Chapter 5

The Ship Design Process

Peter A. Gale

5.1 INTRODUCTION

5.1.1 Definition of Design

Design can be defined as the activity involved in producing the drawings (or 3-D computer models), specifications and other data needed to construct an object, in this case a ship. The purpose of this chapter is to describe the process followed in creating a ship design, in full recognition of the fact that the process varies, to some extent, depending on the type of ship being designed and the personal preferences of the design team leaders. It is also true that, as this chapter is written, the design process is being scrutinized, and in some cases modified, with a frequency and intensity never before experienced. This is primarily the result of the opportunities presented by the accelerating advance of computer technology, coupled with the competition of the global marketplace, which causes all enterprises to constantly review their processes with an eye to improving efficiency.

Thus, there is no single ship design process today and the generic, typical process described here will certainly change somewhat in the years to come. What will not change significantly, it is believed, are:

- The objectives of the design process,
- The need for the designer to understand the shipowner's requirements and, at the same time, to help the shipowner to refine his requirements. (See Chapter 7 – Requirements Definition),
- The time and resource constraints imposed on the process,
- The fact that both art and science are reflected in the process (albeit that the role of science is steadily growing at the expense of art), and
- The fact that creativity and teamwork will always be cornerstones of the process.

This chapter covers both naval and commercial ships. Where appropriate the differences are described. However, to do this for every aspect throughout the chapter would have resulted in a very complicated text. It was decided to *take the high road;* that is, the greater level of design involved in naval ships has been described. It should be noted that for most commercial ship designs the clear definition and use of the design phases become blurred and that the design phases omit many of the described steps.

This is only possible, however, for shipyards with good current ship design and construction experience. For commercial ship types that are new to a shipyard or are of high complexity, such as cruise ships, more design phases, phase content and scope will be required and may approach the level applied to naval ships (see references 1 and 2 for typical commercial ship design practice).

5.1.2 Objectives of Design

The primary objective of the design effort, besides creating the information needed to build the ship, is to satisfy the shipowner's requirements at minimum cost. A ship's life cycle cost includes the design, construction, and operating and support (O&S) costs. For designs that incorporate new technologies [and hence research and development (R&D) costs] and/or significant disposal costs, these also must be included.

One of the responsibilities of the ship designer is to make the shipowner aware of design options that might increase acquisition cost but accrue even greater savings in O&S costs over the ship's life cycle. There are other design objectives as well. The specifications required to test the completed ship and demonstrate that it indeed meets the shipowner's requirements must be developed. Regulatory body and classification society requirements must be satisfied. (See Chapter 8 – Regulatory and Classification Requirements.) Beyond these objectives, the designers must make every effort to create a ship that the shipowner will be pleased with. This means that it must be safe, reliable, and as economical, to operate and maintain as possible, within the constraints imposed by technology and the shipowner's budget.

5.1.3 The Nature of Design

Ship design is an iterative process, especially in the early stages. (See Chapter 11 – Parametric Design.) The ultimate result is postulated and then analyzed and modified. The modified result is re-analyzed and so on until all requirements are satisfied. The reason for iteration is that ship design has so far proven to be too complex to be described by a set of equations, which can be solved directly. Instead, educated guesses are made as to hull size, displacement, etc. to get the process started and then the initial guesses are modified, as better information becomes available. The design spiral, first described in reference 3, has been used to characterize the design process. Figure 5.1 is one of many possible versions of the characterization. In this visualization, the ship designers' move through the design process in a sequential series of steps, each dealing with a particular synthesis or analysis task. After all the steps have been completed, the design is unlikely to be balanced (or even feasible). Thus a second cycle begins and all the steps are repeated in the same sequence. Typically, a number of cycles (design iterations) are required to arrive at a satisfactory solution. Anyone who has ever participated in a ship design knows that this characterization leaves much to be desired. In practice, the process is not sequential, unless the design is developed entirely by one person. Even then, the steps often will not be performed in a prescribed order but rather the naval architect will jump from one spot to another on the spiral, as knowledge is gained and problems are encountered.

In fact, the design process in the early stages is rather unpredictable. Once a baseline concept has been identified and defined in sufficient detail for it to be understood and used

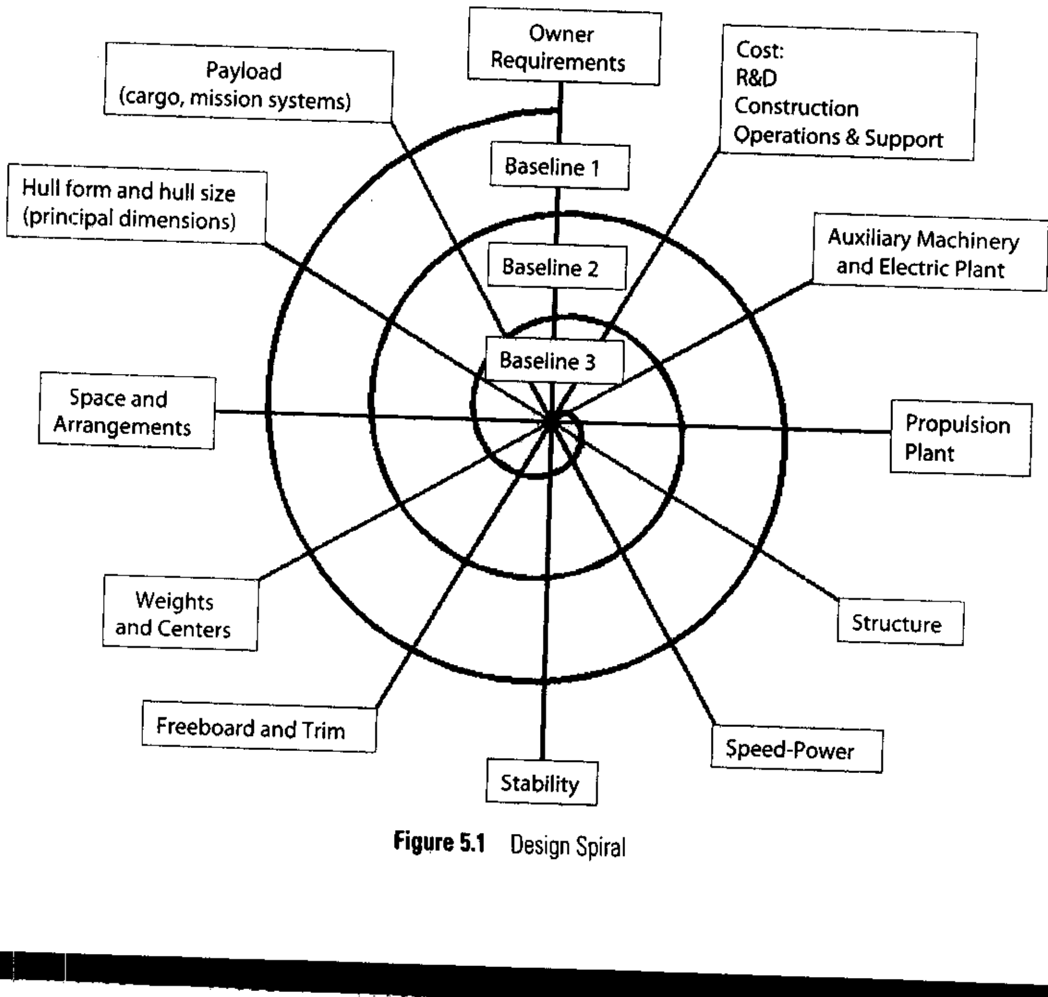

Figure 5.1 Design Spiral

by the principal design disciplines, for example, structures, propulsion, electrical, general arrangements, weight estimation, etc., then design work in these principal disciplines will generally proceed in parallel, as shown in Figure 5.2.

For each discipline, a series of tasks must be performed and there is usually a preferred sequence for the tasks. As each task is completed, the products of the task can be shared with the other members of the design team.

This may sound rather orderly. In fact, major problems are identified in the course of design and the act of resolving these problems typically perturbs the design effort in a number of design disciplines, requiring restarts or reworks of tasks previously completed. The number and severity of the problems identified are generally greatest early in design; they tend to decrease in both respects as the design is developed in greater detail.

A major design effort is planned so that formal updates of the design baseline occur at regular intervals. At these milestones, the current hull form and general arrangements are formally issued to the other members of the team and they are directed to shift to these configurations in their subsequent work.

Today, the current configuration is likely to be a 3-D computer model that all design team members have access to by means of a network, but that can only be updated with the approval of the team leader. When a major problem is identified soon after a baseline update, the design team must decide how to approach its resolution and, when a solution has been found, whether to issue an unscheduled baseline update immediately or to wait until the next planned update. The downside of waiting is that additional work will have to be done. The downside of an immediate update is that in some disciplines, the work stop/restart may delay the discovery of another major problem *just around the corner.*

5.1.4 The Design Environment

Ship design takes place within a surrounding environment that can have a significant effect upon the process. Factors in this environment include:

- economic trends,
- current and pending government policies and regulations,
- the status of international regulations on matters such as pollution control,

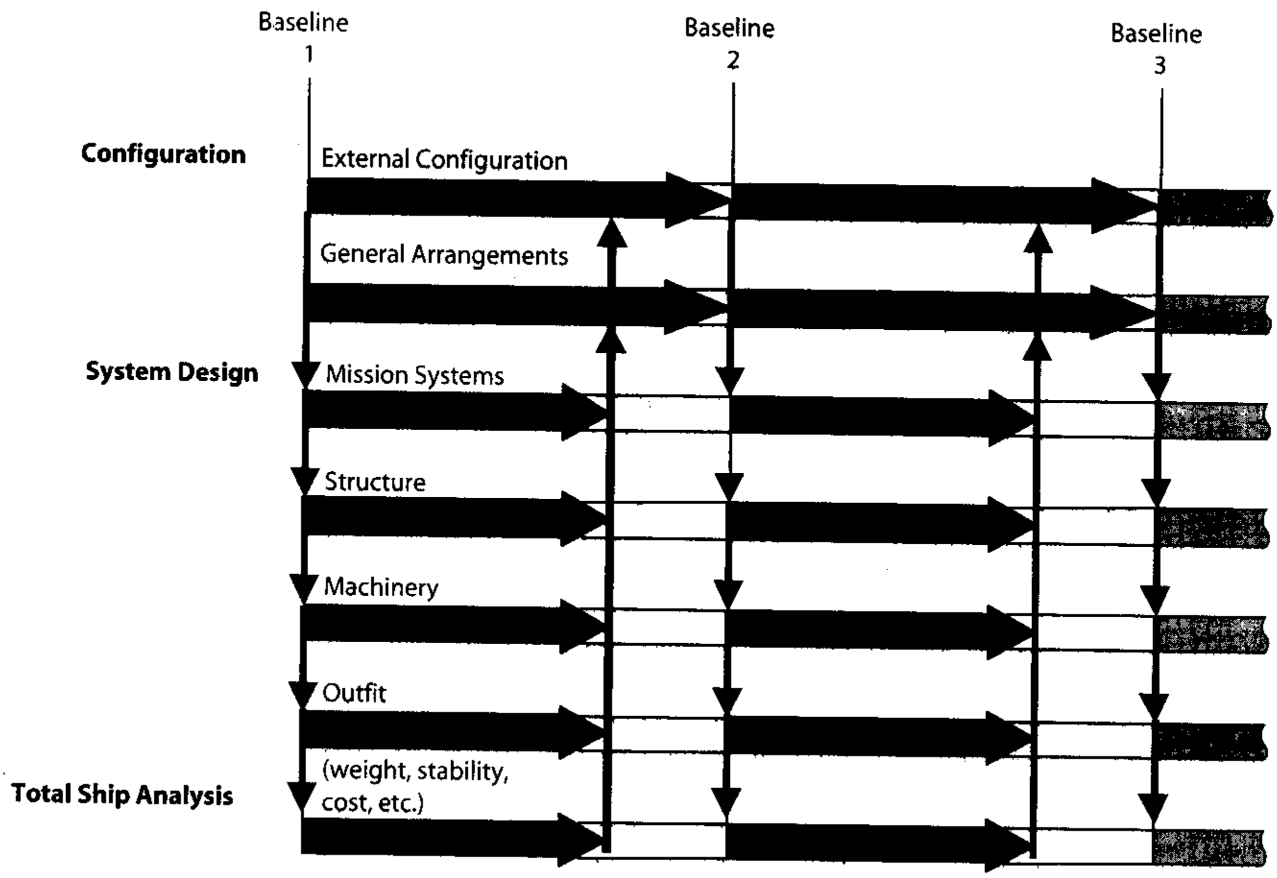

Figure 5.2 Design Development Process

- the breadth and depth of the vendor base for major equipment items,
- the management of the organization within which the design team works and to whom it reports, be that organization a shipyard or a design agent, and
- the prospective shipowner—his foibles, preferences, modus operandi, etc.

For naval and other government ships, additional factors come into play, including the congressional budget process, the terms in office of key decision makers in the Executive Branch and Congress, and political considerations.

Projected economic trends not only affect the viability of a proposed shipbuilding program, but also affect the tradeoff studies and design decisions within the design effort itself. An example is how the projected cost of fuel will affect the decision on propulsion plant type and prime mover. The double hull tanker rules, which resulted from the OPA 90 legislation, are a good example of the impact that pending government regulations can have on ship design.

How will top management interact with the design team? How frequent and how detailed do they want status briefs to be? To what extent do they wish to participate in design decisions? The last three questions apply to the prospective shipowner as well. Good relationships between the design team, the shipowner-to-be and the design team's management can foster mutual understanding, speed up the design process by getting critical design decisions made more quickly, without second guessing, and produce a better product with less stress. Poor relationships between the design team and either of these two groups can cause high stress, burnout and, ultimately, a poorer product.

5.1.5 Design Participants

One person can develop the design for a relatively small, simple ship but typically ship design is a team effort. The team size will generally grow as the design is developed in progressively greater detail. For a small, relatively straightforward ship design, the team size might start at one and ultimately increase to five or six. For a large, complex warship, the design team size might start at 25 to 50 and ultimately grow to many hundreds, assuming that the combat system design integrators are included.

Core team members will always include naval architects, marine engineers and designers with CAD skills for 3-D modeling using the computer. Structural, mechanical, and electrical engineers are also typically represented. Shipyard personnel with expertise in ship construction and production planning are needed, as are equipment vendors with specialized expertise regarding the systems and equipme they offer. Even commercial ship designs may require oth specialized expertise, for example, computational fluid d namics (CFD) analysis, finite element structural analy (FEA), propeller design, acoustic analysis, reliability anal sis, or human factors engineering, which might be obtain via consultants. If the new ship is to be certified by a cla sification society, liaison with that society is establish early in design. Hydrodynamic model testing is still tl norm during the pre-contract naval ship design process, b not for commercial ships, and representatives of the select model basin can provide invaluable assistance to the desig team. It is essential that cost analysis expertise be represente on the team; one or more shipowner's representatives a also important team members.

5.1.6 Design Tools

Ship designers rely upon extensive databases for previou designs, together with lessons learned from operational ex perience with the ships built to those designs. (See Chap ter 11 – Parametric Design.) Increasingly, such data is hel in the computer, in a form, which is readily accessible an easily manipulated to suit the needs of the designer. The de sign team uses a myriad of other design tools. These tool generally exist in the form of computer software used t model the ship geometry or perform analyses of variou types. (See Chapter 13 – Computer Based Tools.) Increas ingly, these ship design and analysis tools are being linke into integrated design systems. These systems can speed u the design process by eliminating much of the time and ef fort spent moving between individual computer program that are not efficiently linked. More often, use of these so phisticated systems does not save time but instead permit the designers to explore more alternatives in greater detai in the time available.

5.1.7 Design Standards

Design standards, as the term is used here, refers to a broad category of second tier design, construction, inspection, and/or test requirements which are normally imposed on a new design. They are distinctly different from the *Shipowner's Requirements,* which are typically top-level performance requirements, such as, cargo capacity, speed, and endurance. If the ship is to be classed, the rules of the designated classification society are a form of design standards. There are national and international regulations pertaining to matters such as personnel health and safety, safe navigation, and pollution control. These regulations are a form of design standards. Shipowners with large fleets will typically have design standards of their own. For example, a shipowner might specify the use of a certain propulsion prime mover to achieve standardization within his fleet. Government agencies such as the U.S. Navy, NOAA and the U.S. Coast Guard have standards or preferences that they apply to designs for new ships that they will operate. Design standards, as defined previously, can have a significant influence on a new design, and even on the design process itself. For this reason, it is very important for the design team to identify all the applicable design standards at the beginning of the design effort. Failure to do this can result in major problems downstream, including delays, wasted design effort and added expense.

5.1.8 Design Constraints

Every ship design must satisfy a purpose and this is usually defined in the *Shipowner's Requirements*. While the shipowner's requirements are not really constraints they set the boundaries for the design.

Constraints apply to every ship design, both the process and the product. Time and cost are nearly always constraints, applied to both the design itself and the delivered product: the ship. Other examples of design process constraints might be the unavailability of sufficient skilled design personnel or required computer software, hardware, or network capability.

Physical constraints might be applied to the design itself for any one of three reasons: the need to build the ship in a specific shipyard and then get it to sea, the need to maintain the ship during its service life, and the need for the ship to visit specific ports.

Assigned Weight	Attribute
1	Cargo carrying capacity
1	Acquisition Cost
2	Energy conservation
2	Manning reduction
2	Reliability
3	Minimum risk
3	Standardization

1 = 10 points
2 = 5 points
3 = 2.5 points

Figure 5.3 Example of Ship Design Philosophy

Frequently, drydock, pier, harbor or canal limitations create constraints. Hull dimensions and air and water drafts are affected most frequently. Bridge or overhead cable heights may limit air draft, the height of the uppermost point on the ship above the water surface. Harbor or canal channel depths often establish the limit on water draft, more properly the navigational draft, or this limit may be set by the sill height in drydocks to be used to maintain the new ship. Hull length and/or beam might be limited by canal lock, drydock, or building way dimensions. The available length at piers the ship will moor to might also limit hull length. These are just some examples of operational considerations that can impose physical constraints on a new ship design.

5.1.9 Design Philosophy

A design philosophy is a weighted list of desired design/ship attributes that is used in the evaluation of design alternatives. Examples of such attributes include:

- first cost,
- operating cost,
- manning,
- producibility,
- operability,
- maintainability,
- reliability,
- mission capability,
- sustainability,
- supportability, and
- risk (cost, schedule and technical).

Each attribute should be measurable in clearly defined units; the shipowner should agree to them all. The design philosophy is a guide used by the members of the design team as they perform trade-offs and evaluate design alternatives during design development. The need for a design philosophy increases when the number of design participants is large and/or when the design team is physically (geographically) separated. A risk in large design teams is that individual members of the team might apply their own personal priorities as they evaluate design alternatives and make decisions. The design philosophy is an attempt to keep all team members *marching to the same drummer* as they make design decisions. Figure 5.3 is an example of a design philosophy that might be used during a new ship design.

