THE ARCHITECTURE OF FRIGATES

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The author presented this paper at the Royal Institution of Naval Architects Symposium on Anti-Submarine Warfare held in London in May 1987 and it is printed here with their permission. Mr Brown would welcome comments, either as correspondence for open discussion in the Journal *or privately to him (55, F Block, Foxhill). Layout is not an easy problem; there is no one right answer, and compromise is essential.*

ABSTRACT

The article discusses the problems of defining the desirable features of the layout for a frigate which will be used in very different ways in peace and war. Since architecture is inextricably linked with design in the widest sense, the development of layout must closely reflect the design process itself. This leads to a step-by-step approach in which constraints are imposed and choices made, reducing an infinity of options to a single solution. Numerical methods may be used to illuminate the problem, and to some extent to compare solutions, but cannot alone lead to the best architecture.

Introduction

A modern warship is an assembly of spaces, many of which serve more than one function, interacting in a complex manner and located within an envelope whose proportions and shape are set by hydrodynamic and other considerations. Furthermore, the structure is supported on, and loaded by, the sea in a most irregular fashion, whilst the arrangement of partitions is governed by structural continuity and the containment of damage to a far greater extent than in buildings on shore.

These engineering problems are difficult to solve and hence the naval architect is so constrained in his layout that the architectural aspect may not be given the consideration which it deserves. The scope for optimizing layout may not be great and indeed it will be difficult to quantify the benefits of one layout *vis-à-vis* another, yet the potential benefits are considerable and hence the search for the 'best' architecture is worthwhile.

Layout as a Part of the Ship Design Process

Ship design involves formulating an economical, material solution to one or more operational objectives within defined constraints. The first elementary step is to sum the demands of the various sub-systems; then in the next phase, the interrelationships, including spatial, between sub-systems will be evaluated.

The architecture of a warship affects its cost, both to build and to run, its fighting capability and the efficiency and comfort of its crew. For these reasons, architecture is one of the major aspects of the overall design problem and, as such, interacts with all other aspects. FIG. 1 illustrates the nature of this interaction.

Initial sizing will have to be made by summing the individual spatial demands but a more considered approach must be adopted as soon as possible. 'Space' has many dimensions; on the one hand it can be length, area or volume, but in addition position and shape may be considered as further dimensions. Some spaces can be used for more than one purpose, reducing the total demand, whilst other space demands may themselves be functions of layout. On the other hand, other requirements—e.g. seakeeping, ease of building—may lead to a ship which has more internal space than

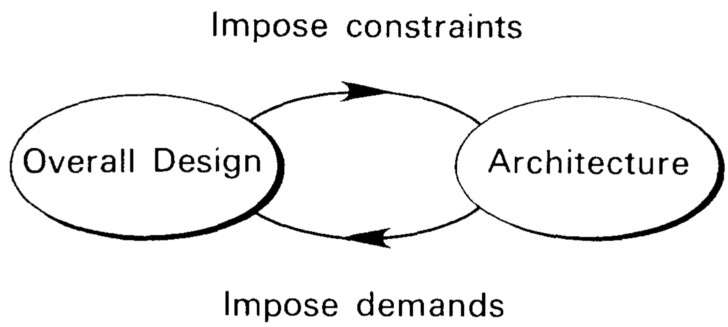

FIG. 1—INTERACTION OF ARCHITECTURE AND DESIGN

that given by the sum of individual demands. For these reasons the author suggests that

$$\text{Space available} \geqslant \Sigma \text{ (spaces required)}$$

rather than the equality used by Andrews[1].

A Philosophy for Architecture

The complex links between architecture and the overall design process lead inevitably to the development of layout in stages corresponding to that of the design. Constraints are applied at each stage but leaving as much flexibility as possible in the next stage, whilst still moving towards a single solution.

FIG. 2 shows that, after the essential task of defining the problems[2], layout is conveniently tackled in some three main levels of detail—Levels 1, 2 and 3, below. At each stage, several decisions are made, reducing the infinity of ways in which some 400 compartments can be arranged to a very few. These few will then be examined in more detail in succeeding stages. It will sometimes be necessary to return to an earlier stage and challenge the assumptions used.

In the final phase, it should be possible to make some numerical comparisons, not in an attempt at a mechanistic solution, but to illuminate the effect of various possible changes.

This apparently simple philosophy is not easy to follow in practice due to the very large number of constraints and cross connections with other aspects of the design. In the following sections the broad approach will be illustrated by specific examples related to the design of an ASW frigate. Some such problems will be examined in depth in order to bring out all the difficulties involved.

Objectives

The layout of a warship falls into the category of a 'wicked problem'[3] in which precisely defining the problem is more difficult than the search for a solution. The starting point must be the views of the operator and these must be sought and understood but, ultimately, it is the designer who is responsible for the success of the ship.

The objective of the procedure outlined in this article is to establish a logical framework which will minimize the adverse effects of the difficult compromises which are inevitable as the design develops. A secondary objective is to establish a basis on which the merits of different layouts can be compared. The ultimate aim is the design of a ship which is easy and hence cheap to build, operate and maintain, is comfortable to live in, and is an effective fighting machine able to withstand damage as well as to inflict it—an aim which can never be expressed in a single factor of merit.

