data as well as descriptions of finished items. For instance, it knows the difference between the inside and the outside of a hull plate, something a CAD surface modeler does not. More interesting, it is includes an object superclass called "compartment" which contains attributes such as "cooling," "lights," "power," and so on. Each of these is of course an entity in its own database, such as cooling in the ventilation datastructure or wire for the lights in the electrical data structure.

Assembly is especially important to represent in structure since assembly is the crux of the modular ship construction method. Different shipyards assemble ships by very different methods, partly driven by their history and

importantly by the amount and arrangement of space in the yard. Most yards are too small and very crowded, forcing modules to be smaller than even their existing cranes can carry. Similarly, different strategies exist for making pipes, and there is little agreement as to how long a pipe section prefabricated in the shop should be. The data models can therefore create standard representations for low level things like flange joints but it is harder to generate standard models for structural modules or pipe assemblies without taking into account different yards' methods. Since a major objective, as discussed above, is to create data models that are independent of who will make and how to make, this problem remains unresolved.

This is clearly an ambitious program that will go on for many years, increasing in sophistication. Or else it will bog down as the implementers grasp what a huge task they have taken on. So far they have not blinked. It is a good lesson for people contemplating product data models to see what it takes to describe technically sophisticated things in detail. An important question is whether NIAM is too detailed. Other information modeling methods exist, some more detailed and complex than NIAM, and some less detailed. It is not clear if they are well matched to the problem of representing things being designed. Efforts like this one will be needed to determine the value of carrying the approach farther as well as evaluating NIAM as the carrier.

Finally, it is worth noting that the progression of representations discussed here follows an evolution from describing things (ships, pumps, etc.) to describing the process for generating those things. A general evolution to higher levels of abstraction is evident, and successor models may be even more abstract.

**Design Process Organization**

An amphibious assault ship designated LX is currently being designed at NAVSEA utilizing a new way of organizing the designers. The engineers are co-located with the task managers. The management structure is approximately as shown in Figure 9.

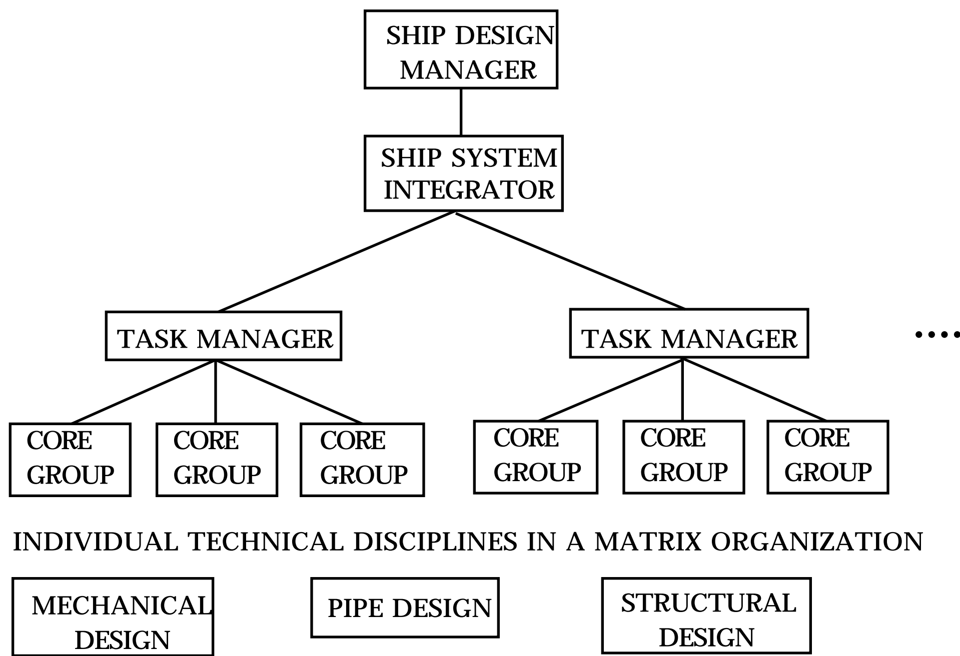


Figure 9. Design Organization for LX Program

There are about 20 core groups assigned to different systems. These groups are responsible for system integration in their arenas. They get skilled help from the functional organizations shown in the lower part of the figure.

The LX program is supported by extensive use of computer technology in which each engineer has a workstation. Intergraph (IG) is being used for all detailed design and data management. As of the date of my visit the NIAM models were not being used in the LX program.

**Final Remarks**

The design and construction of ships is obviously very complex. Ship designers and builders are justifiably conservative given the high cost of failure at sea. Ships take so long to design that there is a strong incentive to keep technical people around for many years. On the other hand, Navy leadership tends to rotate about every three years. All of these pressures tend to produce a large organization that is very difficult to change.

Furthermore, there is probably no sense in trying to find the "right way" to design ships. NAVSEA is still in the process of discovering the opportunities for rearranging the process sequence to take advantage of early availability of certain kinds of design information. It is trying to find the best point in the process to define where the module breaks should be, for example. Each time this topic is visited, the "best" time seems to become earlier.

Computer technology cannot by itself create a new or better process. It can only help implement a process and aid the generation and sharing of

information. Redesigning the process itself is a separate and very challenging problem.

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NIDDESC
April, 1993

figure 7

USED AT:

AUTHOR: NIDDESC/D.J. Martin
PROJECT: Distribution Systems

DATE: April, 1993
REV: 1.0

NOTES: 1 2 3 4 5 6 7 8 9 10

WORKING
DRAFT
RECOMMENDED
PUBLICATION

READER DATE CONTEXT:

NODE: TITLE: Equipment Occurrence NUMBER:

Role Implemented On a Higher Item Level

Figure 4-27: Equipment Occurrence