In practice, the design philosophy is tailored to suit the specifics of each trade-off study to which it is applied. Not all elements of the philosophy apply to each trade-off decision and many trade-offs will require unique performance measures to be evaluated.

5.1.10 Degree of Uniqueness

New designs cover the gamut in terms of their uniqueness. Some new designs are very similar to existing ships with modest changes, for example, somewhat more or less propulsion power or payload. Other designs reflect significant changes from current practice in specific respects, the propulsion plant type might be an example, but in all other respects they are not unique. At the extreme, and quite rare, is the design that is very different from anything considered before. The rare unique design is not only an exciting challenge for the naval architect but it affects the approach to early stage design as well.

For designs that are well understood, that is, similar to what has been done in the past, the design team will have access to a multitude of data for similar ships. This data can be used in early stage design to make quick and reasonably accurate estimates of the principal characteristics (Chapter 11 – Parametric Design) and costs of alternative concepts for the new design. This may be done using ship synthesis models, discussed in Chapter 14, that contain estimating relationships derived from parametric analyses of the body of data on existing ships. The parent ship approach may also be used if the database contains one or more ships that are sufficiently similar to the desired new design. In any case, the large body of existing data pertinent to well understood designs simplifies early stage estimating and makes it possible to readily examine the effects on performance and cost of a large number of primary design parameters, for example, speed, endurance, payload, etc.

On the other hand, for the unique design, the database on existing ships is of little or no value. The naval architect must fall back to reliance on first principles to laboriously develop a small set of point designs, that is, conceptual designs that cover the ranges of the primary design variables of interest. More technical experts will have to be brought in to develop these point designs and they will generally have to develop more design detail than is typical in the initial design phase. An example would be the development of a point design for a high-speed multi-hull with a unique hull form. The estimate of required propulsion power is critical to sizing the hull and estimating its cost. Power at the required top speed is, in turn, a function of the full load displacement. Lacking weight data on similar designs, in order to get a reasonable weight estimate, a considerable effort might have to be expended on an initial structural design. This, in turn, might require a major effort to assess the anticipated hydrodynamic loads on the structure. The point designs, once they have been developed, can be used as parents to explore the effects of parametric variations in other, second order parameters. For the unique design, early stage design progress is slower, more difficult, and the design results are much less certain, that is, there is a higher degree of risk in the results of early stage studies of unique designs. This uncertainty can be partially compensated for by the use of larger design margins as discussed in Section 5.7.

5.2 DESIGN PHASES

The design process is subdivided into phases. One reason for this is that the nature of the work done, the design skills required, the number of persons participating in the design effort, the level of detail of the design deliverables and other features of the design process change over time as a design is developed. Design management is facilitated if the effort is divided into phases separated by intervals, which permit design reviews to occur, along with planning and preparation for the next design phase. Another reason for phasing a design effort is the major milestones in the typical ship development process. An example of such a milestone would be the point at which the budget for the new ship must be established. Another typical milestone would be the point at which specifications and drawings must be completed to solicit shipyard bids for the detail design and construction effort. Note that this milestone might not apply in every case; for example, if a ship design were being developed on speculation by a shipyard.

The number of design phases and the names applied to them vary and this is a source of confusion. For this discussion, the approach developed in the early 1980s as part of the IHI Technology Transfer, and defined in references 1 and 2, which divided the design and engineering effort into Basic Design and Product Engineering, is used.

Basic Design is further subdivided into four phases, designated as follows:

1. concept design,
2. preliminary design,
3. contract design, and
4. functional design.

The latter two phases are often referred to collectively as the "System Design Phase."

Product Engineering is subdivided into two phases:

1. transition design, and
2. workstation/zone information preparation.

During Basic Design, the ship is designed in its entirety, on a system-by-system basis. During Product Engineering, the ship design is translated into a form suitable for modern production techniques and necessary additional information is developed. Some experts consider Functional Design to be part of Product Engineering but it has been in-

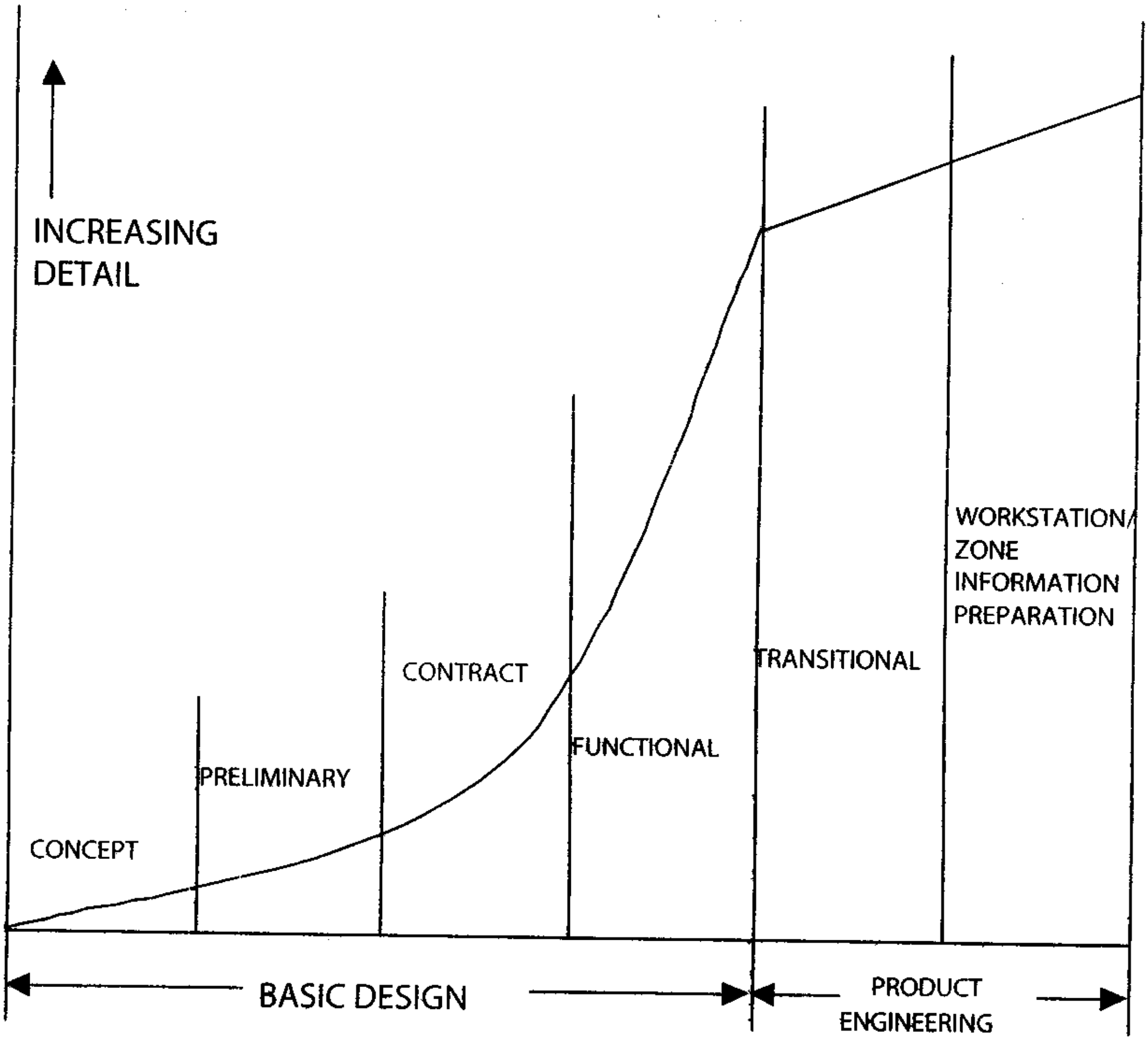

Figure 5.4 Ship Design Phases

cluded here in Basic Design since it remains systems oriented. The first three phases of Basic Design must be completed before the award of a contract for detail design and construction. Note that the traditional detail design phase has been divided here into three phases, namely, functional design, transition design, and workstation/zone information preparation.

Modern techniques for modular ship construction permit extensive pre-outfitting and pre-testing of ship blocks prior to ship assembly. This improves efficiency and saves cost by reducing on-way or in-dock time during ship assembly and by maximizing the amount of advance work done in better working conditions at vendors' facilities or in enclosed buildings at the shipyard. Use of these techniques increases the time required for detail design as well as the level of detail and completeness of the detail design package, which is now up to 20 to 30% larger than in the past. Another effect has been to largely eliminate the traditional overlap between detail design and ship construction. The current philosophy is to resolve problems in the detail design package before *cutting steel*. The extra time and effort spent on detail design is more than recovered by a more efficient construction effort, as can be seen by very flat learning curves for multiple ship construction in Japanese shipyards. That is the benefits of learning are obtained because mistakes and rework on the first ship are eliminated by better and completed design.

Figure 5.4 depicts the design phases and the increase in detail as a design progresses.

5.2.1 Concept Design

This first design phase, referred to herein as *Concept Design* (CD), is sometimes referred to in the naval ship world as the Cost and Feasibility Study phase, or simply the Feasibility Study phase. The principal objective of this phase is to clarify the shipowner's requirements, that is, the ship's mission and principal required performance attributes, which reflect the desired balance between capability and affordability. (See Chapter 7 – Requirements Definition.)

Another objective is to develop a concept design, which satisfies the requirements, as well as a cost estimate and a risk assessment. From the designer's point of view, the objective during this phase is to work with the shipowner to understand and define the ship's mission, that is, to help the shipowner decide what it is that he needs and can afford. When this has been done, a concept design is developed which reflects this mutual understanding.

At the outset, the shipowner will know that he has a need for a new, converted or modified ship and will know in general what functions the ship must perform. However, the shipowner often will not know specifically what the performance requirements are for speed, fuel endurance, cargo capacity, etc. If the shipowner does have some specific values in mind for these variables, the shipowner may not know whether they are compatible with the budget. Thus a systems analysis is required which couples mission analysis with economic analysis. Ranges of each of the key ship parameters are explored in a systematic way, ship feasibility studies are developed for attractive combinations of the parameters, the cost and performance of each total-ship alternative is estimated, a cost-benefit analysis is performed, and feedback is obtained from the shipowner as to his preferences.

Typically several cycles of synthesis and analysis are performed, punctuated by interactions with the shipowner, during which the range of options studied is progressively narrowed. Through this process, a consistent set of performance requirements is established, which can be satisfied by a practical ship design solution and is within the shipowner's budget.

The role of the design team is to perform parametric studies that sketch out the design alternatives of interest in sufficient detail that the cost (capital and operating), performance, and risks (cost, technical and schedule) of each can be assessed and compared. The alternatives are often referred to as feasibility studies because the feasibility of each postulated combination of the major design requirements must be established, that is, is there a viable design solution for each case? Where there isn't, that combination of requirements can be rejected. Where there is a viable solution, that solution can be input into the cost-benefit analysis.

Because performance, cost and risk are being compared among the alternatives, *relative* accuracy and consistency among the alternatives is stressed rather than *absolute* accuracy. Collectively, the set of alternatives must illuminate the capability versus cost versus risk trade-offs of interest to the shipowner. At the conclusion of this process, the mission of the new ship will have been defined along with the principal ship performance requirements, that is, required ship capabilities. In addition, a feasibility study will have been created which represents an initial solution to the stated requirements. Normally, near the end of the phase, this feasibility study is developed in greater detail to become a concept design. This is done to reduce risk, improve the cost estimate, refine and validate the most important derived ship performance requirements, and establish a baseline for the start of preliminary design and its major trade-off studies. The products of a typical naval single feasibility study and a concept design are listed in Tables 5.I and 5.II, respectively.

Figure 5.5, based on a figure in reference 4, classifies all seagoing ships in two broad categories: transport and non-transport, with three and four sub-categories, respectively. The above process description generally applies to all of the sub-categories.

TABLE 5.I Feasibility Study Products (U.S. Naval and Government Ships)

Feasibility Study Report, documenting the following:
Essential performance requirements
Principal hull dimensions and hull form coefficients (Cp, Cx)
Area/volume summary
Configuration sketches: inboard profile and main deck plan
Payload definition, for example, space, weight, critical dimensions, adjacencies, required support services
Description of mission-critical systems and features
Weight/KG estimate, 1-digit level
Propulsion plant type, installed power, and number of propulsors
Installed electric generating capacity
List of major equipment
Manning estimate
Speed/power estimate
Endurance fuel estimate
Intact stability check
Estimates of critical performance aspects, as required, e.g., radiated noise or seakeeping
Cost estimate
Technical risk assessment and risk management plan

In the case of ships designed to transport bulk or general cargo from point to point as elements of a larger transportation system, analyses of the overall system, including its land-based elements, are typically performed. For the ship portion of the system, the fundamental decisions to be made are: number of ships, payload (carrying capacity, in both weight and cubic terms), and speed. Computer models are applied to simulate the operation of a single ship or an entire fleet. Such models range in complexity from simple deterministic models to complex time domain simulations. They generally incorporate simplified design models with the ability to quickly generate ship characteristics corresponding to various combinations of payload and speed. The models estimate the capital and operating costs for each alternative. Optimization techniques can be applied to the major variables to compare alternatives and search for the optimum or graphical output of performance metrics can be shown for the study *option space* so that a human decision-making selection can be made.

It is more difficult to apply the classical systems analysis techniques to ships in the non-transport categories. For the latter types, the number of critical mission characteristics is generally greater and the ability to analyze and compare mission performance as related to these characteristics is more difficult. For example, it is more difficult to predict the ability to detect and catch fish than it is to predict the speed of a transport ship. In a multi-mission warship, arriv-

TABLE 5.II Concept Design Products (U.S. Naval and Government Ships)

Concept Design Report, documenting the following:
Performance specification (initial draft)
Body plan and appendage sketch
Area/volume summary
Concept general arrangement drawings (space *blocks* allocated by function)
Topside arrangement sketch
Payload definition
Description of mission-critical systems and features
Weight estimate
Concept midship section
Propulsion plant description
Machinery arrangement sketch
Electric load analysis and generated selection
Simplified one line diagrams
Master Equipment List (MEL)
Speed-power curve
Manning estimate
Endurance fuel analysis
Estimates of critical performance aspects, as required
Cost estimate
Technical risk assessment and risk management plan

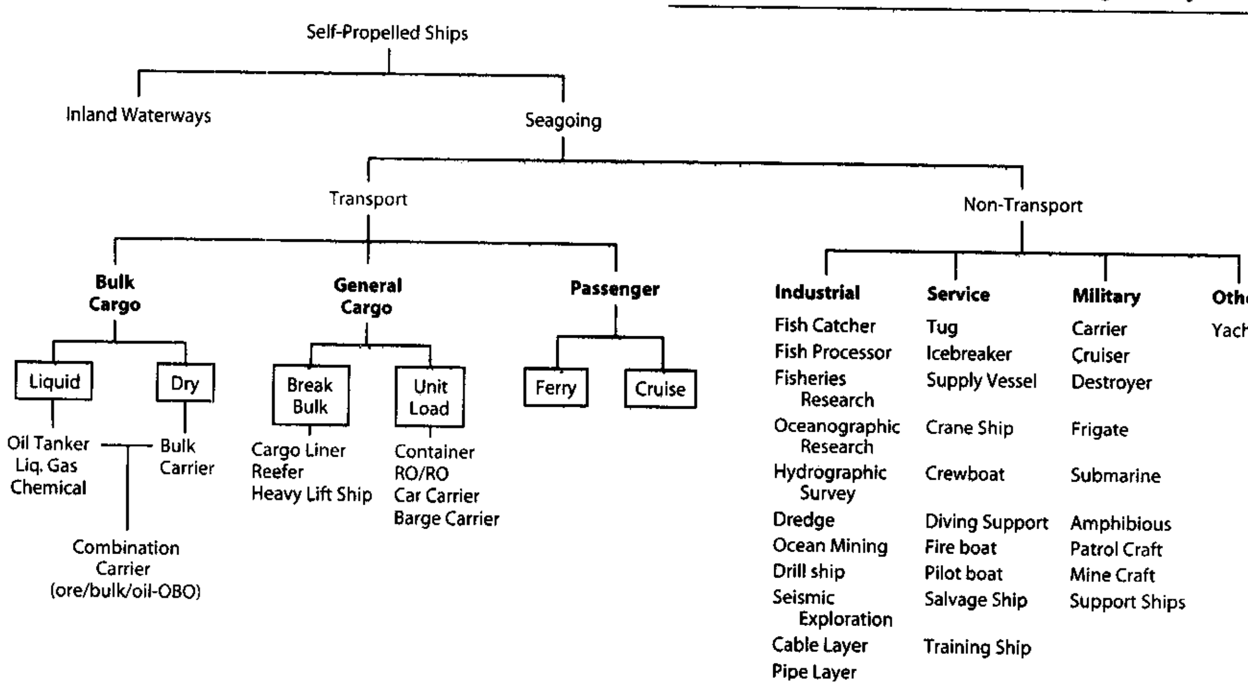

Figure 5.5 Ship Type Categories

ing at a single figure of merit is challenging since it is generally scenario dependent.

5.2.2 Preliminary Design

Design work, for the specific ship, begins in earnest in the preliminary design phase and the size of the design team and the cost of the design effort take a big jump. The following are the objectives of this phase:

- validate the top level ship performance requirements and develop second tier requirements,
- establish ship size and overall configuration,
- select major ship systems,
- quantify ship performance,
- reduce or eliminate major technical, cost and schedule risks,
- refine capital and operating cost estimate, and
- develop draft version of the Build Strategy (see Chapter 14 – Design/Production Integration).

Since the eventual cost and performance of the new ship will be established largely by the end of the preliminary design phase, the work done during this phase is very important. A feasibility study or concept design that satisfies the performance requirements developed in the previous phase will be available and this forms the starting point for the preliminary design effort. During this phase, formal trade-off studies are performed on design issues that will have a major effect on ship size, overall configuration, performance, cost or risk. The study of issues that do not have a major impact on these parameters should be deferred to the following phase. Failure to do so can waste resources and divert the attention of the design team.

Some examples of pertinent issues for trade-off study in this phase are:

- hull proportions (L/B, B/D, etc.),
- hull shape (transom vs. cruiser stern, bow bulb vs. no bulb, topside flare vs. tumblehome, etc.),
- general arrangement,
- propulsion plant type (low speed diesel, medium speed diesel, gas turbine, integrated electric, etc.), (Often addressed in Concept Design phase),
- deckhouse size and location,
- mission-critical payload features, (hardware components, space allocation, arrangement, etc.),
- hull structural configuration, and
- crew size.