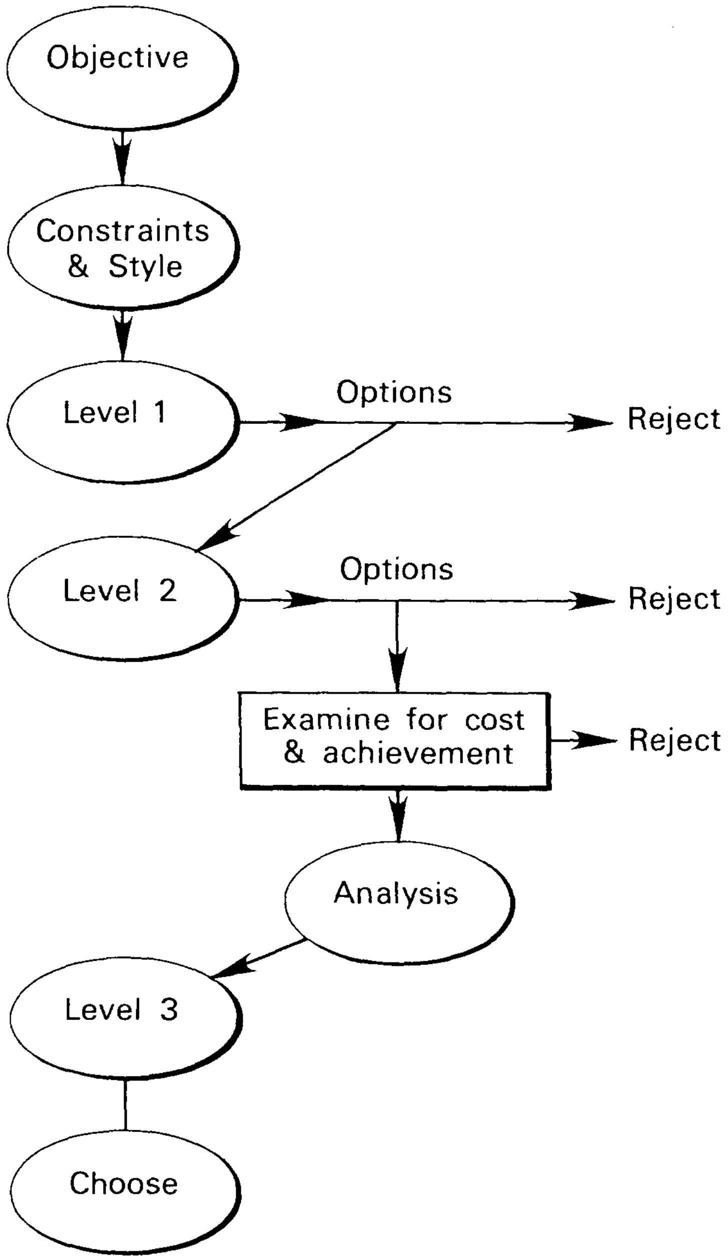

FIG. 2—A PHILOSOPHY OF LAYOUT

Some of the inherent contradictions in this aim are illustrated in the matrix of FIG. 3. Though the warship is designed to fight she will spend most of her life at peace and will be in harbour as often as at sea.

Peace	War
Sea	Harbour

FIG. 3—OPERATING MATRIX

Fighting

Since the primary *raison d'être* of a warship is to fight, weapons and associated spaces must be sited to maximize their effectiveness and minimize their vulnerability. The deterrent effect of a warship in peacetime may be judged more by visible weapons than by the effectiveness of their controls. The ship itself should be subdivided to limit the spread of fire and smoke, NBC contamination, flooding, etc., whilst access is needed to control damage and, in the ultimate, for evacuation.

Living

The Royal Navy is manned by volunteers who have the right in peacetime to expect a conveniently arranged environment and some degree of comfort from the arctic to the tropics[4] and who will fight best if they can get proper rest. The needs of the crew vary widely between peace and war and between sea and harbour.

A warship is the representative of her country and attention to appearance, both exterior and interior, is important and need not be costly[5].

Cost

Cost may be seen as an objective (cost reduction) or as a constraint (cash limit). Under both headings it is necessary to consider both production cost and the through-life cost of ownership.

Space (area) is expensive: as a generalization, it costs some £5000 to add one square metre of empty space to a frigate. Rules of thumb such as this are valid only for small changes and it will also, in general, cost more to add space high up than low down due to the inherent rise of the centre of gravity. Cost per square metre is non-linear and non-uniform. Attention must be directed to layouts which minimize space requirements by judicious juxtaposition which reduces the need for access. On the other hand, generous access and spacious compartments ease both installation and maintenance, including cleaning.

There is a similar conflict between the requirement to reduce vulnerability by zoning, duplication and separation, and that to reduce cost by concentrating into a single space. Costing methods are not adequate in themselves, even on a marginal basis, to give much guidance on the layout style to be selected.

Identification

Constraints

The naval architect must next identify the constraints imposed on his layout, the sources of information and the standards to which he must work and the 'needs' of the user. In practice, the appropriate needs are best identified at each level of layout development. There are a very few components, e.g. the bow sonar dome, whose position is totally fixed and which hence constrain layout.

FIG. 4 shows in the outer ring a number of the problem areas which impinge on the layout of a frigate and, inside, those features of the ship which are directly affected.

Hydrodynamics

The proportions and form of a frigate must be appropriate to its fairly high speed (F_n 0·3) in both calm and rough seas. The beam must provide adequate stability without an excess which would lead to too short a rolling period causing violent lateral accelerations reducing crew efficiency; whilst length and draught must favour low resistance and reduced vertical plane motions. In particular, the requirement for fine ends and 'Vee' sections forward pose difficult layout problems.

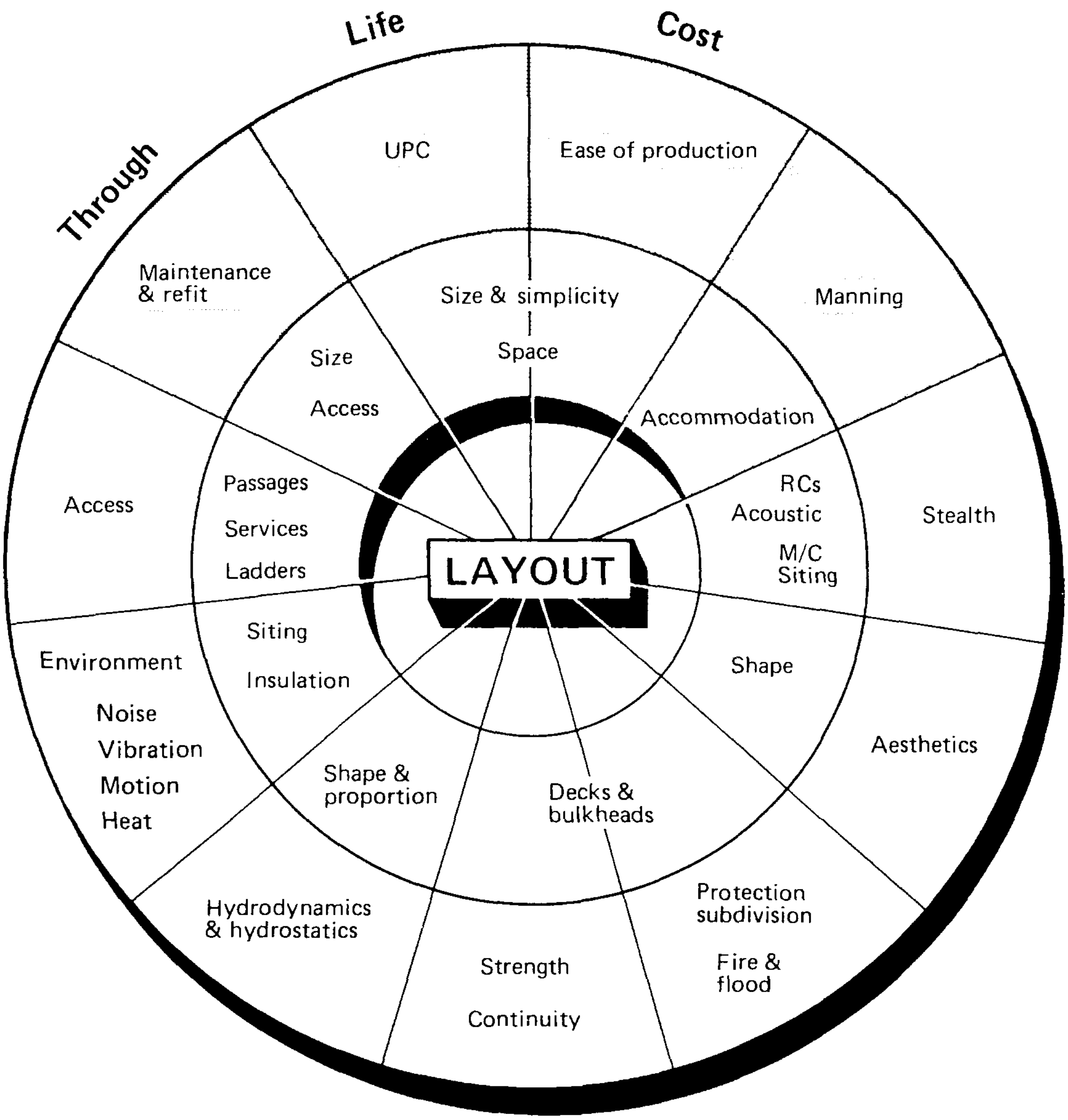

FIG. 4—DESIGN CONSTRAINTS THAT AFFECT LAYOUT. THE OUTER RING LISTS PROBLEM AREAS WHICH DIRECTLY AFFECT THE ARCHITECTURE OF A FRIGATE, WHILST THE INNER RING SHOWS MATERIAL SOLUTIONS

Structural continuity

It is essential that primary structure is continuous in all three planes so that it is able to resist loadings which vary from the sudden shock of an explosion to the repeated loading in heavy seas which can lead to fatigue. This requirement will affect the arrangement of bulkheads and impose restraints on the position and shape of access openings. In particular, the need to end superstructure blocks on transverse bulkheads constrains the design.

Subdivision

The requirement to limit the extent of flooding following damage, and particularly to ensure that the partially flooded ship remains stable, demands a considerable number of bulkheads in loosely prescribed positions. It will usually be found that there is some degree of 'float' in the position of a bulkhead and this can be used to advantage in developing the layout. Doors in bulkheads are undesirable below the intact waterline, leading to the need for vertical access to spaces low in the ship. Similar principles affect the layout of services.

Environmental Constraints

The sea is a very hostile environment many of whose aspects impose further restrictions on the layout. The effect of pitch and heave requires living and working spaces to be sited away from the ends of the ship, whilst the impact of heavy green seas limits the use of the forecastle for vulnerable equipments. Noise, heat and vibration generated by machinery and propulsors can also make some areas of the ship undesirable for men and many equipments.

Stealth

The need to reduce the detectability of a ship may affect its arrangement. In particular, reduction in the size of superstructures and their shaping can affect radar cross-section.

Manning

Both the overall space demand and the layout will be affected very considerably by the number of men in the crew and the standards laid down for their accommodation, e.g. space/man, number of sittings in the dining hall, number of bathrooms and heads, etc.

Standards

The designer will normally be well advised to work within extant standards which represent accumulated experience on problems and successful solutions[3]. He should, of course, examine such general standards for their applicability to his design.

Data

In the early stages, at least, space demand, the primary input to layout—will be obtained by comparison with previous ships. Such data must be compiled and studied at a level of detail appropriate to the stage of the design, there being little value in studying a table with the areas of 400 compartments listed, at the earliest stage. TABLE I, which gives broad indications of the areas and siting of main functional groupings of a frigate, is a suitable starting point.