The ship impacts of some issues studied in this phase will be so large that whole ships must be *wrapped around* the candidates being studied in order to get valid assessments of total ship impacts. These whole ship alternatives may be developed at the feasibility study level of detail or may require greater detail. An initial design baseline is established early in the design phase to serve as a point of reference for the trade-off studies. This initial baseline is generally the concept design created at the end of the previous design phase. Usually the design baseline is updated several times before the end of the preliminary design phase so that the results of major trade-off studies can be incorporated as they are completed.

The preliminary design is developed beyond the initial concept design in all technical areas, regardless of whether they are subject to formal trade-off studies. In design areas not subject to the investigation of design alternatives, a reasonable baseline concept is selected and defined to the appropriate level of detail. For many ship systems, this is the identification and approximate sizing of major system components and the development of a simple one-line diagram of the system. System alternatives will be studied in the following phase.

The Build Strategy for the ship (5,6), reflecting zone construction, is drafted during this design phase, if not earlier. Production considerations are reflected in the design work to the extent practical. For example, in the development of the hull form and superstructure configurations and in defining the locations of decks and bulkheads within the ship, maximum use is made of flat plates and readily formed shapes. If a shipbuilder is developing the design, the shipyard production specification (Shipbuilding Policy), which defines the design processes and production methods and processes to be used to build the ship, must be developed during this phase, if it does not already exist. This specification will influence the contract design effort and the parallel completion of the build strategy. If the design team does not know which shipyard will build the ship (as in the case of a build competition), the Build Strategy may have to be *generic,* that is, suitable for all potential shipbuilders.

Major emphasis is placed on predicting performance to validate that the stated performance requirements have been satisfied. These predictions might include ship speed, seakeeping, station keeping, ability to traverse along a defined track line, acoustic performance, cargo on-/off-load rates, or the ability to perform critical missions in a seaway, as typical examples. If the hull form is unusual and hydrodynamic performance is of critical importance, limited model testing may be done to validate performance estimates. More often, model testing is deferred to the following phase.

Risk identification and reduction is another area of emphasis. Major risks must be identified and alternative ways to reduce them explored. These generally include fallback design options with lower risk but less performance. The objective is to reduce the risks associated with the completed preliminary design to *low* or, where this is not possible, to develop a clear and detailed plan to accomplish this by the end of the next design phase. This must be accomplished before the next design phase is entered. The products of a typical preliminary design are listed in Table 5.III.

Note that the preceding discussion has assumed that a new ship is being designed. Frequently, ship conversions or modernizations are also evaluated as possible solutions to the shipowner's requirements during this design phase.

5.2.3 Contract Design

The principal objectives of the contract design phase are:

- confirm ship capability and cost to the prospective shipowner,
- provide a meaningful and accurate bid package for shipbuilders, and
- provide criteria for shipowner acceptance of the ship.

Extensive additional engineering effort is required to achieve the first objective. Emphasis is placed on the development and refinement of ship systems across the board. Trade-off studies deferred from the previous phase due to their lesser ship impacts are now performed. The technical portion of the bid package is developed by the design team and consists of a ship specification, drawings, and other ship descriptive data, for example, the weight estimate.

For each ship system, the following tasks must be performed:

- derive lower tier performance requirements from the higher level ship performance requirements,
- develop and evaluate alternative system concepts (where this has not been done in the previous phase),
- make system selections,
- complete engineering work on the selected system, and, finally,
- develop system specifications and drawings.

The ship hull form, including appendage definition, and general arrangement are further refined. Formal configuration control is often invoked near the mid-point of this design phase. Arrangement drawings are developed for many of the ship's internal spaces and for topside system installations, for example, anchoring and mooring, boat handling, communications and navigation, and helicopter facilities.

As the ship systems are designed, careful attention is paid to the integration of the ship systems and their human operators and maintainers. As part of this effort, for naval ships, the ship manning requirements are refined and training requirements are defined. Reliability, maintainability, and availability (RMA) analyses are performed, as are studies and design work related to the ship's maintenance and

TABLE 5.III Preliminary Design Products (U.S. Naval and Government Ships)

Preliminary Design Report, documenting the following:
Performance specification
Lines drawing and appendage sketch
Area/volume report (req'd vs. actual)
General arrangement drawings (to individual compartment level)
Topside arrangement drawing
Line of sight analysis
Payload definition
Descriptions of principal ship systems and features
Weight report (3-digit level, KG and LCG)
Structural midship section
Preliminary scantling drawings
Propulsion system analysis
Machinery arrangement drawings
Shafting arrangement
Preliminary propulsor design
Electric load analysis
HVAC load analysis
One line diagrams
Typical space arrangements
Deck systems arrangements
Ship control and communications systems analysis
Preliminary Master Equipment List (MEL)
Preliminary ship manning analysis
Stability analysis, intact and damaged
Speed-power curves
Endurance fuel analysis
Seakeeping and maneuvering analyses
Model test plan
Other performance estimates, as required, for example, radiated noise
Preliminary availability analysis (Ao)
Maintenance concept
Supportability concept
T&E plan (draft)
Preliminary safety analysis
Build strategy (draft)
Shipyard production specification (Shipbuilding Policy)
Cost estimate
Technical risk assessment and risk management plan

support requirements, often referred to as Integrated Logistics Support or ILS.

The ILS effort addresses issues such as:

- the ship maintenance philosophy (for example, what maintenance work will be done at sea by the ship's crew vs. work done in port by shore-based personnel),
- the repair parts required to be stowed aboard ship,
- parts commonality and interchangeability between ships,
- re-supply of the ship with stores and repair parts,
- approach to ship configuration control and the tracking of maintenance actions,
- the required shore-based facilities for ship support including spare parts stowage and maintenance facilities, and
- planned maintenance strategy and schedule (restricted availabilities, overhauls, and dry dockings).

The Build Strategy drafted during preliminary design is validated and approved during this phase (5). It includes the design and engineering plan, and the block and zone definitions to be employed during ship construction. The ship production plan is also developed. It includes the key event schedule and the selected approaches to advanced outfitting and ship assembly and construction.

Technical specifications required for the advanced ordering of long lead equipment and materials are developed. All aspects of ship performance are analyzed and the stated performance requirements validated. A full program of hydrodynamic model tests is typically performed for naval ships, some of which support the propeller design, which is also typically developed in this phase. Final tests of the design propeller mounted on the final hull model may not be completed until the following phase, however.

Traditionally, critical ship systems and spaces such as the anchor handling system and the navigation bridge were modeled using small or full-scale physical mockups to ensure correctness and to permit review by the shipowner. Today, however, 3-D models with simulation and walk-through capabilities, developed by computer, are replacing physical mockups. If land-based testing will be required for essential elements of the ship, these tests and the associated site requirements will be defined during the subsequent functional design phase.

The ship specification is perhaps the most important product of contract design (see Chapter 9 – Contracts and Specifications). The specification is, of course, essential if the shipowner plans to have shipbuilders bid for the detail design and construction task. However, even if a shipbuilder is developing the design, the specification is required in order to acquaint others in the yard with the work required and to arrive at a valid estimate of the anticipated build cost. The ship specification typically is a mix of performance and *how to* specifications, the latter reflecting the shipowner's preferences and the shipbuilder's preferences if the specification is prepared by the shipbuilder. It includes the test and trials requirements for the new ship, as well as acceptance criteria for each test and trial requirement. These criteria must be met for the shipowner to accept the ship. The ship specification also contains requirements for the documentation that must be delivered with the ship, documentation necessary to properly support the ship throughout its life. Because of the importance of the ship specification and the drawings referenced in it, it is carefully reviewed prior to the completion of the design phase. In the review process, specifications and drawing integration is emphasized, to ensure that there are no conflicting requirements between sections of the specification and/or the various drawings. Obviously, the specification language must be unambiguous. Table 5.IV lists products that may be included in a contract design.

5.2.4 Functional Design

This design phase, and the other two that follow, are only briefly described herein. See references 1, 2, and 7 for additonal detail and other references.

During Functional Design, the Contract Design is developed further to complete the design on a system-oriented basis. The products of a typical functional design are listed in Table 5.V. All design calculations and configuration definition are completed and all design decisions still outstanding are made.

Detailed naval architectural calculations are performed, including structural and vibrations analyses. The sizing of all structural scantlings is completed. All hull outfit is defined in detail, including the complete definition of all material. All marine engineering and electrical design calculations are completed, as are system arrangement drawings and diagrams.

System arrangements (drawings or computer models) are prepared for systems such as the mooring system that do not lend themselves to diagrams. Sized distributive systems are shown on the system plans. The completed diagrams for piping, electrical and HVAC show pipe, cable and vent duct sizes, cable types, bills of material and system routing in assigned wire ways or system corridors.

Typical sections are indicated for pipe and vent duct runs. The first revision of the budget control list is issued, which advises all concerned of updated material quantities and weights. Manufacturing drawings are prepared for all long-lead-time items that are to be built by the shipyard. Purchase technical specifications not developed earlier are completed. Shipowner and regulatory body comments on and approvals of the completed design are obtained. Vendor se-

TABLE 5.IV Contract Design Products (U.S. Naval and Government Ships)

- Ship specification
- Lines drawing
- Appendage drawing
- General arrangements (outboard profile, inboard profile, all decks and holds)
- Topside arrangement
- Capacity plan
- Weight report (3-digit level, KG and LCG, 20-station weight distribution, gyradii)
- Structural design criteria manual
- Midship Section
- Steel scantling drawings (decks, bulkheads, shell expansion, typical sections, deckhouse)
- Machinery control system diagrams
- Propulsion and auxiliary machinery arrangement drawings (plan views, elevations, and sections)
- Propulsion shafting arrangement
- Propeller design
- Electric load analysis
- Electric power and lighting systems - One line diagrams
- Fault current analysis
- Navigation system diagram
- HVAC load analysis and design criteria
- Ventilation and air conditioning systems diagrams
- Piping systems analysis
- Diagrammatic arrangements of all piping systems
- Fire control diagram by decks and profile
- Mechanical systems arrangements, for example, deck, hull and ship control systems
- Living space arrangements (berthing, messing, sanitary, recreation, etc.)
- Commissary space arrangements
- Pilot House, Chart Room, and other working space arrangements
- Interior communications system diagram
- Master Equipment List (MEL)
- Preliminary ship manning document
- Pollution control systems report
- Loading conditions
- Floodable length curves
- Trim and stability booklet
- Damage stability analysis
- Endurance fuel analysis
- Hydrodynamic model test results, for example, resistance, propeller open water, self-propulsion, maneuvering, seakeeping, etc. and performance assessment reports
- Stack gas flow analysis
- Evaluations of other aspects of required performance
- Availability analysis (Ao)
- Maintenance Plan
- Supportability Plan
- Crew Training Plan
- T&E Plan
- Safety analysis
- Procurement specifications for long-lead-time and other important outfit components, for example, main propulsion engines, diesel generators, reduction gears, anchor windlass
- Models and Mockups
- Cost estimate
- Technical risk assessment and risk management plan
- Initial regulatory body review
- Building plan
- Budget control list (estimated weight of all required material by material family or cost code)
- Production plan

lection is completed and vendor drawings are approved. Advance equipment and material is ordered.

5.2.5 Transition Design

During transition design, all design information is transitioned from systems to block and zone orientation as complete block and zone design arrangements and the ordering and assigning of all materials are completed (7). Drawings and product models also indicate subdivisions and material-ordering zones. The Shipyard's Shipbuilding Policy and the Contract Build Strategy will define how the ship will be built; for example, how major machinery items will be loaded, how auxiliary machinery and other components will be fitted, what work will be done on-unit, on-block (before and after turnover), and on-board. The breakdown of each zone into sub-zones is also defined.

A virtual prototype of the ship is developed, either on paper or by 3-D modeling in the computer. Zone design composite arrangements are developed from the distribution system routing diagrams developed in the previous phase. The zone design arrangements show all visible items seen from the viewing plane, no matter how small. All elements are included. The required zone/unit material quantity is also developed. Interference checking occurs as the work proceeds. All working, maintenance, and access requirements are checked.

Structural design work is completed and structural drawings for each block are developed, each with an accompanying bill of material.

5.2.6 Workstation/Zone Information Preparation

During this phase, all drawings, data and other information required by the production and other service departments to construct the ship are prepared. This includes drawings,

TABLE 5.V Functional Design Products

Hull		
General arrangement- Compartment and access (C&A) drawings	Rudder and propeller lifting gear arrangement	**Electrical**
Outboard profile	Anchor handling arrangement	Electrical Load analysis
Lines drawing	Mooring arrangement	One-line diagram
N.A. drawings, for example, hydrostatics, cross curves of stability, docking drawing	Life-saving equipment arrangement	Short circuit analysis
Block arrangement and list	Hull piping system diagrammatics	List of motors and controllers
Frame body plan (based on faired lines)	Purchase Technical Specifications (PTS)	List of feeders and mains
Structural block drawings with scantlings	Advanced Material Ordering (AMO) Lists	Electrical equipment and installation diagrams
Major foundation drawings	Steel List per block	Switchboard drawings
Welding plan	**Machinery and Piping**	List of Portable electrical equipment
Hull fitting drawings	Machinery arrangement	Electrical system weights
Hull weights, centers, and block lifting data	Shafting arrangement	Purchase Technical Specifications (PTS)
Lists of hull outfit	Stern tube arrangement	Advanced Material Ordering (AMO) Lists
Lists of hull fittings	Machinery space and wheelhouse control console arrangement	**HVAC**
Nameplates and Notices	Machinery piping system diagrammatics	Heating and cooling analysis
Summary paint schedule	Diesel exhaust arrangement	HVAC diagram and equipment list
Summary deck covering schedule	Lifting gear in machinery space	HVAC insulation schedule
Summary hull insulation schedule	Machinery and pipe insulation schedule	HVAC system weights
Furniture list	Unit and equipment foundations	Purchase Technical Specifications (PTS)
Plumbing and fixture list	Machinery and foundation weights	Advanced Material Ordering (AMO) Lists
Galley arrangement	Purchase technical specifications (PTS)	**Production Planning**
Accommodation arrangement	Advanced material ordering (AMO) Lists	Work station information plan and schedule
Steering gear arrangement		Block outfitting and erection schedule
Rudder and rudder stock arrangement		Zone outfitting schedule
		Tests and Trials schedule

sketches, parts lists, process instructions, and production aids such as templates, marking tapes, and software to control robots doing plate burning/marking and pipe fabrication. The work required to produce an entire zone is broken down into many work packages, each defining a much smaller task. A typical guide for work package size is that no more than three workers can complete the work defined by the package in no more than two weeks, or no more than 200 work hours.

Production planners size the work packages and either use the information needed by the workers, prepared by Engineering and develop it further to complete the package. Only the information needed to complete each work package, including production aids, is included. Each work package is broken down into separate workstations. Again, the workstation information is complete, the worker needs no other information to complete the job, and no unnecessary information is provided. The workstation information is provided on A4 or letter size sheets and typically consists of sketches and a parts list. The sketches show the work as the worker will see it; upside down, for example, if the work is to be done upside down. Structural workstation/zone information is developed for: burning plate, cutting shapes, processing plates or shapes (bending, flanging, or drilling), subassembly construction, assembly construction, block construction, and block erection. Block assembly sketches are developed; these permit the designer to consider block access requirements during construction. Planning and production personnel also jointly develop work sequence sketches. They define in considerable detail how the ship will be put together. Outfit work station/zone information is developed for shops, assemblies, blocks and zones. For the shops, workstation information for both processing and assembly is developed for hull fittings, pipe, sheet metal, foundation structure, joiner, paint, and electrical. Workstation information also is developed for machinery installations on units.

5.3 DESIGN PROCEDURE

In the preceding section, the design process was described in terms of the design phases that a design normally passes through as it evolves. In this section, the nature of the work done in the early design phases is described in more detail. Again the focus is on naval design.

The early design phases are the most mysterious to, and most misunderstood by, those who do not practice the art of ship design. A generic step-by-step procedure is outlined for developing a single ship feasibility study, the first step in the design process, and a single conceptual design. Then, broader aspects of the subsequent design development process are described. Emphasis is given to the trade-off study process, the concept of design baselines and their updates, and the design integration process. The reader is reminded that normally many ship feasibility studies are developed in the process of assisting the shipowner to decide on the major requirements for a new ship. Several conceptual designs may also be developed as major design alternatives are explored.

5.3.1 Getting Started

Once the major performance requirements and constraints for a new design have been established, design work can begin. Initial attention is focused on the mission(s) of the ship and its payload (weapon suite) or cargo requirements. These two parameters will have a dominant effect on the size, configuration and key features of the completed design, as well as on the process used to arrive at the design. To illustrate, consider the design of an aircraft carrier, a containership, a buoy tender, and an inter-island passenger/cargo ship that must beach itself at ports of call without normal pier facilities.

The primary payload of the aircraft carrier is its air wing. The primary mission of the carrier is to support the air wing: to house, maintain, fuel, arm, launch and recover, and provide command and control functions for the aircraft in the air wing and to care for the pilots and other air wing personnel. Because of the dominant effect of the carrier's flight deck and hangar on its design, initial design effort will focus on the flight deck and hangar and their configuration.

In the case of the containership, the number of containers to be carried is critical. Initial design effort will focus on the arrangement of these containers. How many will be stowed in the hull and how many above the weather deck? Based on the container dimensions, what are appropriate hold lengths and what are sensible hull beam and depth possibilities based on the number of container rows and levels to be stowed in the hull?

In the case of the buoy tender, buoy handling will be addressed first. Will buoys be handled forward or aft of the deckhouse? How will the buoys and their anchors and chains be lifted on and off the vessel?

In the case of the inter-island passenger/cargo ship, the required beaching capability is addressed first. What beach slopes are anticipated and how much cargo weight can be brought how close to the shore line for various combinations of hull dimensions and fullness coefficients? Once the ship is beached, how will passengers and cargo be moved from the ship to the shore?

These examples demonstrate that the design approach is influenced by the ship's mission and payload or cargo characteristics, as well as by the attributes of the ship itself. The ship designer will initially focus on gaining a full understanding of these requirements and characteristics and formulating, in their mind, overall ship concepts and configurations that will satisfy them. In doing this, the required ship design speed will be a primary consideration. Many concepts suitable for relatively low speeds will not be feasible if the required speed is high.

The naval architect will also judge whether the design will be weight, volume, or *main deck* limited. In a weight-limited design, the buoyancy required to float the weight of the ship and its payload establishes the ship's principal dimensions. In a volume-limited design, the internal space required to accommodate the payload and other ship functions establishes the principal dimensions; thus space analysis is of major importance from the outset. For weight-limited designs, space requirements need not be rigorously addressed in the initial design cycles. In a main deck limited design, the objects to be carried or built upon the deck establish the ship's length and/or beam. The aircraft carrier is an obvious example. The lengths of most surface combatant ships are determined by the so-called *stack-up* length, the sum of the deck lengths required for weapons, sensors, propulsion air intakes and exhausts, aviation facilities, anchor handling and mooring equipment, etc. (see Chapter 54 – Naval Vessels). Today most ship types are volume-limited.