Development of a coherent layout philosophy must rest to a considerable extent on reports from sea. Such reports are inevitably subjective and in order to obtain a reasonable impartial overall viewpoint, the designer must go to sea for a considerable period under operational conditions, as well as accepting input from the operators themselves. The subjective nature of such reports should be reduced by using properly constructed questionnaires and by the use of work study techniques. The crude input from the crew, in peacetime, is likely to emphasize convenience and comfort rather than military virtues. Even combat experience can be biased; the 'lessons of the Falklands' do not include ASW experience.

TABLE I—*Space breakdown under primary functions for an ASW frigate*

Deck	03 & above	03-02	02-01	01-1	1-2	2-3	below 3
Main Machinery & Major Auxiliary Machinery Spaces	—	—	—	—	—	511	417
Uptakes & Downtakes	—	110	104	76	77	—	—
Air Conditioning/Refrig.	—	4	33	60	147	30	—
Operational & Weapons Control,							
Bridge, AIO, MCO, EW, etc.	—	50	20	—	110	115	—
ASW	—	—	5	5	40	50	60
AAW	14	50	30	25	10	—	—
Accommodation							
Messes and Cabins	—	8	54	215	353	300	—
Galley, Dining Hall, Wardroom, Canteen, Pantries	—	—	5	69	181	—	—
Access Passageways & Lobbies	—	36	57	124	275	55	21
Stores	—	—	22	28	106	159	87
Workshops	—	—	17	46	17	—	—
Offices	—	—	—	48	12	—	—
Weapons, Magazines, power ASW/AA	—	12	5	7	20	1	16
Air (inc. Workshops & Magazines)	—	—	107	131	20	5	45

Figures are in square metres

Design Style

Before starting the design itself the design team will make a number of broad statements on policy for the design and, collectively, these statements are described as the 'Design Style'.

Role

The primary role of the ship will define a number of priorities in the arrangement of systems. For an ASW frigate, the siting of the helicopter deck is of prime importance, whilst in an AAW ship clear firing arcs for the weapons may be the first choice. What can never be clear is the relative priorities of a secondary requirement of the primary role with respect to a primary requirement in the secondary task. It is fortunate that the requirements for prime sites in ASW and AAW are generally very different.

Modular design

Modularity is an approach to warship design which decouples the ship from the weapons systems and other 'self-contained' packages for the purposes of design, development, production and modernization. This is achieved by precise and controlled definition of standardized functional and physical interfaces between the ship and its weapons. The approach can be applied to systems other than weapons but, since the main impetus for modularity arises from the disparity in the rate of technological change between platform and weapon systems, the advantages of applying a similar methodology to less rapidly evolving systems are usually marginal. In international collaboration projects, where the basic ship may have to accommodate a range of national alternatives, the advantages of a modular approach may be greater even if the ship has to be a little bigger.

The only warships in service using a modular design are the Blohm & Voss built MEKO vessels[6]. The U.S. Navy is well advanced with an alternative approach called 'Ship Systems Engineering Standards' (SSES)[7]. These two systems differ considerably in their approach in that MEKO is based largely on existing weapon systems and is aimed at reducing production costs. SSES is a more comprehensive approach which, by explaining and defining interfaces, margins, etc., is aimed at easing the introduction of new weapons technology into ships. SSES was originally developed for large ships but the concept is being extended into frigates.

Cellularity, described by Gates[8], is a somewhat simpler but more limited approach to modular design in which access and installation envelopes are defined together with the dimensions of appropriate 'boxes'. Standardized supplies of services are also provided.

The fixed size and shape of any of these modules impose limitations in the layout as do the interfaces specified for services. A feature of cellularity is that soft spaces should be arranged adjacent to weapon cells so that the latter can grow should the built-in margins become inadequate. The displaced spaces must then be re-arranged elsewhere, possibly by extending the superstructure.

Margins

If it is envisaged that the weapon fit of a ship is to be altered or enhanced during its life, then margins of weight, stability, strength, space and services will be needed. The provision of space margins is very difficult since the additional space will usually be required in a particular location. Attempts in the past to allocate specific space for growth have usually failed either because the space was occupied at an early stage or because it was not where the requirement developed. The provision of extra space adds to cost but with rigorous control during design and building a margin can be preserved as an investment for the future.

Zoning

It seems convenient and cheap to arrange centralized power supplies, data systems, etc., and for individual weapon systems to draw their requirement from a single distribution main. Such an arrangement is very vulnerable to damage and involves a complicated distribution system which may impose a high maintenance load. Zoning is the opposite of such a dispersed style of design and is characterized by the grouping together of the essential elements of a function[9]. Such a function can range from the straightforward damage control concept with zones which are autonomous in preventing spread of flood, fire and smoke; or the function can be extended to the operation of a complete weapon system, comprising sensors, control, magazines and launcher, together with ancillary services and a prime power source. The autonomy of a zone will be further enhanced if the crew who will fight there also live there with sleeping, eating and sanitary spaces, although in practice cost and convenience in peacetime operation will preclude such total independence. Even if living spaces cannot be fully zoned there may be a case for splitting accommodation of each grade into forward and after areas to reduce the risk of losing all of a key grade from one hit and to minimize the movements involved in going to action stations as was done in ships designed during the Second World War.

It will not usually be practicable within a realistic budget to duplicate primary supplies within each zone and hence cross-connections to adjacent zones will be needed as an alternative in the event of breakdown or damage or during maintenance. The advent of distributed processing and data highways incorporating multiple redundancy makes the possibility of zoning of major weapons systems more realistic than hitherto. This is particularly so for an ASW ship where the two main sensors (the bow and towed arrays) are separated by a ship's length. (It is assumed that, whilst these sensors are complementary, the existence of only one would permit some capability, albeit degraded).