5.3.2 Feasibility Study

The development of a ship feasibility study is the first step in the design development process for naval ships and is often performed by shipowners for complex commercial ships. Four primary physical criteria must be satisfied by any ship design, in addition to the requirement that the design elements must be packaged in a feasible overall ship configuration. These physical criteria are, available internal volume must equal or exceed the total required volume, weight must equal buoyancy, there must be satisfactory intact stability, and the installed propulsion power must be capable of propelling the ship at the required top speed.

These four criteria must be addressed in the initial design process. A typical sequence of steps followed in developing a feasibility study is shown in Figure 5.6. The four primary criteria are noted down the left side of the figure. The steps in the generic design process are numbered in the figure and are discussed below.

It is important to note that the sequence of steps depicted in the figure is not inviolate. A different sequence is often better suited to a particular design problem. Also, there is an interaction between the analytical process described below and the process used to define the external configuration of the ship. Some designs lend themselves to the very early definition of some features of the external configuration. When this is the case, it can affect the steps in the analytical solution procedure. Regardless of the sequence used, the same solution should be arrived at, if consistent assumptions and decisions are made as the iterative process unfolds. Each step will be described in the following sub-sections.

5.3.2.1 Principal performance requirements

At the outset, three principal performance requirements must be known or assumed. They are, payload (cargo deadweight and stowage factor), maximum or sustained speed (design speed), and fuel endurance (design voyage distance).

Values for these can be found in the different ship type design chapters in Volume II of this book. In addition, assumptions must be made for certain ship characteristics, including the ship type, hull type, propulsion plant type, principal hull form coefficients, and the design margins to be applied. The effects of varying the latter assumptions can, and often are, explored by performing additional feasibility studies.

By *ship type* is meant the overall hull configuration and method of support, for example, conventional displacement monohull, SWATH, planing monohull, catamaran, trimaran, hydrofoil, air cushion vehicle (ACV), or surface effect ship (SES). As the term *hull type* is used here, it refers to major features of the hull form: transom vs. cruiser stern, flared vs. tumblehome topsides, bulbous bow vs. no bulb, etc. Note

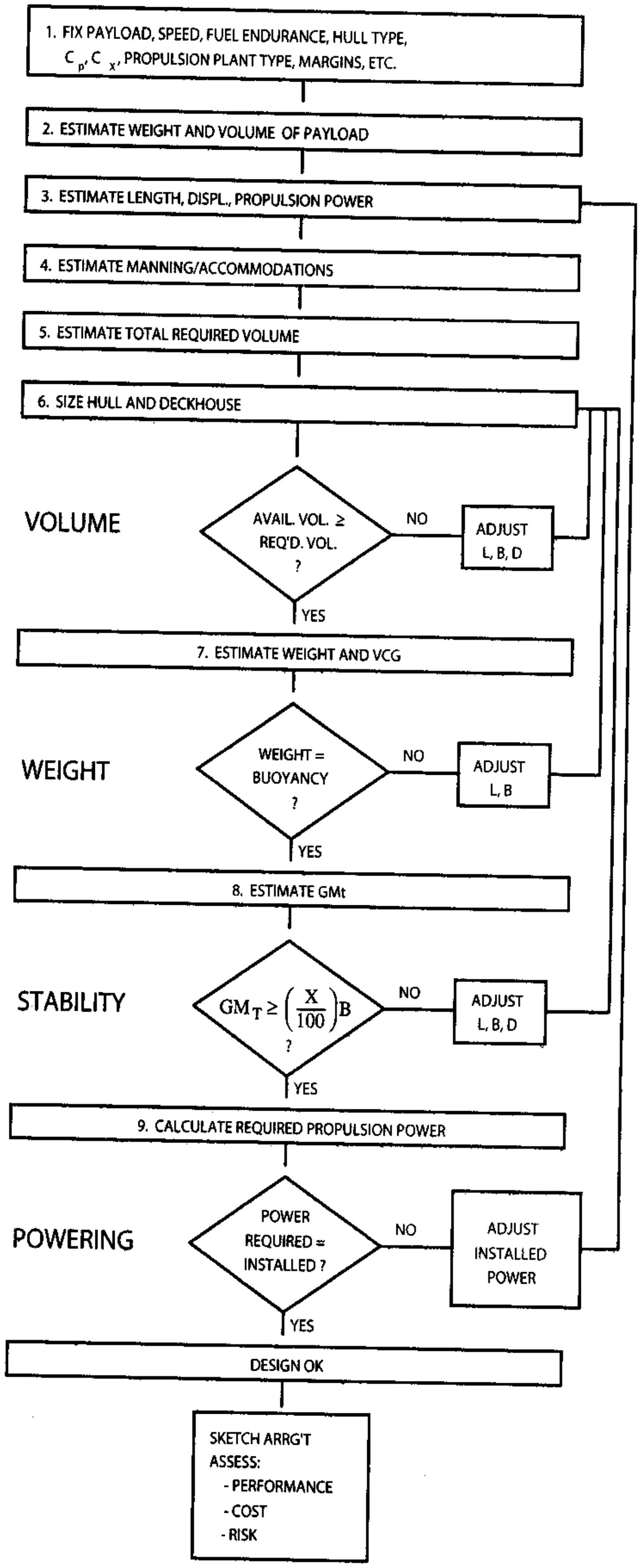

Figure 5.6 Feasibility Study Process

that the procedure outlined herein applies in principle to any ship type. The specific steps followed will vary, especially for the non-displacement ship types.

The propulsion plant type might be medium speed geared diesel, low speed directly connected diesel, geared gas turbine, or geared fossil fuel or nuclear steam turbine, all connected by shafts to propellers in the conventional manner. Electric drive or integrated electric drive plants might be considered, with a variety of generator prime movers. Combined plants such as Combined Diesel or Gas Turbine (CODOG) might be considered as well as various propulsors, including conventional open propellers, water jets and podded propulsors. To develop a single feasibility study, a single plant type must be assumed. Other propulsion plant alternatives are often evaluated with the aid of additional feasibility studies.

For a displacement monohull, the principal hull form coefficients are the longitudinal prismatic coefficient, Cp, and the maximum section coefficient, Cx. For many commercial ships with Cx about 0.98, Cb is used instead of Cp. Together these coefficients establish the block coefficient, Cb. Cp has a major influence on hull resistance and hence powering. Cx has a major effect on the vertical center of buoyancy and on the vertical center of gravity of items stowed low in the hull. Hence it has a significant effect on intact stability. Both coefficients affect the space available in the hull as well as the buoyancy provided by the hull. Initial values of these coefficients are selected based on the designer's experience and judgment. Alternative combinations of values are often studied later.

Design and Construction (D&C) margins, also known as *acquisition margins*, are applied to early stage design estimates to account for unknowns, errors in prediction techniques and the likelihood of design changes as the design requirements are refined during design development. Construction margins are applied to compensate for growth during construction. In some acquisitions, the shipbuilder will not be known during the early design stages; nor will the many vendors who will supply equipment. These uncertainties also translate into weight and KG uncertainties that are addressed by margins. It is expected that D&C margins will be depleted as the ship design and construction process unfolds. Typical margin categories include weight, KG rise, ship service electric power, HVAC loads, hull resistance, space and accommodations. Design and Construction margins are separate and distinct from service life allowances, which some shipowners require to be provided in a new ship at delivery. The latter allowances are provided in anticipation of growth during the ship's life of attributes such as weight, KG, and required electric power. Appropriate D&C margins and service life allowances must be incorporated in the feasibility study. The ship designers are responsible for the selection of D&C margins; they must also provide for all shipowner-specified service life allowances.

5.3.2.2 Payload weight and volume estimation

Payload weight (cargo deadweight) and volume are estimated. The definition of *payload* must be clear and consistent with the estimating relationships described later. The term *payload* as used here refers to weapons and the equipment, supplies and crew to support the cargo and/or other items directly related to the ship's mission. Ship endurance fuel, fresh water, provisions and other consumables are not included. Some might define this *payload* as consisting solely of variable load items carried to perform the ship's mission. For ship sizing purposes, however, it is probably best to take a broader view and define payload to be any built-in ship systems and spaces that directly support the ship's mission, in addition to the variable loads themselves. An example would be the scientific gear and laboratory spaces on an oceanographic research ship, as well as the equipment used to raise and lower the scientific gear overboard from the deck of the ship. In this example, the payload consists of a number of installed systems and shipboard spaces, as well as scientific supplies and equipment that can be loaded onto and off of the ship. Payload weight and volume estimation is relatively straightforward for commercial ships such as crude oil tankers, bulk carriers or container ships where the entire payload is cargo, although variable cargo densities can complicate the task. It is more difficult for payloads that include installed ship spaces and systems. Note that the payload volume, which must be provided within the hull and/or the deckhouse, must be distinguished from payload volume, which will be carried external to the hull envelope, such as containers loaded on deck.

5.3.2.3 First estimates of principal characteristics

Initial estimates are made of hull length, full load displacement and installed power. Almost any values can be used for the initial estimates but the closer they are to the final result, the fewer iterations will be required to get to closure, when using the spiral design or similar single point design approach. These estimates are generally based on empirical plots or equations derived from a statistical analysis of existing ship data for the particular hull type and ship mission being considered. Displacement might be estimated from a plot of payload weight versus displacement (or Deadweight Coefficient for commercial ships), length might be estimated from a plot of length vs. displacement, and installed power might be estimated from a plot of power per ton versus Froude number.

5.3.2.4 Determination of manning/accommodations requirements

The total number of accommodations to be provided is estimated. This is generally based on a manning estimate (provided by the shipowner for commercial ships), increased by an allowance for transients and perhaps a D&C margin and/or a service life growth allowance.

5.3.2.5 Estimation of required volume

The total required internal volume is estimated. Initially, this is a gross figure that reflects the payload (cargo) volume plus the volume required for crew living, propulsion machinery (total machinery space volume, including air intakes, exhaust uptakes, and shaft alleys), tankage, stores, access, ship control spaces, voids, and other miscellaneous spaces. For the initial estimate, an empirical plot of total internal volume versus payload (cargo) volume is often used, based on data for ships with similar missions and hull types. More detailed estimates will be made in later iterations.

5.3.2.6 Sizing of hull and deckhouse

The hull and deckhouse are sized to provide the required internal volume. A split between the hull and deckhouse volume is chosen. This might be based on a factor chosen from previous designs, or it might be based on a tentative deckhouse sketch with an associated deckhouse volume. Deducting the estimated deckhouse volume from the total required volume yields the required hull volume. Hull length, beam, depth and block or prismatic coefficient, are adjusted until the necessary hull volume is provided. Empirical plots of hull proportions such as L/B, B/D, and L/D for ships with similar hull types and missions are often used as a guide in this process. Extreme proportions will often lead to problems: too great a L/B ratio and too low a B/D ratio could result in deficient stability, and too great an L/D could result in adverse hull girder strength. *Large object volumes* with specific minimum dimensions to be accommodated within the hull, must be considered when selecting the principal hull dimensions. Examples might be an engine room, a large cargo hold, an aircraft hangar or a missile magazine. *Large object volumes* typically have a vertical height that exceeds one normal deck height; they may also have an unusually large length or beam.

5.3.2.7 Weight and center of gravity estimates

The full load weight and Vertical Center of Gravity (VCG) (KG) are estimated. Lightship weight groups and load items are treated separately. Lightship weight components are initially estimated in major groups, using selected *parent ships* or empirical plots of data for ships with similar missions and hull types. Hull structural weight might be estimated from a plot of hull steel weight versus LBD/100 (cubic number), machinery weight might be based on a plot of machinery weight versus installed power for the assumed plant type, etc. Living space outfit is generally a function of crew size while hull outfit might be a function of LBD/100. Lightship KG is generally estimated by using KG/D factors for the individual weight groups based on data from similar ships. Load items are estimated or computed. The variable portion of the payload weight estimated in Sub-section 5.3.2.2 is known. Endurance fuel weight can be estimated initially, and then computed once a speed-power curve has been estimated in Sub-section 5.3.2.9. Load KG is estimated by assigning KG values to the individual load items based on the naval architect's vision of the ship configuration and data for similar ships.

At this point, weight is checked against buoyancy. Since L, B, Cp, and Cx are known, the draft required to float the ship's weight can be computed. If it is too great (navigational draft constraint exceeded or freeboard too low, based on either required regulatory freeboard or empirical criteria derived from successful designs), L and/or B can be increased, which affects available volume and weight. Hull depth might be reduced in an attempt to avoid excess volume, if adequate freeboard could be achieved. Deckhouse size (volume) also might be reduced. Note that Cp and/or Cx also could be increased at this point to reduce draft but the naval architect may choose not to, seeking a solution at the selected Cp and Cx values with the idea that other Cp and Cx combinations also will be studied later. If the calculated draft is too low, perhaps not enough draft to swing a propeller of reasonable diameter, L and/or B could be reduced; D and/or deckhouse size would have to be increased commensurately to maintain adequate internal volume. Again, note that Cp and Cx could also be varied in the effort to find a solution. At this point, weight and volume have been evaluated. Bear in mind that displacement weight must equal buoyancy, but that the available volume may exceed the required volume. If the available volume must exceed the required volume in order to provide sufficient buoyancy, this is an indication of a weight-driven design such as an Ore Carrier.

5.3.2.8 Stability check

The transverse metacentric height, GMt, is estimated to check initial intact stability. Note that initial stability at large heel angles and damage stability are evaluated at a later point in design when the required design detail is available.

To estimate GMt, estimate KMt and subtract KG, making a reasonable correction for tankage free surface (see Chapter 11 – Parametric Design). The two constituents of KMt, KB and BMt, are each estimated based on the known quantities L, B, T, Cp, and Cx, and the results summed. The transverse moment of inertia of the waterplane, It is estimated from the waterplane coefficient, Cw. Cw is estimated from Cp, recognizing that a transom stern significantly affects both Cw and It. GMt/B is computed and compared to a predetermined criterion of acceptability, generally ranging from 3 to 10%, depending on the ship type and its intended mission (lower for cargo ships, mid-range for passenger ships, and higher for warships). If the criterion is exceeded, the result might be accepted, at least temporarily; if the criterion is not met, corrective action must be taken. Either KG must be reduced or KMt increased. KG can be reduced by reducing D or deckhouse size or by lowering weights within the ship. At this early stage, reducing KG by lowering weights is not really feasible since individual weights have not yet been located within the hull. Reducing deckhouse size yields small gains and reducing D may be infeasible due to freeboard requirements or large object volume dimensions, for example, the required height of a low-speed diesel engine room. The most effective way to raise KMt is to increase beam since BMt varies as B squared, and this is generally the approach taken. Length may be reduced at the same time, if possible, to avoid excessive hull volume.

5.3.2.9 First estimate of propulsion power

The power required to propel the ship at the desired maximum or sustained speed is estimated. This estimate can be much improved over the Subsection 5.3.2.3 estimate since the hull dimensions and form coefficients are now known, along with a better estimate of ship displacement. Assumptions have been made regarding the general characteristics of the hull shape at the ends, for example, whether or not there is a transom or bow bulb. Bare hull resistance is estimated using one of the established techniques; for example, a standard series, a regression analysis, or test results of a similar hull. The principal hull appendages are identified, permitting an estimate of appendage drag to be made. Overall propulsive coefficient is estimated and shafting and reduction gear losses are accounted for (or electric losses in the case of an electric ship). The resulting required propulsive power is compared to the installed power assumed in Step 3 of Figure 5.6. If the installed power is equal to or somewhat greater than the required power, a tentative solution has been achieved. If the installed power greatly exceeds the requirement, it must be reduced. If it falls short of the requirement, it must be increased. In either case, the assumed propulsion plant must be modified and the process repeated, starting with Step 5. The revised propulsion plant is likely to have a revised engine room volume and hence the total required volume will change. If the fuel endurance is specified at a speed other than the specified maximum or sustained speed, the speed-power estimate in Step 9 will include the endurance speed so that a refined estimate of fuel weight can be made. This is a common situation for fossil fuel naval ships that cruise much of the time at fuel-efficient speeds and spend very little time at high speeds.

This completes the description of the nine steps listed in Figure 5.6. Even if a tentative solution has been achieved in the first pass through the process, it may be repeated starting at the step described in Sub-sections 5.3.2.4 or 5.3.2.5, using more refined estimates for the various parameters. This greatly improves the quality of the study and reduces risk. Required volume, weight and KG are prime candidates for refinement.

An arrangement sketch must be developed in order to validate the tentative solution before the study can be accepted. As a minimum, an inboard profile and main deck plan view must be depicted. A typical transverse section through the ship's midbody would be the next priority. Even if it were not required for validation, the customer would want to see a sketch anyway. The term *sketch* is used deliberately. Detail is not desired, only a simplified outline of the hull and deckhouse boundaries and the principal internal subdivisions: decks and bulkheads. Large object volumes should be located and identified. The primary reason for the sketch is for the naval architect to ensure that a satisfactory ship arrangement can be developed within the selected principal dimensions. In profile, does the selected hull depth permit a satisfactory allocation of deck heights to be made with adequate space in the overheads to run distributed systems? Can the heights of large object volumes such as the engine room be accommodated efficiently? Does the selected hull length permit a satisfactory arrangement of main transverse bulkheads? Can the lengths of large object volumes such as the engine room and cargo holds be accommodated efficiently, considering the requirements for collision and after peak bulkheads? Can one or more deckhouses with the required total volume be satisfactorily located on the hull so as to provide proper alignment with the engine room below deck, for example? Is the main deck length (and beam) adequate to accommodate all of the required topside functions? The minimum length required to do this in naval ship design is referred to as the *stack-up length*. The stack-up length often sets the hull length in ships with cluttered topsides such as surface combatants or in ships with specific topside cargo stowage requirements, such as heavy lift ships or container ships.

After a practical arrangement sketch has validated the study, capital and operating and support (O&S) costs can be estimated. Risks also must be assessed. Unique aspects of performance, beyond the usual calm water speed and fuel endurance estimates, are sometimes evaluated, albeit in preliminary fashion. Ship motions and maneuvering predictions are examples.

Countless versions of the feasibility study development process outlined above have been programmed for speedy execution by computer. These programs, termed synthesis models, differ primarily in four ways: level of detail, degree of tailoring to specific ship types, approach to user interaction, and solution approach. Some programs are quite simplistic and contain only rough approximations for estimating relationships; others are very sophisticated and estimate parameters such as weight and space in considerable detail (see Chapter 13 – Computer Based Tools). Some programs are finely tuned to deal with a particular type of ship, for example, a container ship, and a particular hull form type such as a cruiser stern hull with bow bulb; others are much more flexible. Some programs run without user interaction after the necessary inputs are provided; others permit the user to interact with the program and *steer* the computer towards a particular solution. Graphical interfaces that permit arrangement sketches to be developed *on-line* are becoming more common. Some programs iterate and converge to a single solution internally; others produce a huge matrix of solutions and point out to the user which ones fail to meet one or another of the prescribed acceptance criteria.