The principal benefit of zoning is seen as being improved survivability of the main ship functions. Since it will inevitably lead to some duplication, an increase in ship size and cost may be expected. However, the greater ease of outfit due to shorter and simpler system runs may offset this to a significant extent. The extent to which a cost increment is justifiable to improve the survivability of a ship and its operational capability after a hit is a very complex question which will be influenced by the 'value' of the ship (in operational as well as financial terms) and by its self-defence capability.

The concepts of duplication and separation are necessary adjuncts to zoning. These are means by which facilities that cannot be provided locally are duplicated and the duplicated sources separated to as great an extent as possible.

Layout—Level 1

During the earliest phase of design only first order estimates of ship size, form and cost are required. Hence for sizing purposes, space demands based on historical data will very often be adequate. An early decision is on the number of decks and the size of the superstructure. For frigates as understood in the R.N. it is likely that there will be one deck height above the machinery spaces; more would lead to an unworkable upper deck layout, and wasted space for uptakes, etc.; less would lead to structural and access problems. However, a long, structurally effective superstructure (e.g. Type 22) must be a possibility. To minimize both windage and radar cross-section a very small superstructure is preferred (TABLE II lists spaces which are seen as necessarily located above the upper deck). Since beam is controlled within fine limits by stability and rolling considerations, length becomes the only free variable.

TABLE II—*Spaces which must go in the superstructure*

	Area m²
02 Deck	
Bridge	45
Tracker office (ADMS)	36
Chart House	9
Navigator's cabin	9
Scot office	8
Flag locker	6
01 Deck	
CO's Suite	40
Radar office	25
ESM office	20
Tracker office	30
1 Deck	
NBC Cleansing Station	16
Lobby	20
Battery Charging	8
Upper Deck store	8
Hangar	175
Uptakes & Downtakes (at 1 Deck)	65

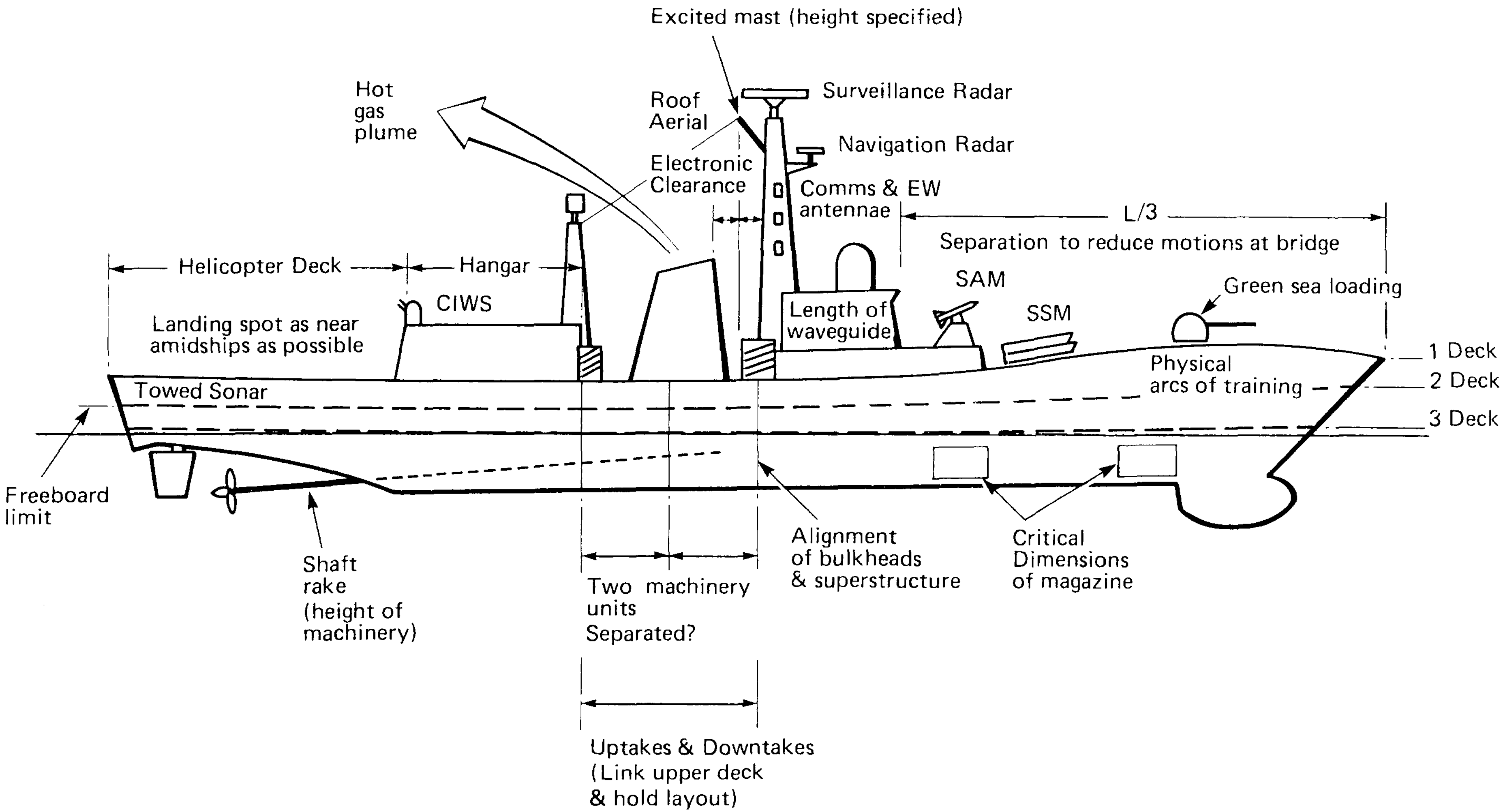

FIG. 5—SOME CRITICAL DIMENSIONS AND SEPARATIONS. ONLY THOSE AFFECTING LAYOUT ARE SHOWN

Minimum length will then be set by upper deck layout (Fig. 5), particularly the helicopter deck and hangar arrangements. The impact of the machinery uptakes and downtakes (particularly significant for gas turbines) and the need for structural continuity couples the upper deck configuration to the position and length of the main machinery spaces. The machinery blocks by themselves represent a major space demand and moreover cannot be represented as a simple volume demand since the width and depth of the spaces will normally be determined by the overall ship dimensions. For these reasons the overall configuration of the main machinery spaces (represented as position, block length or lengths and number of decks over) must also be considered. The line of shaft may have a major design impact.