The advantages of a synthesis model include speed, repeatability, relative accuracy, and the ability to capture the best thinking of all the *experts* in the organization developing the model. Relative, as opposed to absolute, accuracy is essential in the early stage design process. When alternatives are being evaluated and compared, capturing the true *delta* between the alternatives is of paramount importance. In the past, parametric studies were done manually, often by different individuals. The true deltas between alternatives were often lost due to differing assumptions or round-off errors.

On the other hand, synthesis models are costly to develop and require continuing *care and feeding* to keep up with advancing technology. The primary use of synthesis models is in the concept design phase; that is, to develop ship feasibility studies. They also are used in later design phases to perform trade-off studies, for example, study the effects of varying hull proportions, form coefficients, etc. and to assess the total ship impacts of subsystem alternatives; for example, alternative propulsion plants, habitability standards, margin policies, etc.

5.3.3 Concept Design

A concept design represents the further development of a specific feasibility study. The work is done to reduce risk, improve the estimate of project cost, refine and validate the major ship performance requirements established previously and, not least, to establish a baseline for the start of preliminary design and its major trade-off studies. In developing a set of feasibility studies, emphasis is given to relative correctness, that is, to establishing the correct *deltas* between studies in the set. In developing a concept design, emphasis shifts to absolute correctness, that is, how large and heavy is this specific ship really going to be and what will it really cost?

Concept design, and all the design phases, which follow it, is really a parallel process, as depicted in Figure 5.7. Three critical steps, as shown in the figure, initiate the process.

First, the exterior envelope of the ship is defined for the first time. This consists of the hull and deckhouse boundaries. The assumptions reflected by the selected feasibility study are translated into a specific initial shape for the ship. These initial assumptions include parameters such as the principal hull dimensions (L, B, T, D), principal hull form coefficients (Cp, Cx), freeboard and deckhouse volume.

For the initial hull form, an existing hull may be used or a new one developed *from scratch*. The existing hull may be modified to match the desired dimensions and form coefficients. Techniques for doing this are well known (8) and today are integrated into naval architecture software packages, such as TRIBON and FORAN. The initial deckhouse configuration must reflect the desired volume and also numerous practical considerations such as realistic molded deck heights, sight lines from the bridge, provisions for propulsion air inlets and exhausts, and maintenance of the required working deck areas. Even in this initial definition of the hull and deckhouse, production considerations should be given significant weight.

After the hull and deckhouse boundaries have been defined initially, the principal internal subdivisions must be established. The process of doing this is sometimes referred to as *decking out* the design. Deck locations within the hull and deckhouse are defined, as are the locations of the principal bulkheads, both transverse and longitudinal. The naval architect performing this task uses judgment based on experience plus knowledge of the numerous influencing factors. These factors include considerations such as realistic molded deck heights (at least 2.6 m today) necessary to achieve desired clear deck heights, practical double bottom depth, desired frame spacing for efficient structure, and the transverse bulkhead spacing needed to meet cargo stowage, floodable length and damage stability requirements. Production considerations and the need for structural continuity are given high priority in establishing the internal subdivisions. Advice may be sought from experts in these areas. At the same time, it is important to remember that this is simply a starting point, and that all design decisions tentatively made at this point will be thoroughly reviewed later in the design process before they are *locked in*. The *decking out* process may require small changes to certain of the input parameters. The hull depth, for example, may be adjusted to provide the desired number of internal deck levels in an efficient manner, that is, without either inadequate or excessive *tween-deck* heights. Hull or compartment length might be modified slightly to equate to an even number of frames at the desired spacing.

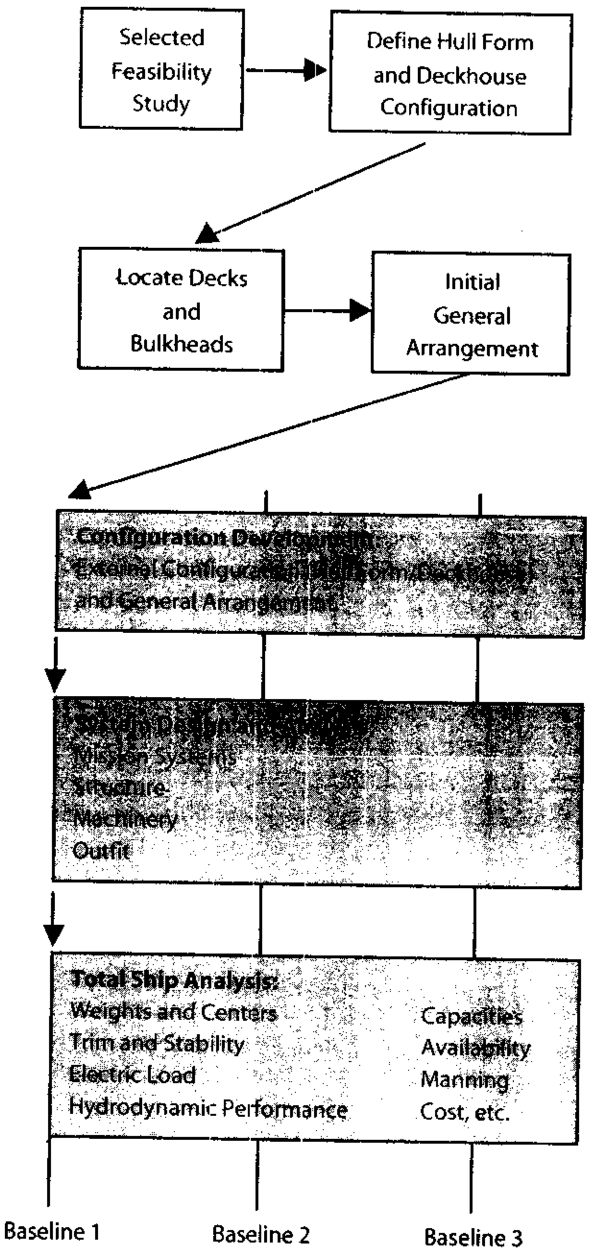

Figure 5.7 Naval Ship Concept Design Process

After the *decking out* process is completed, an initial general arrangement drawing is developed. The drawing depicts all so-called *large object volumes* such as the engine room and cargo holds. These are spaces whose heights are greater than a single normal deck height. Smaller spaces with normal deck heights are not individually defined at this point. Rather, blocks of space are allocated by function, for example, crew living, office and administrative spaces, navigation and other ship control spaces, workshops, etc. In the process of defining the initial general arrangement, it may be necessary to modify deck or bulkhead locations or even the deckhouse boundaries.

After the initial hull envelope and general arrangement have been defined, parallel design development can proceed in a number of functional areas, as depicted in Figure 5.7. The parallel design development effort extends beyond the concept design development and, in fact, continues through all the remaining design phases. The ensuing design development activities can be classed as design and analysis activities, as depicted in the figure. As system design and total ship analysis proceeds, conflicts with the initial hull envelope and/or the general arrangement will be identified and must be resolved. Resolution may necessitate changes in either the hull envelope or the general arrangement. For example, development of the propulsion plant, including the initial machinery arrangement, may indicate the need to lengthen the engine room, which in turn will require a change to the general arrangement.

Figure 5.8 is a depiction of the concept design task categories after the initial configuration definition (Baseline 1 in Figure 5.7). Additional detail is provided. There are strong interactions between both the ship envelope and the general arrangement and three of the eight areas of system design activity noted in the figure. These are structures, propulsion plant and mission systems. Similarly, there are strong interactions between most of the areas of system design activity and the eight analysis activities noted in the upper block of total ship analysis tasks. For example, most areas of system design will contribute products to the area/volume analysis, the weight estimate, the electric load estimate, and the Master Equipment List (MEL). The topics listed in the second block of analysis tasks have equally strong interactions but with fewer system design tasks. There are strong interactions between both the hull form and the weight estimate and the hydrodynamic performance and stability analysis tasks. The general arrangement also has a strong interaction with the damage stability analysis task. Noise and vibrations analysis tasks are strongly linked to the general arrangements and to the principal noise sources: propulsion and other rotating machinery and the propulsor itself. Fuel weight and volume are linked to the required propulsion power at the endurance speed, as well as to the efficiency of the propulsion and electric power generating plants at that speed.

As design development proceeds, interim products are produced in each of the system design and total ship analysis task areas and fed to other areas that use them as inputs or as information updates. Frequently, updated information will reveal problems or *disconnects* in the design that the team must set to work to resolve. For example, the damage stability analysis may reveal the need to change transverse bulkhead spacing at the after quarter point which is at odds with the general arrangement. Such disconnects cannot be predicted in advance and the skill of a design team may be measured by how quickly they can be identified, addressed and satisfactorily resolved.

Figures 5.7 and 5.8 are generic in that they are applicable to the entire system design process once the initial hull envelope and general arrangement have been defined. In concept design, not all of the tasks identified in Figure 5.8 will be performed; others will receive varying degrees of attention, depending on the design problem at hand.

Tasks emphasized are those with the major influence on overall ship size, cost, performance and risk. Examples of tasks not performed in concept design might include the availability, noise and vibrations analysis tasks. Tasks given minimal attention might include the manning analysis task and the following design tasks: Outfit and Furnishings (O&F), fluid systems, HVAC system, and auxiliary machinery/mechanical systems. For concept design, there is insufficient detail to develop a manning estimate based on workload considerations. It would be premature to spend much effort defining O&F details. Design effort in the systems task areas mentioned above might be restricted to selecting a reasonable baseline system concept, describing it by means of a highly simplified 1-line diagram and, for that concept, identifying major system components and estimating their sizes by ratiocination from similar ships.

5.4 DESIGN DEVELOPMENT

In this section, the design development process, subsequent to the development of an initial concept design, is discussed. This process occurs during the preliminary, contract and functional design phases.

5.4.1 Overview

The design development process is a parallel one, performed by persons with expertise in the various design disciplines. These persons develop their portions of the design in parallel, exchanging data at appropriate points in the process. The initial concept design provides the data that is needed to start this parallel development process. It is the initial de-

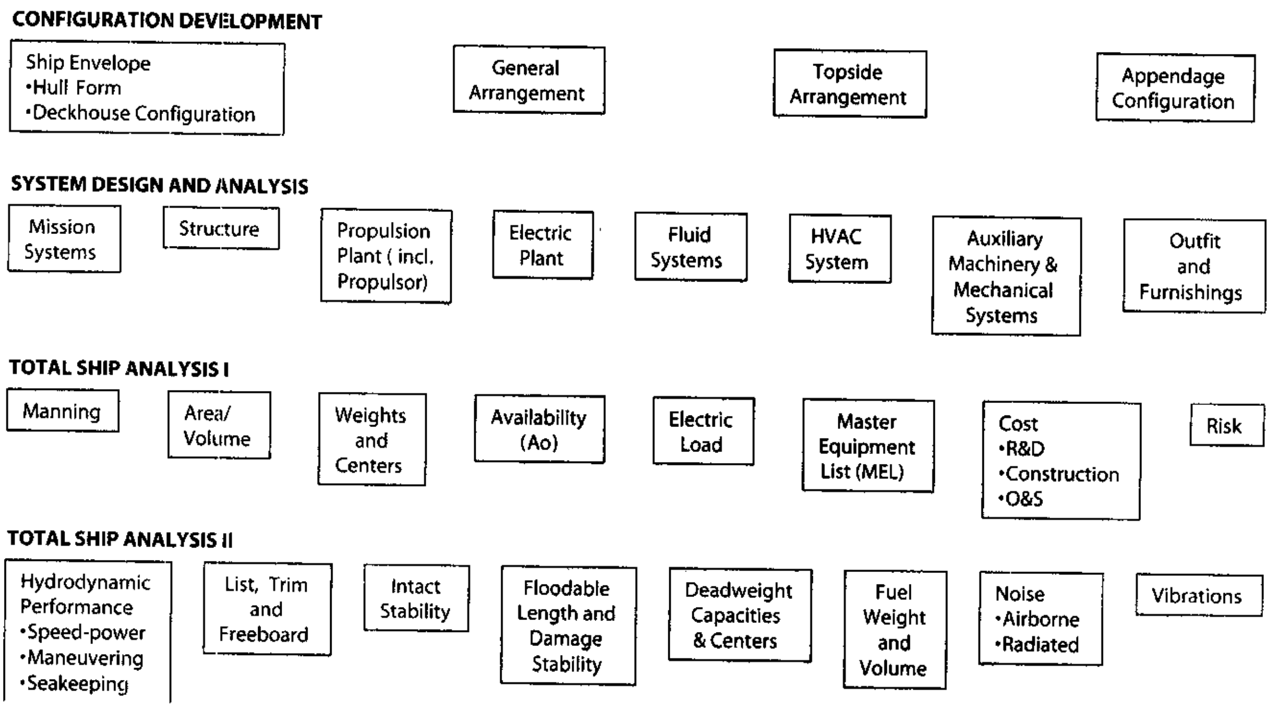

Figure 5.8 Concept Design Task Categories

sign baseline. The design development process generally reflects the classical systems engineering process with two principal objectives: to optimize the total ship system at the expense, perhaps, of individual subsystem optimization, and to address production, operation and support aspects too often neglected, for example, producibility, reliability, maintainability, supportability, operability, life cycle cost and human systems integration (manpower, personnel, training, safety and health hazards).

In each design discipline, the development process consists of the following generic steps: requirements derivation, synthesis of alternative concepts, evaluation of the concepts, selection of the preferred concept, and further development of the selected concept. This may lead to the exploration at finer levels of detail of additional alternatives for elements of the parent concept. Thus, after the initial requirements derivation, the process consists of a trade-off study followed by design development effort. This cycle may be repeated several times before the design is fully developed.

The development effort in each discipline is referenced to the overall ship design baseline in order to keep the overall effort on track. The design baseline represents an integrated total ship design, at the level of detail to which the design has been developed. Periodically, the design baseline is updated and reissued to the design team. The updated baseline reflects interim design decisions, which have been made in the various disciplines as result of the ongoing trade-off study and design development process.

The design team leadership must ratify all such decisions before they are incorporated into the baseline. Several design baselines might be developed and issued over the course of a single design phase. As noted in Figures 5.7 and 5.8, some design development tasks are purely analysis tasks. These are referenced to the current design baseline. The orderly process outlined previously is disrupted when design problems are identified which involve more than one design discipline. The affected design disciplines must work together quickly and efficiently to solve such problems and minimize the disruption to the overall development process.

5.4.2 Trade-off Studies

Trade-off studies are an essential element of the design development process. The challenge is deciding which design issues must be subjected to a formal trade-off study and for those, deciding when the study should be done and to what level of detail. Design issues can be categorized in various ways, including:

- impact on ship cost, performance, and/or risk,
- impact on ship size and/or configuration, and
- multi-discipline vs. single discipline.

Issues that have a major impact on ship cost, performance or risk should be dealt with early in the process while issues with lesser impact can be deferred. It makes sense to do this since studies done too soon may have to be reworked if there are significant changes in the design baseline. Issues with a significant impact on ship size and/or configuration must be dealt with at the total ship level, that is, these impacts must be evaluated. Issues with little or no impact on overall ship size or configuration can be dealt with at the individual system level. Issues with significant impacts can be subdivided further into those with effects so dominant that they require alternative ship concepts to be developed and evaluated vs. those whose impacts can be assessed without deviating from the baseline ship concept. Some issues can be studied by a single design discipline while experts representing several disciplines must address others.

In planning and executing the design development process, these categories should be considered and greater attention given to the more important ones. In general, the highest priority should be given to multi-disciplinary studies with significant ship size and/or configuration impacts. These studies should be planned in greater detail and performed as early in the process as possible. By so doing, the overall efficiency of the design process is maximized and the chances of major downstream perturbations of the design baseline are minimized. Formal trade-off studies are necessary to achieve a near-optimum design solution but they require time and resources. Thus the number of such studies undertaken must be tailored to the available design time and resources. A few studies of critical issues done well are always preferable to many mediocre studies of lesser issues. The shipowner will often identify specific issues that he wishes to see formally studied. The products of a trade-off study of several design alternatives should typically include the design requirements, descriptions of the alternatives, and estimates of the following attributes for each alternative, relative to the design baseline: design and engineering cost, if there are significant differences, procurement cost, operating and support cost, weight, space, electric load, manning, reliability, maintenance requirements, support requirements, training requirements, operability, risk (technical, cost and schedule) and pertinent aspects of performance, such as speed or seakeeping. The list of attributes to be evaluated is tailored to suit each trade-off study (see Sub-Section 5.1.9).

The recommendation of each completed trade-off study must be reviewed and approved by the leadership of the design team before it can be incorporated into the next update of the design baseline.

5.4.3 Design Integration

Total ship optimization is the primary purpose of design integration. Other objectives are to:

- ensure ship feasibility,
- satisfy the shipowner's requirements and constraints, and
- facilitate ship construction.

An optimized ship design is a *balanced* ship design. A balanced design is not optimized at the system or sub-system levels, that is, *give and take* has occurred between elements of the design. An optimized total ship will typically not have optimized systems and sub-systems.

In this regard it may be useful to view the ship as comprising different levels. Level I is the total ship. At Level II are the major ship systems such as hull, machinery, mission systems, etc. Level III comprises elements or sub-systems such as structure, propulsion, electrical, control, communications, and auxiliary machinery. Level IV consists of components such as prime movers, generators, reduction gears, shafting, and propulsors. Design integration is normally focused on the interfaces between elements at Level III and below.

Interfaces are classified as either functional or physical. Functional interfaces refer to the service transfers between various functional elements of the ship (electric power, cooling water, communications, data, etc.), while physical interfaces refer to the spatial relationships between ship elements. Functional interfaces are most critical during the early design stages and must be resolved by the start of functional design. Physical interfaces are dealt with at all stages of design, but receive the most attention in the later stages of design, when issues such as alignment, physical support, interconnection, and routing are addressed in detail.

Six critical areas receive special attention during the design integration process. They are:

1. weight vs. buoyancy and draft, freeboard, trim and list,
2. stability,
3. hull girder strength,
4. space balance; that is, required vs. available internal volume, and deck area,
5. ship energy balance; that is, required vs. available energy of each type (electric power, steam, compressed, air, cooling water, etc.), and
6. ship control; that is, the interfaces between the ship control system and every dynamic functional element of the ship.

Ship design is performed by engineers and designers, typically organized along functional lines. Elements of the organization are responsible for elements of the design. Thus there are organizational interfaces that are related to the interfaces between ship system elements. Certain principles must be adhered to when organizing for ship design if design integration efforts are to be effective. They are:

- assign responsibility for complete functional elements to a single, lowest-level organizational unit,
- assign responsibility for closely interacting functional elements to a single organizational unit,
- distribute responsibility evenly between organizational elements,
- assign a manageable number of organizational elements to any one supervisor,
- establish one organizational element responsible for whole-ship characteristics (tests and trials, manning, RMA, safety, cost, etc.) and for system engineering of areas which cut across several organizational elements, for example, ship control,
- staff with a high percentage of competent and experienced engineers and designers,
- keep the total design organization small, and
- avoid the introduction of organizational elements whose sole responsibility is the review of another organizational element's work.

The first two principles avoid introducing organizational interfaces where hardware interfaces do not exist. The next two principles assure a manageable workload for the various levels of supervision so that decisions involving system compromises can be made in a timely and efficient manner. The fifth principle assures proper attention is given to the total ship system characteristics. The last three principles are necessary for efficient performance.

An experienced design team will effectively address their interfaces with a minimum of direction and control from management and, the smaller the number of personnel involved, the fewer will be the number of communication channels and the more effective will be the exchange of interface data. Frequent, rapid and effective communications are a key to efficient design integration. Communications are essential, and a challenge. A collocated design team facilitates communications. Modern communication techniques permit *virtual collocation* of the members of a widely dispersed design team. However, virtual collocation is unlikely to ever equal the effectiveness of face-to-face exchanges of data and opinion.

In the initial concept design phase, the design team is small and communications are frequent and informal. The individual team members perform design integration as they work. Integration is an interactive and iterative function, and this is facilitated during concept design when the design team is small and, normally, collocated. As the design proceeds hrough preliminary and contract design, the integration function is no less important, but proves more difficult. Integraion is important because during these phases decisions will e made on systems, sub-systems, and possibly even equipnent that will determine the cost and performance of the hip. The integration function is more difficult because as the lesign matures it becomes more detailed and complex and, s a result, the size and diversity of the design team grows. For a complex warship, it has been estimated that as many s 40 different engineering disciplines ultimately may be involved, although not all on a continuous basis.

For complex ship designs, it is, therefore, common to create and empower a Design Integration Team (DIT) in the preliminary design phase or shortly thereafter. The DIT is focused on total ship design integration and its members are dedicated to that task. Typically, the DIT is staff to the ship design project manager and is empowered to act in his/her name. The members of the DIT are typically senior engineers with broad experience and with a total ship perspective. Collectively, their experience covers the full scope of topics and issues to be addressed during the design. Specialists in the functional design organization perform synthesis, analysis and trade studies. The DIT's objective is to achieve that combination of subsystem features and performance that provides the *best* or optimum combination of total ship cost, performance and risk, within the bounds of economic and technological constraints. In some engineering organizations the functional groups are quite strong and independent, and resist oversight and direction. This has led to unbalanced ships where one function or element has been emphasized at the expense of others. The key is to make all decisions on what is best for the *total ship*. The DIT must be empowered by top management to make the tough decisions. And, of course, they must serve as honest brokers.

5.4.4 Design Planning and Control

The objectives of design integration have been described as well as its nature. The concept of the Design Integration Team has been introduced. Turning now to the design integration process, it can be described as three sequential activities for a specific design phase. These are up-front planning, in-process control and formal reviews at the end of the phase.

5.4.4.1 Planning

The first and perhaps most important activity is proper planning of the design phase. Many designs are started on a casual, ad hoc basis and there is little or no opportunity for formal planning. For each subsequent phase, however, formal planning before the start of the phase is essential. The work effort in each task area must be defined, including the approach to be taken, the inputs required from other task areas, the deliverables or products to be created, the work schedule, including the dates for inputs, outputs and intermediate milestones, and finally, the labor hours and resources required. Resources could include computers, facilities, funds for model construction and testing, etc. The DIT must take the lead in creating an overall, top-level design schedule. This must address intermediate project milestones at which the design baseline will be formally updated, as well as the dates for major reviews of the entire ship design. The individual plans for each task area must be integrated with this overall plan and with each other. Emphasis must be placed on the interfaces between the various functional elements. These interfaces must be identified and recognized by the affected parties on both sides of the interface. The dates for the exchange of interface data must be scheduled such that there is sufficient time to complete the design of the affected elements of the design. The DIT must identify major design issues that can only be addressed by the joint action of two or more functional areas. The DIT must lead the effort to develop action plans to address these issues and see that they are incorporated into the overall design phase plan. The DIT must also ensure that the design phase plan includes the effort to produce the design products that that it needs to do its job.

5.4.4.2 In-process control

The second design integration activity is in-process control. The DIT plays a key role in controlling the effort of a large design team. The DIT continually assesses the developing design, but periodic meetings and design reviews are held as well. Minutes are taken and action items assigned and followed up. The DIT can employ several design control techniques. One is to formally update the design baseline at regular intervals during a lengthy design phase. A six-week interval is typical. The interval can be shorter for smaller teams and those working to an accelerated overall schedule. Formal updates of the design baseline help to keep all members of the design team working on the same design. They also serve to keep the current design baseline relatively up to date and reflective of recent design decisions, made since the previous baseline *refresh*. This reduces the amount of rework that must be done by the design team members as they shift their own work to the new baseline. If the update interval is too short, team members must stop work and shift to the new baseline too frequently. If the interval is too long, team members spend too much time working to a badly outdated baseline. Shifting to the new baseline when it is finally issued is a major task and too much costly re-work is required.

Another control technique is to require formal approval of changes to specific elements of the design baseline such as the lines drawing, the general arrangements or the Master Equipment List (MEL). Since the MEL can go down to a very detailed level such as the 5-digit Extended Ship Work Breakdown Structure (ESWBS) level, and is constantly changing, formal approval should be reserved for the *big-ticket* items. The hull lines and the deckhouse or superstructure configuration define total internal volume. The general arrangement drawing or 3-D arrangement model defines the subdivision and spatial arrangement of the ship's enclosed volume. These drawings can be used to control overall ship size and internal arrangement by controlling the changes made to the drawings as the design is developed. The design team leader may delegate change control authority to the DIT or may retain this authority but look to the DIT for its recommendation on each proposed change. The power to control changes must be exercised judiciously. Two important issues are when to apply formal change controls and what features or parameters should be controlled. If formal controls are applied too early in the design effort, they can stifle innovation, burn up valuable resources in managing the effort and destroy design team morale. Morale plummets if it becomes too difficult to get approval of straightforward changes intended to improve the design or solve a recently discovered problem such as a physical interference. On the other hand, later in the design process, formal configuration control procedures become mandatory to avoid the devastating ripple effects if one person or functional group unilaterally makes an ill-advised change without adequate consultation with design management and the other affected parties.

Design resources can be controlled to some extent by a technique called *design budgeting*. For example, the DIT might establish a light ship weight budget with each element assigned to the functional area with cognizance, such as, structure, propulsion, O&F, etc. Each functional area is then tasked to attempt to stay within their allocated budget as the design is developed. The estimated or calculated weight is compared to the budget value at regular intervals and the trend is tracked over time. This approach also can be employed with other design parameters such as electric power load and other support services, system availability, and manning. The collected trend analysis results for each parameter are updated and distributed among the design team on a regular basis. The allocated budgets for any parameter can be modified with or without increasing the overall budget, if during design development it becomes clear that re-allocations are indicated. This technique is useful for sensitizing the design team to the importance of certain design parameters and for enlisting their aid in efforts to meet the overall goals. On the other hand, if the approach is applied too rigidly, a great deal of work can be wasted in futile efforts to reach an unobtainable goal. In the case of attempts to save weight, this not only wastes engineering effort but also generally drives up ship cost as well since lighter weight systems and materials generally cost more.

A very effective control technique is the in-process design review. At these informal reviews, the individual responsible for a specific element of the ship design presents the design approach, status and current design configuration. A typical design review agenda is shown in Table 5.VI. In attendance are the DIT and other members of the design team responsible for the design of elements or subsystems that interface with the element under review. Frequently, misunderstandings regarding the interfaces between elements are identified and resolved on the spot; in some cases, the design approach is modified as a result. The DIT has the opportunity in such reviews to verify that the subject design effort is *on track* and that no attractive design options are being overlooked.

During the design development process, unanticipated

TABLE 5.VI Design Review Agenda

Major design requirements
Trade study results (if applicable) and documentation
Area/volume requirements (vs. space allocations)
Compartment arrangements
One-line diagrams
Performance analysis results
Specifications status
Status of MEL inputs
Cost (current estimates vs. allocations - design, construction, O&S)
Manning (current estimate vs. allocation)
Weight (current estimate vs. allocation)
Producibility considerations
Test and Validation requirements and status
Risk assessment and status
Logistics support
Reliability, maintainability, and availability
System safety
Status of formal deliverables
The way ahead (plans to complete work)
Review of assigned action items

technical problems are often identified that must be promptly addressed by the design team. When these problems involve issues within the purview of more than a single organizational unit, the DIT is chartered to take the lead in seeking a solution. Oftentimes, an ad hoc working group (sometimes called a *tiger team*) is formed if the problem or issue is particularly complex. Members are drawn from the organizational units most directly affected by the issue. Engineering effort may be required to synthesize and analyze one or more alternative solutions to the problem.

The DIT must quickly develop a plan of action in concert with the affected parties and then manage the resulting study in parallel with the on-going mainstream design effort. The study results must be reviewed before a recommendation as to the best resolution can be made.

The preceding discussion of the design integration process is primarily applicable to the system design phases through contract design, when the focus is on the identification and resolution of functional interfaces. Physical interfaces are addressed in the early design phases also, but at a fairly high level, in terms of space, weight and support services requirements. Space assignments, adjacencies and access requirements are addressed via the general arrangements drawing. One-line diagrams define support services. In the functional design phase, the focus turns to physical integration, which must be addressed in comprehensive detail. During functional design and beyond, two major activities occur. One is the development of assembly and installation (A&I) details, that define how each piece is mated with another, for example, a stiffener to the adjacent plate, or a piece of equipment to its foundation. The other activity is the entire process of physical integration. The A&I details are important to the shipbuilder but the physical integration process is a much greater challenge to the design team. This process concerns the arrangement of all the items in an area or zone of the ship so as to optimize performance, producibility and cost, as well as eliminate all interferences. Typical items in a zone are structure, joiner work, insulation, distributive systems (for example, power cable, vent ducts and piping), equipment, furniture and other outfit items. To remain competitive, it is mandatory that an efficient physical integration process be employed.

Traditionally, 2-D drawings and physical models and mockups have been used to support the task of physical integration and to document its results. Today, computer-based 3-D geometry models are replacing these techniques.

Overlay drawings are transparent, multi-sheet, plan view drawings for a control area showing the deck arrangement, overhead structure, lighting arrangement, and the optimum run for each distributive system. The sheets are overlaid and then combined by an experienced team composed of experts in each discipline. These experts optimize the combined system designs, eliminating interferences in the process. The product is a single master overlay drawing for the control area. Hole control drawings are the results of a procedure implemented during detail design to ensure that the structural penetrations required to run distributive systems do not impair the strength of the hull and superstructure.

Composite drawings are another means of performing physical integration. A composite drawing is a single drawing showing all of the system runs, equipment and other obstructions in a control area in multi-views. The master overlay drawing described above is a single view composite drawing. Composites are more accurate than overlays but overlays are simpler and can be produced more quickly and cheaply. On some designs, composites are used selectively to supplement the overlays in particularly important and congested areas. The Interface Control Drawing (ICD) depicts selected features of two or more interfacing items to ensure compatibility between and among them. ICDs are developed after a local area has been designed to control the resulting configuration. The ICD permits subsequent design activities to proceed independently and concurrently with assurance that the specified interface previously agreed upon is adhered to. One example of an ICD is a drawing of a section of deck structure showing the distributive system penetrations. The ICD defines the physical interface between the distributive systems in the area above the deck and those in the area below. Another ICD example is an Outline and Mounting (O&M) drawing that defines the physical interfaces between a piece of equipment and its foundation, support system connections, and adjacent ship structure, joiner work, equipment and other systems.

Physical models and mockups are built when drawings are not considered to be adequate for full evaluation and physical integration of the design. These situations are typically portions of complex, high value ship designs that are especially congested, such as the propulsion machinery rooms, Navigation Bridge, and ship control spaces.

As was previously mentioned, today the drawings and physical models and mockups described above are giving way to the computer-based 3-D geometry model. As the design team develops the physical details of the design, they are captured in a single 3-D model that steadily grows in complexity. Members of the design team can view the model at any time and from any point of view. The computer can be programmed to identify and flag each physical interference to facilitate their elimination by the design team. *Slicing* the 3-D computer model with any desired intersecting plane can readily produce any drawing mentioned previously.

5.4.4.3 Formal design review

The third and concluding activity is a formal design review performed at the conclusion of the design phase. During this review, all elements of the ship design are scrutinized to ensure that they are complete, fully integrated, and collectively describe a ship design that meets the shipowner's requirements, is producible, and is economically viable. The DIT plays a leadership role in the final design review. If a specification is included in the design deliverables, it is also carefully reviewed for completeness, technical accuracy, and consistency, both internally and with other elements of the design package. After the specification has been completed, it is distributed to all concerned parties for their individual reviews. Comments are collected, collated and again distributed to all concerned. Finally, a reading session is held to which all parties are invited. At the reading session, the comments received on each specification section are reviewed and consensus is reached on the disposition of each. Failing consensus, the design team leadership will make the decision. To save time, when a difficult issue is identified, it is assigned to an individual and taken *off-line* for further consideration of the comments received, debate on the issues, and development of a specific recommendation. The recommendation is then brought back to the reading session for final discussion and approval. The recommendation may necessitate changes to other parts of the design package. A specification reading session typically lasts for several weeks. The time is well spent, however, since the session is an invaluable opportunity for everyone with a vital interest to voice their concerns and also hear the concerns of others. The resulting specification and design package is greatly improved by this interaction.

5.5 DESIGN TOPICS

The ship design process is undergoing significant change. This includes the adoption of new tools, new processes, and new management practices. These trends are briefly discussed in this section. Some are essentially *stand alone* topics, but others describe approaches that build upon and support each other.

5.5.1 Systems Engineering

5.5.1.1 Description

Systems Engineering (SE) is a formal process for the design of complex systems to meet technical performance and supportability objectives within cost and schedule constraints. The SE process involves both technical and management aspects. Its principal objective is to achieve the optimum balance of all system elements so as to optimize overall system effectiveness within cost and schedule constraints, albeit at the expense of sub-system optimization. The SE process transforms an operational need into a completed system design employing an iterative process of functional analysis, design synthesis, system analysis, evaluation and decision, and system documentation. Per the International Council on Systems Engineering (INCOSE), as quoted in Table 2 of reference 9, the SE process focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design and system validation. The SE process integrates related system technical elements and ensures the compatibility of all physical, functional, and program interfaces. The SE process embraces technical disciplines that cut across the traditional functional discipline boundaries as key elements of the total engineering effort. These disciplines include: reliability, maintainability, supportability, safety, manning, human factors, survivability, test engineering and production engineering. During system development, the SE process gives great weight to customer needs, characterizing and managing technical risk, transitioning technology from the R&D community into the system development effort, system test and evaluation, system production, and life cycle support considerations.

Per reference 10, the objectives of the SE process are:

- ensure that the system definition and design reflect requirements for *all* system elements: hardware, computer software, personnel, facilities, and procedural data,
- integrate the technical efforts of the design team specialists to produce an *optimally balanced design*,
- provide a comprehensive indentured framework of system requirements for use as performance, design, interface, support, production and test criteria,
- provide source data required to produce and test the system,
- provide a systems framework for logistic analysis, *integrated logistic support* (ILS) trade studies, and logistic documentation,
- provide a systems framework for production engineering analysis, producibility trade studies, and production/manufacturing documentation, and
- ensure that life cycle cost considerations and requirements are fully considered in all phases of the design process.

It should be noted that reference 10 is the source of much of the information presented in this section.

5.5.1.2 History

The development of formal SE processes is linked to the development of increasingly complex systems utilizing advanced technologies and incorporating human operators as well as computers in analysis and decision-making roles. Increased system complexity has increased emphasis on the definition of requirements for individual system elements as well as definition of the interfaces between system elements. A formal hierarchy of linked requirements is developed, spanning the gamut from top level total system requirements down to requirements for the smallest elements of the system. Increased system complexity has also seen an explosion in the effort required for computer software development relative to hardware development. Today, the software development effort for complex systems may equal or exceed the hardware development effort. Increased system size and complexity has forced expansion of the engineering workforce required to develop and field the system, as well as increased specialization within the workforce. Collectively, these trends have inevitably forced the managers and integrators of complex systems to expand and formalize their development procedures and processes under the *systems engineering* umbrella.

The origins of SE go back to well before WW II. However, the SE process for the development of complex systems was first formalized in the mid-1950s in connection with US Government ballistic missile programs. MIL-STD-499 was issued in 1969 to provide guidance on SE principles and processes to the US defense industry. MIL-STD-499A, issued in 1974, has been a foundation document in the development of the field. INCOSE was formed in 1990 to support SE practitioners with guidance documentation and sponsorship of workshops and symposia for the exchange of innovative ideas. MIL-STD-499B was drafted in 1994 but never issued. In its place, EIA/IS-632, an interim commercial standard, was issued in June 1994. This document has since been formalized and issued in Jan 1999 as EIA-632.

5.5.1.3 Process

The SE process is, in fact, a collection of processes. There is a fundamental process, almost a philosophy, which is surrounded and enhanced by a number of other processes that complement or focus on particular aspects of the fundamental process. Examples are processes for risk management and requirements development and allocation. The fundamental SE process is depicted in Figure 5.9.

The process is iterative; it is repeated in increasing detail in each phase of the system development. The fundamental process is also utilized by many elements of the design team in parallel. It is followed at the total system level by those with overall responsibility for system integration while, at the same time, it is being followed by the developers of individual subsystems, elements and components. Remember that one person's system is another person's subsystem! The principal steps in the process are shown in the figure. Each step is briefly discussed below.

Initial Requirements: Initial requirements are needed to start the system development process. Typically these requirements are contained in an initial draft system requirements document. They reflect an operational need and consist of mission objectives, environments and constraints, and the relevant measures of effectiveness for the new system.

A detailed description of how these initial requirements are developed is beyond the scope of this discussion. Generally they come from the customer for the system with major inputs from the operating forces that are potential system users.