During this first stage it is important that a large number of options is considered, exploring different upper deck and machinery type and block configuration as the only means of deriving assurance that an optimum arrangement has been achieved. At the end of this stage, it should be possible to reject most of these options 'by inspection' and to carry three or four through to the more detailed investigation of the next stage.

The main aspects affecting layout, for consideration at this level, are as follows, in a suggested order of priority for an ASW frigate:

(*a*) Number of decks.

(*b*) Superstructure size and arrangements.

(*c*) Arrangement of flight deck and hangar for greatest operational effectiveness.

(*d*) Siting of machinery, including vulnerability considerations.

(*e*) Communications and radar fit including electro-magnetic compatibility and RADHAZ[10].

(*f*) Arcs of fire for weapons.

Other aspects which, though of somewhat lesser importance, must still be considered include:

(*a*) Access along the decks and into the ship.

(*b*) Machinery removal routes.

(*c*) Replenishment at sea (RAS) arrangements.

(*d*) Ship handling equipment—winches, bollards, etc.

Helicopter Deck

The helicopter is the main armament of an ASW frigate and its requirements for operation in all weathers must be given priority. Helicopter operation must be treated as a total system with consideration not only of take off and landing but also of maintenance, preparation, manoeuvring on deck, spreading rotors, refuelling and re-arming[11].

Such considerations will lead to requirements for:

(*a*) Space in the hangar and a deck free of obstruction.

(*b*) Limits on perceived motion, both lateral accelerations which affect re-arming, etc., and vertical velocity and roll angle which limit flying.

(*c*) Wind velocity and turbulence (with implications for superstructure design).

There is no point in improving one aspect if the total operation is dominated by a different limit.

Lloyd and Hanson[11] have shown that the total operation in a conventional frigate is likely to be dominated by ship motions and that, other things being equal, there is a significant gain in operability if the landing spot is moved towards amidships, a point also made by Barrett[12]. Such an arrangement is not easily met within the constraints of a small frigate. Obstructions behind the landing spot are understandably unwelcome; a deck at high level seems to imply a lift and hangar below which would be expensive and might lead to reliability problems. A possible alternative is sketched in FIG. 6 in which the landing deck is sponsoned to port and a narrow island superstructure to starboard carries sensors, an after weapon system, and the winch for a towed sonar. Ship handling gear, bollards and fairleads, are arranged on a small step below flight deck level.

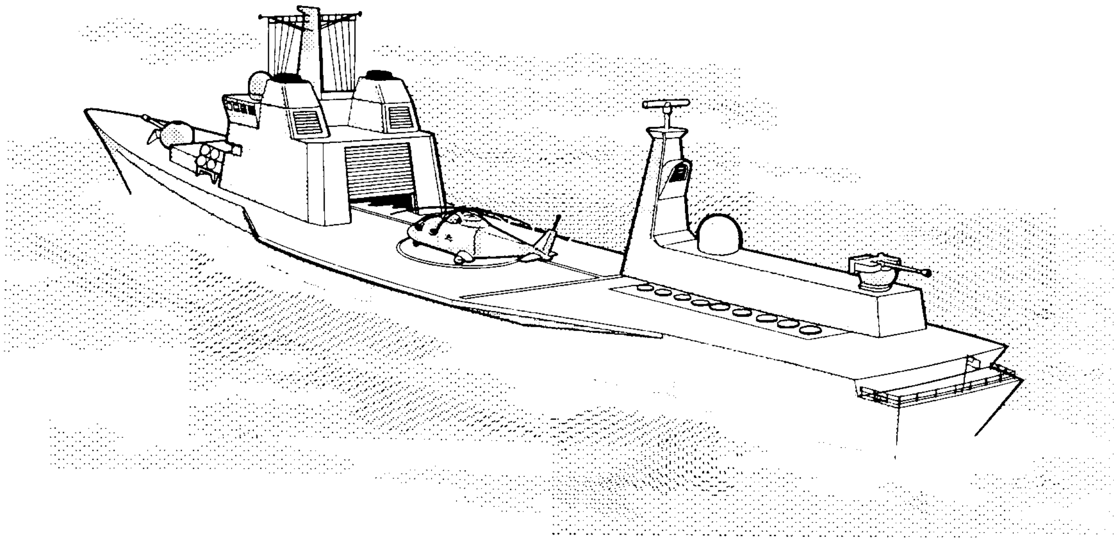

FIG. 6—A POSSIBLE FRIGATE LAYOUT WITH THE HELICOPTER DECK SPONSONED TO PORT AND THE AFTER SUPERSTRUCTURE ON AN ISLAND TO STARBOARD

Studies done for MOD by British Maritime Technology (BMT), have shown that to minimize wind turbulence over the flight deck, superstructures forward should be symmetrical and narrow, 'clean' of minor projections and with after edges rounded. The deck edge should also be rounded; mast and funnels should be small and rounded. Ideally the landing deck should have an air gap of 3 metres below it—unlikely to be achievable in a frigate.