Functional Analysis: Functional Analysis (FA) is a method for analyzing the initial top level requirements for a new system and dividing them into discrete tasks or activities. FA defines the essential functions that the system must perform based on the system mission requirements. FA consists of two activities: the identification of system functions, and the allocation of system requirements. FA is performed in parallel with the second step in the fundamental process, design synthesis, since there must be interactions between the two activities. FA starts with the

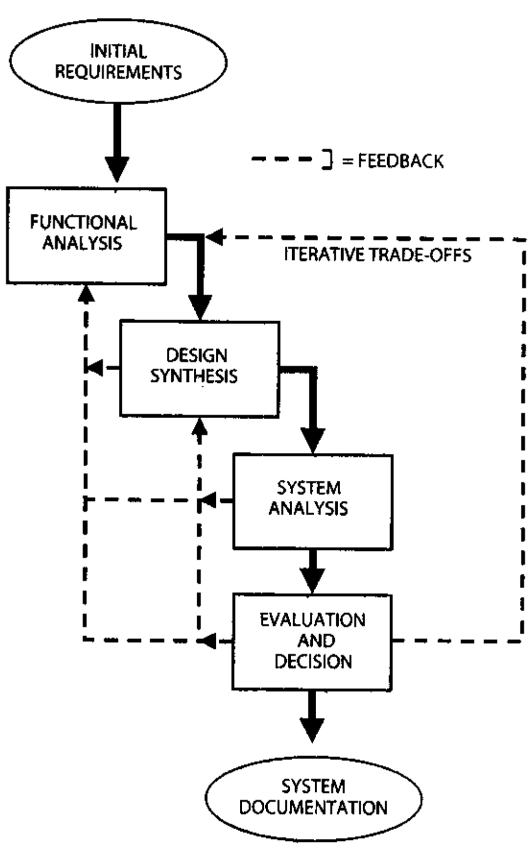

Figure 5.9 The Systems Engineering Process

identification of the top level system functions and then progressively allocates the functions to lower levels in the system, for example, each top level function is subdivided into several second tier functions, each of which is further subdivided, and so on. There is a dramatic increase in the number of functions to be performed at each lower level. A decimal numbering system, applied to each function, is used to maintain traceability between the functions identified. There are five system element types: hardware, computer software, facilities (for production and service life support), personnel, and procedural data. Each identified function is assigned to one element or to combinations of elements. Each function is described in terms of inputs, outputs, and interface requirements. *Functional Flow Block Diagrams* (FFBDs) are used to document the results of function identification. The FFBD depicts the sequential relationship of all the functions to be performed at one level, that is, the time-phased sequence of the functional events. Some functions can be performed in parallel and this is reflected in the diagram. The FFBDs are developed at several levels. A single function block at Level 1 is subdivided into many blocks at Level 2. For some time-critical functions, time line analysis is used to support the functional analysis and design requirements development.

Requirements Allocation: Requirements Allocation (RA) proceeds after the system functions have been identified in sufficient detail and candidate system design concepts have been synthesized. RA defines the performance requirements for each functional block depicted in a FFBD and allocates the functional performance requirements to individual system elements (hardware, computer software, personnel, technical manuals, or facilities). The performance requirements are stated in terms of: 1) purpose of the function, 2) performance requirements, 3) design constraints, and 4) requirements for aspects such as reliability, human performance, safety, operability, maintainability, and transportability. RA decomposes the system level requirements to the point where a specific hardware item, software routine, or trained crew member will fulfill the needed functional/performance requirements. RA is complete when further decomposition of the functions/tasks does not result in additional requirements for hardware, software, facilities, or personnel. Supporting analyses and simulations may be required to allocate system level requirements. RA is the logical extension of the initial functional identification; it is generally done prior to completion of preliminary design.

The end result of RA is the system specification and lower tier specifications. RA results are documented using a Requirements Allocation Sheet (RAS) or the equivalent commercial computer software. Both performance and design requirements are captured in the RAS, which has a flexible format. Performance requirements may be qualitative or quantitative. The personnel requirements for all tasks are defined. Design constraints such as dimensions, weight, and electric power are defined and documented in the RAS, along with all functional and technical interface requirements. Some performance requirements or design constraints can be allocated to lower levels of the system, for example. weight. A technical budget is established when a design or performance parameter is allocated among the system elements.

Design Synthesis: Design synthesis is sometimes called *conceptual design*. It provides the engineers' response to the requirements outputs of functional analysis. Its goal is the creation of a system or design concept that best meets the stated system requirements. Technology options are combined in a creative process that is constrained by the laws of physics. Inputs from all functional areas (engineering specialties) that significantly affect the result are utilized. Typically, several possible technical approaches are postulated and, for each approach, several system concepts. For each system concept, several design concepts are typically synthesized and assessed. Two tools are used to document the resulting candidate design solutions, that is, the overall configuration, internal arrangement of system elements, and principal attributes of each design concept: the *Schematic Block Diagram* (SBD) and *Concept Description Sheet* (CDS). SBDs define the functions performed by the system and the interfaces between system elements. As the concepts that survive the screening process are developed further, SBDs are developed in greater detail. Ultimately, they are used to develop *Interface Control Documents* (ICDs). For attractive design concepts, physical and analytical system models are developed later in the synthesis process. These models are used to support the subsequent system analysis by means of simulations, for example. The CDS is the initial version of the Concept Design Report, a technical report that documents the completed concept design. This report includes drawings and technical data such as weights, MEL, etc. The results of system analysis for the concept, described next, are also typically included in the report.

System Analysis: Once a design concept has been synthesized, its mission effectiveness (overall performance), costs and risks are analyzed. The assessments may be either quantitative or qualitative, depending upon the attribute being analyzed, the number of candidate concepts, and the extent to which the concepts have been defined. As the design development proceeds, the number of attributes analyzed and the sophistication and level of detail of the analyses will tend to increase. Early phase analysis typically consists of quick quantitative assessments using empirical data based on past designs and reflects many simplifying assumptions. For a few critical aspects of performance, more detailed qualitative assessments might be made. In the later stages of development, much more sophisticated modeling and simulation is done, coupled with physical model tests in some cases. It is often very difficult to evaluate overall mission effectiveness for complex, multi-mission systems. Instead, the aspects of performance with major effects on mission effectiveness are identified and analyzed individually. Development, production and operation and support (O&S) costs are typically analyzed for each option being considered. Risk is assessed using standard procedures. Two parameters are evaluated: first, the probability that a failure might occur, and second, the potential impact of that failure.

Evaluation and Decision: Trade-off studies are an essential part of the systems engineering process. Once several alternative design concepts that satisfy a set of requirements have been developed and analyzed, the results of the analysis must be evaluated and a decision made. This is typically done using a standard trade study methodology that provides a structured analytical framework for evaluating a set of alternative design solutions (candidate concepts). There are seven steps in the standard methodology as discussed in reference 10. Each step is briefly described below.

- Step 1: Precisely define the objectives and requirements to be met by the solution candidates (the Functional Analysis step described previously).
- Step 2: Identify the solution candidates and screen out the obvious losers (Design Synthesis).
- Step 3: Formulate selection criteria and, if possible, define threshold and goal values for each (minimum acceptable and desired values, respectively).
- Step 4: Weight the criteria. Assign numerical weights to each criterion according to its perceived contribution to overall mission effectiveness. Mathematical techniques can be used to factor in various opinions as to the preferred weights.
- Step 5: Prepare utility functions. This is a good technique for translating diverse criteria to a common scale, for example, comparing speed vs. endurance vs. cargo capacity vs. on-off-load times for a sealift ship. The utility score for each criterion varies from 0 to 1, representing the threshold and goal values, respectively. The utility function is a curve on a 2-D plot; a notional example is shown in Figure 5.10. The shape of the curve must be defined based on a judgment as to the relative value of incremental performance improvements at various points in the threshold to goal range.
- Step 6: Evaluate the alternatives. Estimate overall performance and other required attributes such as risk (System Analysis). Then score the overall mission capability vs. cost. Calculate the cost/capability ratio (or its inverse) for each alternative.
- Step 7: Perform sensitivity analysis. Assess the sensitivity of the resulting overall score to changes in criteria, weights, and utility functions. This enables a more informed judgment to be made as to whether one alternative is clearly preferred over the others.

System Documentation: The system design must be documented as it evolves. Traditionally, this has been done on paper by means of documents such as specifications, drawings, technical reports, and tables of data. Today, this is increasingly done utilizing integrated design systems and producing the desired documentation on CDs. In the future, Smart Product Models will contain all necessary design documentation; see Section 5.5.2.

5.5.1.4 Relationship Between Systems Engineering and Traditional Ship Design

van Griethuysen (11) has stated that:

> In many ways systems engineering is no more than a generalized model of, and framework for thinking about, the engineering process, which needs tailoring to be applicable to a particular product and project. It is, therefore, self-evident that marine products have always been designed and produced using a form of "systems engineering" even if those particular words were rarely used. It is also true that much of naval architecture and marine engineering concerned with design and management is undoubtedly an example of systems engineering.

It is true that the traditional ship design process is an example of SE and that naval architects designing ships are systems engineers. It is also true that the rigor of the SE

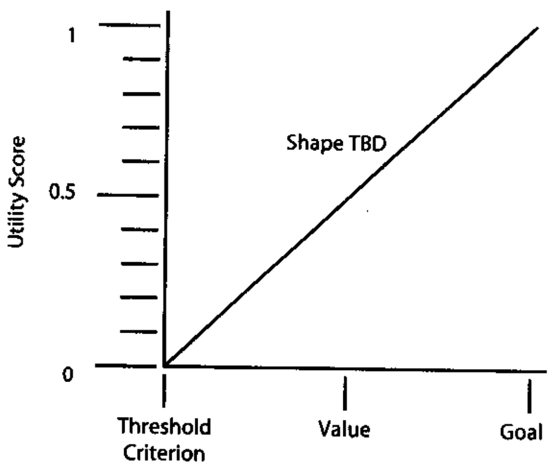

Figure 5.10 Sample Utility Curve

process is required to design a successful modern multi-mission warship or complex commercial ship such as a cruise liner, with all of its hardware, software and human factors complexities. The fundamental SE process differs from the traditional ship design process primarily in the functional analysis step, including requirements allocation, and, to a lesser extent, in the system analysis step. Naval architects have not traditionally performed a complete, rigorous functional analysis for each new ship design because it was not necessary. The ships being designed were not complex enough to warrant it; the functions to be performed, the associated performance requirements, and the links between these performance requirements and the system elements were well understood. Nor have naval architects traditionally performed the complete system analysis required for complex systems, including the formal and comprehensive assessment of overall mission effectiveness. The functional analysis and rigorous system analysis steps are second nature to combat systems engineers but are not as familiar to most naval architects and marine engineers. Naval architects and marine engineers who are members of the multi-disciplinary team designing a modern warship must understand and actively participate in these processes.

5.5.2 Concurrent Engineering and IPPD

Concurrent Engineering (CE) is the totally integrated, concurrent development of product and process design using collocated, cross-functional, empowered teams to examine both product and process. The essential tenets of CE are customer focus, life cycle emphasis, and the acceptance of design ownership and commitment by all team members. It reflects the view that design, whether it is art or science, should not occur in isolation.

CE, with its focus on consensus, has its greatest value for developing systems which require widest acceptance for their success, such as those that directly impact the survival of individuals. This success is also its greatest weakness resulting in *design by committee* and *groupthink*. It must be realized that CE is not a science but a human art, which cannot be quantified.

In the past in the U.S. there has been widespread emphasis on work specialization, and the result often has been a *stovepipe* organizational structure. These *walls* impede communications and the transfer of information. CE is not new; many of its techniques and tools have been around much longer than CE, but CE packaged them into an integrated philosophy. CE was *invented* to remove the walls discussed above. Its implementation, therefore, goes to the very structure of an organization and its management philosophy

Experience has shown (12,13) that CE cannot be implemented gradually and gracefully; an *all or nothing* approach is required.

Implementation of CE requires moving from:

- department focus to customer focus,
- directed individual or group to coached team,
- individual interests to team interests,
- autocratic management to leadership with empowered followers, and,
- dictated decisions to consensus decisions.

Such changes are clearly difficult to implement. They require the expenditure of time and money. Perhaps an even greater challenge is changing the culture of the organization. Top management must understand that CE is not a quick fix, but there are potential long-term benefits. CE is not *the flavor of the month.* Managers and workers at all levels may be fearful of giving up some individual authority, but they must recognize that change is necessary in order to remain competitive in a world economy.

Why then should CE be adopted? The primary benefit is improved design and production productivity and design quality (12). This can lead to increased market share. This is achieved by:

- understanding the customer's requirements, both qualitative and quantifiable, and the cost impact of satisfying these requirements (see Section 5.5.5).
- an objective appraisal of one's own (current) products and those of the competition (bench marking), and,
- minimizing the time (and hence the cost) from initial design through production and fielding.

A basic premise is that the ship designer has many customers. These include the shipbuilder who must take the products of design and turn them into a ship. It also includes those who will operate and maintain the completed ship through its service life. Experts on crew training and logistics are also *customers*, particularly if the design includes new technologies. Finally and *foremost*, the prospective shipowner/operator is a customer.

These different groups view the ship design from different perspectives. They have different goals and objectives, and they bring different experiences and expertise to the team. The basic premise of concurrent engineering is that the early involvement of *all* these different customers will produce a better product. Expressions such as Integrated Product Teams (IPT) and Integrated Product and Process Development (IPPD) are now widely discussed. The word *integration* is significant. Coupling process and product is also worthy of note, since it recognizes that if you hope to improve the product (the ship), you must first examine and improve the processes used to design and build the ship.

What then does the application of CE mean to the ship designer? In the past, ship designs were often developed by a *stove piped* design organization without the direct, early participation of the future ship's builder, shipowner, operators and maintainers. Nor were specialists in unique but important disciplines such as manning, cost, safety, reliability, and risk analyses involved from the outset. When these and other groups did get involved, after the design was largely complete, it was generally in a *review and comment* mode. By this time, changes would be difficult to incorporate without cost and schedule ramifications. In addition, an *us versus them* relationship might exist.

In contrast, a design team that employs CE principles also includes experts in:

- requirements analysis
- cost analysis (acquisition and O&S),
- the *Ilities* (reliability, maintainability, availability),
- manning, including training,
- manufacturing/producibility (production engineering),
- material procurement,
- tests and trials,
- marketing, and
- in-service support.

A shipowner's representative is also a team member.

The basic premise of CE is that it is better to make design decisions (at all Levels) based on real time (or near real time) feedback from all who have an interest in designing, producing, marketing, operating, and servicing the final product.

This approach has a common-sense appeal, and CE, IPT, and IPPD have achieved a certain vogue in the US, within both industry and the Government. These approaches are adopted in order to get disparate groups to communicate better and thus to eliminate the *stovepipes*. They are, therefore, a means to an end. Of interest, some other shipbuilding countries have seen no need to take such measures, having a successful tradition of getting groups to work in concert without the need for formal, ad hoc CE teams.

The term concurrent engineering is sometimes confused with concurrent development. The latter primarily refers to warships where new systems (combat, weapons, and propulsion) may be developed simultaneously with ship design development. This presents a unique set of risks and challenges. If new, fully defined, systems are *frozen* too soon, they may prove to be obsolescent when the ship is completed years later, particularly electronic systems. Yet, if selection is delayed to permit the concurrent development and maturing of new systems, these systems may prove to be difficult to integrate when their ship impact characteristics (space, weight, kW, manning, etc.) are well defined. This topic, however, is beyond the scope of this chapter.

5.5.3 Collocation

The decision to collocate the design team should be noncontroversial since it leads to better integration and communications, and those intangibles such as teamwork, a sense of ownership, and esprit de corps. However, in a large engineering organization, many designs or products may be being pursued at the same time, and/or the functional engineering codes may have other tasks: Research and Development (R&D), In-service Engineering (ISE) for ships at sea or in overhaul, and *fire drills*. The argument against collocation is that dedicating resources to a single project would dilute the total available resources. Thus, collocation can only be justified for high priority, high visibility, or high-risk programs. Top management must resolve the benefits of, and the counter-arguments to, collocation as it sets priorities.

In the past, collocation referred to physical collocation and up to 100 percent dedication. While, it is believed that there is still no substitute for face-to-face communications, today shared computer networks, shared electronic databases, video teleconferencing, and even e-mail, can allow the design team to *virtually* collocate. In some recent ship acquisitions, ad hoc industry teams have been formed, with different and, often, new partners. Team members are usually separated geographically, as well as organizationally, and *electronic* collocation is a given. In such a distributed design environment, communications, database management, and security must receive a high priority in planning, maintenance, and operations. If a key communications system goes down, productivity quickly suffers. Face to face meetings should still occur regularly. The design management plan must ensure that sufficient resources are provided for the tools needed to support the virtual collocated team, and for the necessary travel.

5.5.4 Integrated Design Systems/Modeling and Simulation

The application of computers to the ship design process continues to evolve. In the (not that distant) past, a design site could be recognized by:

- many engineers working with pencils and paper, hand books, mechanical calculators, slide rules, and trig tables, and
- a large number of draftsmen laboring over drawing boards with T-square's, triangles, French curves, battens and batten weights (ducks).

Perhaps the first computer applications used computer programs written to solve discrete, math-intensive problems in order to save labor and achieve more consistently accurate results. This required adapting physics-based models (PBM) to the computer. Languages were rudimentary by today's standards, data was input by punch cards and batch processed on a mainframe in non-real time (often over night), and output was typically tabular numerical data; graphical output lay in the future. As local PCs became available (and later, powerful engineering workstations), turnaround time was reduced. These engineering programs (there are scores in the marine field alone) were developed by engineers (and organizations) to suit their specific needs, often on an ad hoc, stand-alone basis. Accordingly, many different computer languages were used, documentation was often meager, and the various programs could not *talk* to each other. Over time, commercial programs were developed in the U.S. and overseas. This field is described as Computer Aided Engineering (CAE) (see Chapter 13 – Computer Based Tools).

At the total ship level, computer-based ship design synthesis models have been in use for several decades. They permit a large number of concept alternatives to be generated quickly. Such models are only as good as their databases, and thus are not as useful when an entirely new (novel) design is being considered. They provide answers that are relatively correct, which is adequate for making comparisons.

Soon, the computer also started to be used to generate 2-D lines drawings using commercial software. Even with a skilled practitioner, establishing the initial baseline was relatively slow, but subsequent changes and revisions could be incorporated much more rapidly than in the manual process. The next evolutionary step was to 3-D computer drawings (or solid models). Preparing 3-D drawings by hand required art as well as science. Technology enables the rapid preparation of 3-D computer drawings based on an available 2-D baseline. This field is described as CAD (Computer Aided Design; see Chapter 13 – Computer Based Tools).

In the 1980s, drawings (analog or digital) described the ship's geometry. Interference checking in highly congested areas of the ship was very difficult, labor intensive and time-consuming. Many times problems would not be discovered until ship construction started, resulting in costly and time-consuming rework. Today, highly congested areas of the ship can be modeled in 3-D (solid modeling). This might include piping systems, structures, installed equipment, ventilation ducting, electric power cables, passageways, doors, and ladders. Potential interference problems can readily be identified and resolved.

Independently, shipbuilders (and others) were applying the power of the computer to manufacturing (CAM). Initially this was restricted to NC (numerically controlled) machines that performed very discrete tasks (for example, milling machines). Later, computer lofting was used to dimensionally describe structural plates and shapes and, ultimately, to direct cutting heads and shaping rollers. Eventually, shipyards developed 3-D computer models to aid in *interference checking* between systems competing for space within a compartment. Previously this had been accomplished by overlaying 2-D drawings on a light table. Shipyards procured commercial CAM programs, or developed their own, or created hybrids. There were no industry standards; indeed, the shipyards viewed these programs as proprietary.

Essentially all of the CAE, CAD, and CAM programs discussed above were developed independently, some by Governments (navies) and some by industry. These standalone programs solved discrete problems. Standards and interfaces were poorly defined. There was little or no linkage.

What has been described thus far represented at best a federation of a myriad of programs. The next step was to develop a truly *integrated design system* (Figure 5.11).

CAD programs describe the *geometry* of a system or, even the total ship. A natural extension to the use of CAD has been the relatively recent development of 3-D digital product models. In addition to providing an accurate geometric description, they also include product characteristics such as mass, material properties, electric power/cooling requirements, and manning requirements.

Originally conceived to facilitate communications between design team members, product models are becoming the primary vehicles for transmitting the ship design description to the shipbuilder. This has the potential to eliminate the need for the shipbuilder to develop its own 3-D model. This reduces time, cost, and the introduction of errors. Issues such as interface standards and protocols must, however, be addressed. In addition, upon ship delivery, the *as-built* 3-D product model will provide the basis for configuration control and managing changes throughout the ship's operational life.

CAE programs describe the *behavior* of a system, or even the total ship. A natural extension to the use of numerous CAE codes has been the relatively recent development of dynamic (vice static) physics-based models.

In a recent U.S. Navy design of an amphibious warfare ship, dynamic physics-based modeling was used to quantify the forces placed on the boat crane when handling boats in Sea State 3. (The seakeeping analysis for the selected hull form was imported into the program to provide ship motions). The program was used to evaluate commercial cranes to see if they could satisfy the requirement. Performance parameters were then used to specify system requirements in commercial terms, and eliminate the use of the typical multi-tier military specification. This is an example of the application of an Integrated Design System (IDS) where the geometry model and the engineering analysis models can readily communicate with one another.

When a 3-D product model and physics-based models are married, the result is a *smart product model* (SPM). The SPM can also include bills of material, manufacturing processes, maintenance requirements, and cost analysis tools—the list is endless. When the SPM is combined with state-of-the art visualization and high-speed computers, *simulation based design/virtual prototyping* (SBD/VP) becomes possible. As is well known, ships are rarely prototyped because of the time and cost involved. There is no real *fly before buy*. As a result, in series production many ships may be under construction before the lead ship delivers. To minimize risk, developmental systems may be tested in land-based test sites or at sea. This, however, is expensive and, for naval ships, occurs late in the ship development cycle.

The ship as a whole is not tested until after delivery. It is only then that the actual performance achieved can be measured against the desired capabilities established many years earlier. At this stage, schedule and cost considerations preclude correcting all but the most severe deficiencies. SBD/VP offers the opportunity to short circuit this process by the use of virtual ship prototypes in a virtual environment.

In the deck crane example mentioned above, experienced deck seamen were able to *operate* the crane in real time, and provide feedback to the designers. Virtual prototyping has been used to mimic the loading and off-loading of tracked and wheeled vehicles from a sealift ship.

The ultimate goal is to be able to conceive, design, build, and test the ship in a computer long before any manufacturing proceeds.

5.5.5 Risk Analysis

The dictionary defines risk as a chance or possibility of danger, loss, injury, etc. Risk is part of life. It results from the inability to accurately predict the future, and a degree of uncertainty that is significant enough to be noticed. Any key factor that is unknown represents risk. Risk is therefore tied to knowledge or, more accurately, the lack thereof (see Chapter 19 – Reliability-based Structural Design).

The synthesis and analysis of an engineering system often involves the development of a model. Today this frequently means a computer-based model. In fact, however, a model is simply an abstraction of reality, and engineers have always employed them (a sketch of a ship or a system or a mathematic expression or formula is therefore a model). Model uncertainties arise because of simplifying assumptions, simplified methods, and idealized representations of real (physical) behavior and performance.

At the beginning of the design process, knowledge can be categorized three ways:

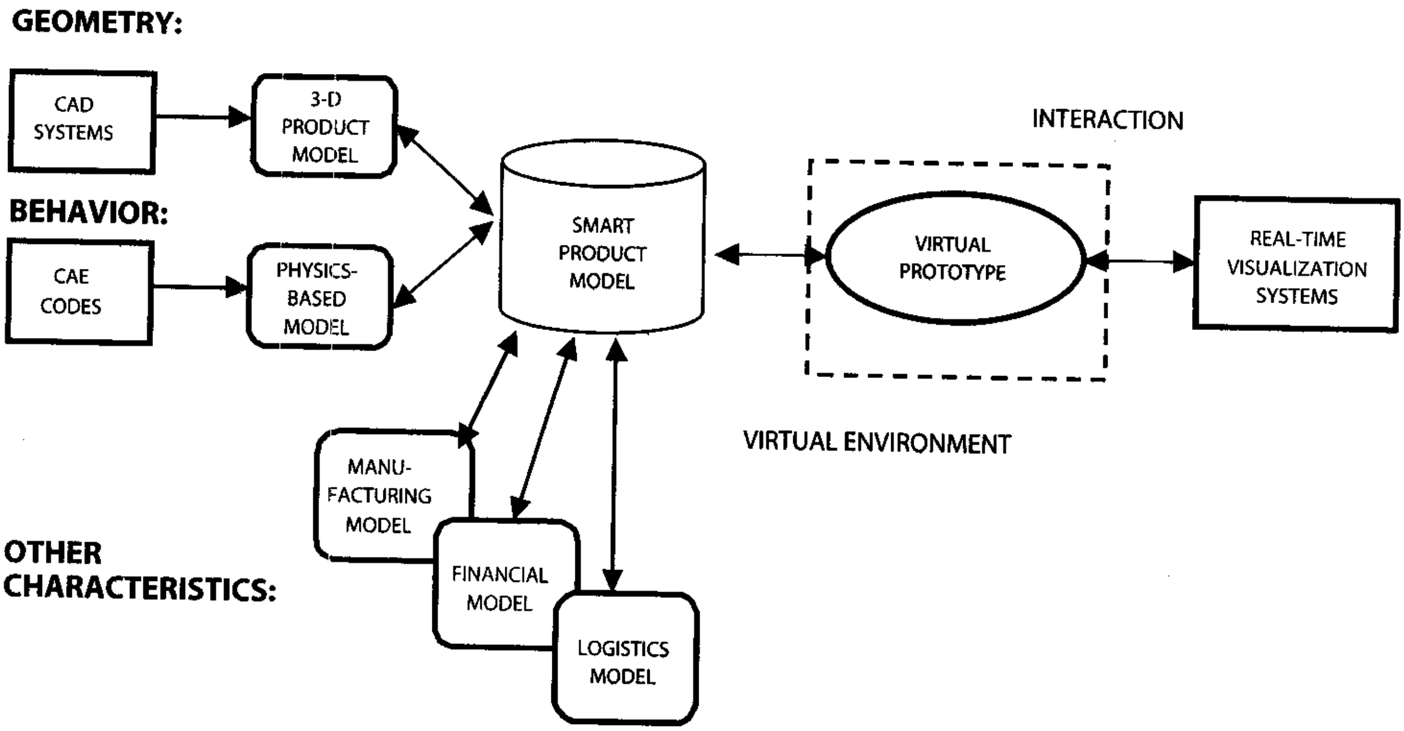

Figure 5.11 Integrated Design System

1. that which is known,
2. that which is unknown, *but* known to be unknown, and
3. that which is unknown, and *not* known to be unknown.

An example of something that is known is the body of knowledge. This might be publicly available or unique to the team (proprietary). There should be no risks associated with applying this knowledge.

In the ship design process, however, not everything can be known at the beginning. During the early concept stages, for example, simplifying assumptions are made based on experience, parametric studies, or databases of similar ships. As the design matures, analysis, detailed engineering, and model tests will confirm (or modify) the earlier assumptions. This is a part of normal design development, and margins may be applied to ensure that the performance envelopes are not violated. Typical margins include speed/power, weight and VCG, but may also include kW and HVAC requirements, and manning (accommodations). It also may be prudent to develop fallback positions. Since the genesis of risk is uncertainty, applying additional engineering resources may be appropriate (for example, apply resources to accelerate model testing, or the development and testing of a new system). As the design matures, the *known unknowns* will move into the *known* category and risks will be reduced.

In ship design development there are also unknown unknowns. By definition, they cannot be quantified, and are difficult to anticipate. History tells us, however, that on a *statistically significant basis* they will arise. Examples include an unanticipated change in shipowner requirements or a new shipowner or major decision maker for government programs, major cost or schedule changes, loss of key design personnel, an energy crisis or labor unrest causing loss of productivity during construction, new national or international regulations, a *technology breakthrough* (or a technology failure), and a major vendor leaving the business or ceasing production of a line of equipment. Another example that falls into the category of an unknown-unknown is human error. Anticipating such risks is obviously quite difficult since it can only be done subjectively, even if by experts.

Design has been defined as the selection and integration of systems and subsystems to meet the requirements and constraints. Risk, whether technical, cost, or schedule, must be of concern to the design team. Every effort must be made to identify risks and work to reduce them during the design and construction process. This activity is termed Risk Analysis. Risk analysis consists of three major components: risk assessment, risk management, and risk communications.

Risk Assessment is the process of deciding how significant a potential hazard is. First, the hazards are identified and qualitatively described. The design engineer has traditionally been primarily concerned with technical risk (performance), but should also be concerned with cost and schedule risks since design decisions may influence them. There are also secondary risk areas such as the market place, national and world economic trends, energy crises, availability of labor, legislation, etc. Risks are identified after an analysis of the customer's requirements and constraints, and an assessment of the needed technologies and capabilities.

After the risks are identified, they are prioritized so that management attention and resources can be focused on those risks that are most important. A common approach is to estimate both the likelihood of an event (probability of occurrence) and the associated consequences. The probability of occurrence will range from zero to unity. High probabilities will be assigned, for example, when the required technology is pushing the state of the art and is untested. Conversely, a low probability of occurrence is assigned when using proven technology or off-the-shelf equipment. Next, for each risk the severity of consequence is estimated (severity could also be ranked on a zero to unitary scale). A high number is assigned if the program is threatened (either from a performance, cost, or schedule viewpoint). A low number is assigned when there are fallback positions. When the two numbers are multiplied together, an overall risk ranking is produced.

While is it impossible to avoid value judgments (that is, bias and preconceptions), the assessment should be as objective and consistent as possible.

Commercial software programs are available to assist in these tasks. The more sophisticated might explore the premise that probabilities are not unique but, rather are distributed (a rectangular or triangular function might be assumed, or a bell shaped curve, or a skewed curve). Monte Carlo simulations can be applied in a computer model a large number of times until the pattern becomes evident. These programs are also useful for conducting sensitivity analyses.

Risk Management is the process of selecting alternatives and deciding how to *mitigate* an assessed risk. For purposes of this discussion, the designer is primarily concerned with engineering risks, but risk management involves consideration of a variety of factors including engineering, technology, economics, political, legal, and even cultural considerations. Risk mitigation can be designed to either reduce the probability of occurrence of a risk, or the consequences, or both. After alternative risk mitigation actions have been developed and the cost to execute them estimated, senior managers decide which to implement.

Risk Communications is the process by which information is exchanged about risk. During the course of design development, risks must be tracked and reported. Risk should be an agenda item during all design reviews. If there are a large number of risk areas, periodic risk reviews can be held to ensure that all risks are being managed, that the assessments are current, and that the mitigation plans are achieving their desired results. If new risks are identified, they must be assessed as described previously, and mitigation plans developed.

5.5.6 Decision-making

Decisions must be made at every stage of the design development process in the course of choosing among the technical alternatives that are typically available to meet functional requirements. There are two classes of decisions (14), namely when:

1. technical alternatives are finite and available (as in a catalogue), and
2. alternatives must be synthesized.

Traditionally, it has been assumed for both classes of decisions that the technical requirements are mutually compatible. Thus feasible alternatives can be developed, selection criteria (an objective function) established, the criteria applied and a selection made. No real decision-making is involved. However, when the requirements governing a selection are in conflict, which is often the case in design situations, the designer's priorities will determine the solution. In such cases, the decision-making process is as important as the facts upon which the decision is based. Multiple Criteria Decision Making (MCDM) methods (15) are designed to address this kind of problem. The MCDM approach clarifies the trade-offs between objectives and permits them to be manipulated; better decisions are the result.

There is a large array of methods that deal with multiple criteria problems. Four Multi-Attribute Decision Making (MADM) models are described, evaluated and demonstrated in reference 15. They are:

- Weighted Sum
- Hierarchical Weighted Sum
- Analytical Hierarchy Process (AHP)
- Multi-Attribute Utility (MAU) Analysis.

All of these MADM methods simplify and clarify the design decision-making process by transforming multi-dimensional decision problems to a single criterion, a Figure of Merit (FOM), which is used to indicate the overall design *goodness* for each alternative. All the methods allow subjective assessments to be translated into quantitative values for evaluation purposes. The quantification process does not make the decision process objective, but it does allow the design team to explore the effects of their choices of attributes, weights, etc. The latter three methods all represent improvements over the traditional weighted sum technique at the expense of added complexity. Including risk and uncertainty in the evaluation is desirable; however, doing so adds further complexity. The reference presents a quantitative method for performing cost-effectiveness trade-offs using the DDG 51 as a ship design example. The importance of evaluating cost and effectiveness separately in performing such trade-offs is emphasized. They are independent qualities. If the cost and effectiveness FOMs for each alternative are plotted, the design team may be fortunate enough to find that the optimum solutions plot along a rough curve. In this case, the *best* of the optimum solutions will generally lie at the knee of the curve.

Quality Function Deployment (QFD) is a management tool developed by a Japanese shipbuilder in the late sixties to support the design process for large ships. QFD is a method for structured product planning and development. It translates customer requirements into requirements for the product development team. QFD has also been defined as *a system for designing a product or service based on customer demands and involving all members of the producer or supplier organization.* QFD is a planning and decision making tool; it is a good example of concurrent development. QFD enables the development team to identify the customer's wants and needs and then to systematically evaluate each potential product attribute in terms of its contribution to satisfying the needs. The process involves constructing one or more matrices or *quality tables*; see Figure 5.12, from reference 16. Matrix 1 in the figure is termed the *House of Quality* (HOQ) due to its shape.

The first step in the process is to identify the customer's requirements such as wants and needs, likes and dislikes, termed the WHATS. The customer is defined as any user of the design. Thus there is typically more than one customer, for example, the shipowner, the ship operators (future crew), the shipbuilders, the future ship maintainers, etc. The needs and desires of these *customers* are identified, based on consensus, and then prioritized (weighted). Many representatives of each customer group might be polled to assist in this step.

The next step is to develop the HOWS, that is, the design requirements (technical measures of performance) that, if met, will produce satisfied customers. There must be at least one HOW for each WHAT and there may be more. Also, each HOW will typically influence more than one WHAT. The HOWS and WHATS are then correlated by means of a 2-D matrix, the WHATS along the left side and the HOWS along the top. This matrix, the HOQ, is an effective aid in untangling the complex web of relationships between the WHATS and the HOWS. The HOWS associ-

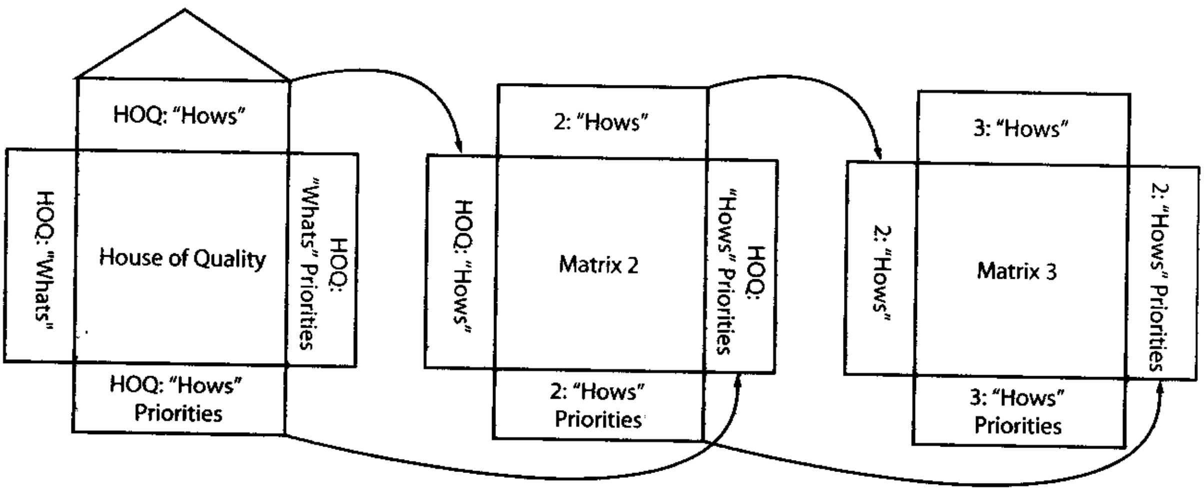

Figure 5.12 QFD Matrix Chain

ated with each WHAT are noted in the appropriate boxes of the matrix and the strength of each association is estimated. By this means, the relative benefits of each HOW can be expressed numerically, that is, the HOWS can be prioritized or weighted. In addition, the HOWS can be correlated with one another and the strengths of the relationships noted. This is done in the *attic* of the HOQ.

Strong positive correlations indicate synergy and possibly duplication. Negative correlations indicate conflicts and opportunities for trade-offs. Ultimately, the HOWS are quantified by "how much," that is, specific performance objectives expressed in measurable terms. In more sophisticated analyses, the cost of each HOW is estimated (design development, construction, and TOC). This can be combined with the weights (relative importance) of the WHATS, and the development team can see what the cost vs. performance actually is.

Typically, the HOWS in the HOQ (Matrix 1) are not sufficiently detailed to be used directly in product design. The matrix chain depicted in Figure 5.12 is provides the required definition. In each successive matrix, the WHATS are the HOWS from the preceding matrix and the HOWS represent a more specific, detailed decomposition of the performance measures, attributes and characteristics of the product being developed.

In each successive matrix, correlations can be identified and the strengths of these correlations can be judged. By this multi-step process, the customers' desires can be linked to system features and the relative importance of various system features can be assessed. This knowledge can be used to influence the allocation of design resources and the numerous trade-off decisions that must be made during design development. The QFD approach and philosophy can be applied to numerous other aspects of the product development process. The brief outline above is intended only to give the reader an indication of the basic QFD goals and approach. In addition to providing design guidance, QFD shines at facilitating self-interviews within the design team, consensus building and improving communications among the stakeholders in a large project.

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