Machinery

The interaction between upper deck layout and machinery layout is primarily governed by the size and arrangement of uptakes. In turn, uptake position depends on decisions on machinery unit arrangement. Grouping the propulsion and auxiliary machinery into units, each of which can drive the ship when the other is out of action can reduce considerably the probability of mobility being lost from a single hit. This probability is further reduced if the machinery units are separated.

TABLE III—*Propulsion machinery arrangement v. vulnerability*

Number of Compartments	*Arrangement*	*Number of independent units*	*Probability of losing mobility from one hit* %
2	ER, BR	1	50
2	ER, BR	2	25
2	ER, -*, ER	2	10

ER = engine room; BR = boiler room; -* = another compartment between

TABLE III indicates the advantage in separating machinery into units, itself a form of zoning. The figures given are illustrative only, since the numerical values depend very much on detail layout of the ship and the capability of the weapon.

Electric drive, with multiple widely spaced prime movers can further reduce the chance of losing mobility. Separation of machinery units will demand at least two funnels with a major impact on upper deck layout. Such an arrangement would seem consistent with a midship flight deck. Siting prime movers high up reduces the space lost in uptakes.

Shaft rake and critical machinery dimensions (e.g. gear box size) may pose overriding limits on the position of machinery units.

Layout—Level 2

At Level 1, the 'needs' are all too obvious. At Level 2 a more formal, but still simple analysis is desirable before commencing layout. A simple form of association matrix and quasi-static circulation diagram, discussed in the next section, may be an appropriate starting point.

The scope for variation is diminishing rapidly at this stage and decisions taken previously may need to be reconsidered. The overall approach remains a hierarchical one in which main blocks of spaces are positioned, possibly with alternatives, and successively smaller or less important spaces sited in the remaining areas. The requirements and ordering will vary from class to class; for an ASW ship, the following may be thought as appropriate. The analysis methods discussed later can be used together with subjective judgement, to attach figures of merit to different options.

Access

Good access both on and below the weather deck, is required for the movement of men, particularly from cruising to defence stations, for embarking stores and their transfer to users, and for services. Particular attention must be paid to reducing the time needed for RAS, since during this operation the ship is virtually out of action. The main horizontal access will be on 2 deck with vertical routes up and down in each main watertight section. (Unobstructed fore and aft access on the upper deck is also highly desirable). Various options exist for the access routes on 2 deck, either one or two passages, sided or near the centreline. Points to consider in selecting any one arrangement include the following:

(*a*) If services are run through sided passageways they are vulnerable to small arms fire and splinters unless protected. On the other hand, such passages offer some protection from splinters and blast to spaces inside and duplicated services are most widely separated if at the sides. For damage extending over more than half the beam and for protection against penetrating missiles, sided passages have an advantage. The use of sided passages makes it easier to close one for maintenance work.

(*b*) Hatches for vertical access are likely to be adjacent to passages and, for structural continuity it is desirable that these hatches lie within the line of machinery uptakes and downtakes. (FIG. 7). This condition is not easily satisfied with sided passages and care will be needed to avoid structural problems leading to early fatigue cracking.

(*c*) Passages near the dining halls and canteen are likely to be obstructed by queues. Either a second passage or at least an extra wide one is needed. Similarly, movement to action stations can be eased with two passages in which one-way traffic can be enforced.

(*d*) Storing routes—RAS point to storeroom and storeroom to galley and to magazines—need special consideration.

(*e*) Main and auxiliary machinery spaces will often require large shipping openings. Complicated compartments, which would need a lot of stripping out, should not be arranged in way of such openings.

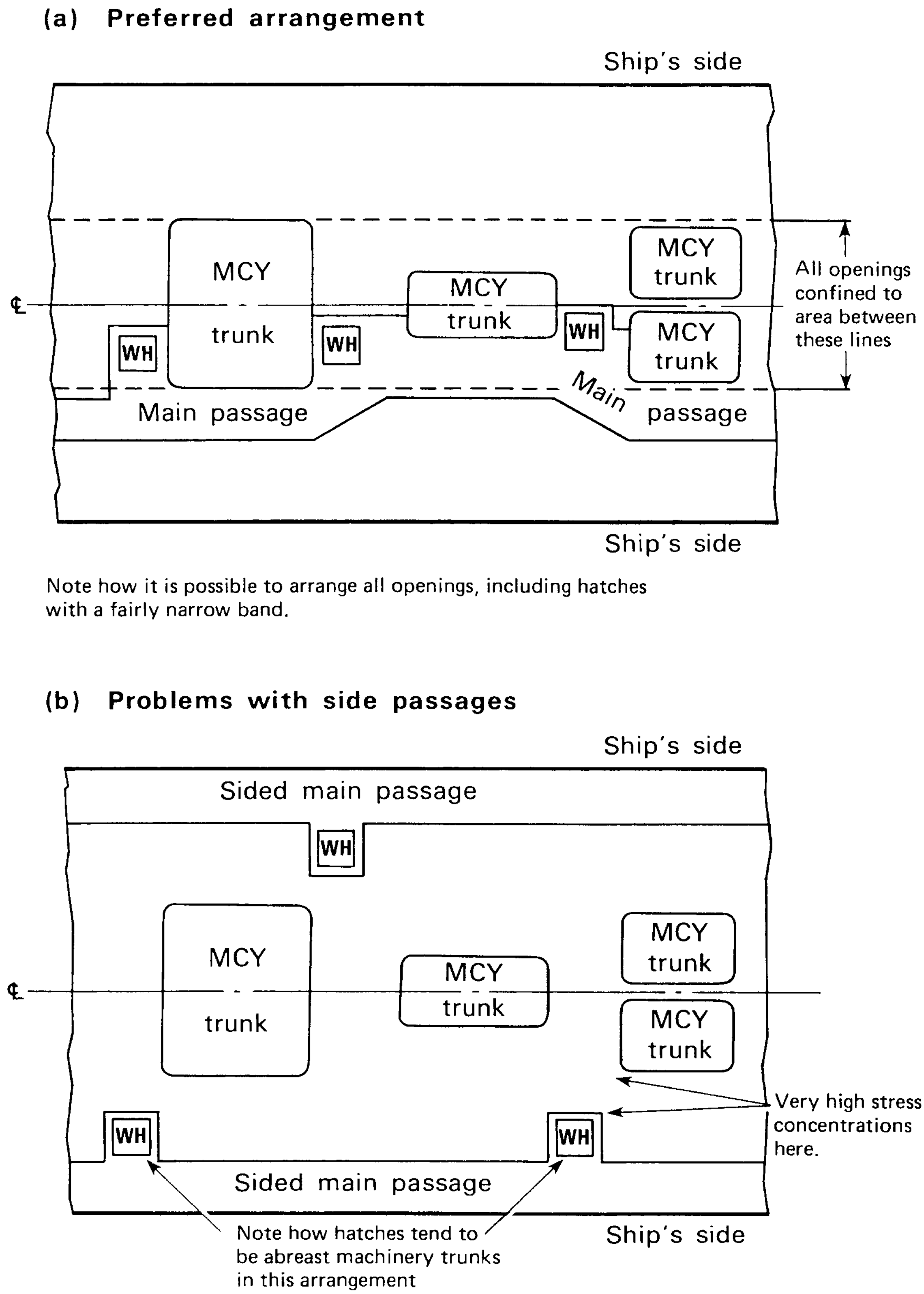

FIG. 7—ARRANGEMENT OF OPENINGS IN DECKS

TABLE IV—*Access Space*

Deck	*Area of passages, hatches, etc.* % of total
Superstructure	10
1 deck (internal)	15
2 deck	20–25
Lower decks	5

The space devoted to access in a frigate is considerable, (TABLE IV), particularly in the most desirable areas, and it is worthwhile to make considerable efforts to reduce the *requirement*. Compartments should be sited to minimize the length of passage which should, however, be generous in width.

Operations Room Complex

These are large spaces (see TABLE I) with a big crew and are not easy to locate. If close to the bridge the length of wave-guides and cables will be reduced and the command task eased. On the other hand, vulnerability, particularly from small arms and splinters, is reduced if these spaces are below the waterline. It will be necessary to arrange some of the electronic warfare compartments high up to reduce the length of wave-guides from sensor to set. The operations room is absolutely critical to the fighting capability and up till now it has not been possible to duplicate such a space within the cost and space budgets of a frigate. The reduction in the size of electronic units, distributed processing and multiplexing offer a real prospect of improving the chances of survival of the ship's brain in the next generation.

Magazines

A magazine explosion can sink a ship and it is desirable to protect them by placing them below the waterline. Conversely, it is desirable to stow as many weapons close to the launcher as possible and, in the case of vertically launched missile systems, all will be high in the ship. Where such stowages are essential, ballistic protection may be needed together with a fire suppression system.

Fuel Tanks

Fuel, being liquid, may be stowed in tanks of awkward shape which cannot be used for other purposes. However, there are many constraints which affect their position and it is likely that deep tanks, adjacent to the machinery block will be preferred. Alternatives, with their advantages and disadvantages, are discussed below.

Double Bottom Tanks under the machinery were usually used in the larger ships of yesteryear. This arrangement gives a very short run of services to the machinery, a smooth, easily maintained machinery space bilge and a slight degree of protection.

On the other hand, the geometry implies that the weight of the machinery is raised and, as fuel is consumed, the centre of gravity of the ship will rise further. Almost certainly, water displacement (or ballasting), will be needed which, in turn, means high duty painting of the tanks. Shallow double bottom tanks, with much internal structure are difficult (expensive) to preserve. In general, double bottom tanks are not likely to be a satisfactory solution for a frigate though there may be appropriate cases.

The crown of *deep tanks* should be fairly low (below the waterline if possible) giving some protection to the fuel from missiles and helping fire fighting in that a foam blanket can be produced over the tanks. Gravity feed tanks should not be employed.

Tanks should be close to the machinery, avoiding long pipe runs on both cost and vulnerability grounds. This implies tanks fore and aft, or between, machinery units in a prime site which could be used for other purposes. A compromise in which some fuel is displaced to the awkward spaces at the ends of the ship is worth consideration.

Galley and Dining Halls, etc.

These are large spaces which should be adjacent to each other and require good access to cold and cool rooms, dry provision stores etc. Good access for people with adequate queueing space is needed, as it is for the canteen. The space needed is a direct function of the number in the crew (TABLE V).

The crew cannot operate for long without food and each zone requires some provision for hot drinks and, if possible, hot food. It may be advantageous to provide a separate wardroom galley to act as an emergency cooking place after damage. Dining spaces should be sited in areas of low vertical acceleration to minimize nausea. Fortuitously, this suggests a space over the engine rooms where the fairly high noise levels can be accepted.

TABLE V—*Space requirements for Galley and Dining Hall (current practice)*

Space	*Area* m^2
Galley	0.31 × complement
SR Dining Hall	0.43 × senior rates
JR Dining Hall	0.32 × junior rates
Wardroom & ante-room	2.6 × officers

Numerical Techniques

These techniques can be grouped under two main headings, those which attempt to quantify the 'need' and those which analyse the performance of a stated function.

The Need

The simplest starting point is the Association Matrix. In this the designer will indicate the level of importance of the association between compartments or activity groups using a numerical scale. A typical matrix for a frigate is shown in TABLE VI.

Such a matrix will still be based on subjective assignment of values, but by breaking down into elements the nature of the problem can be better understood. It is possible to use the matrix directly to:

(*a*) Position the compartment(s) with the highest external association with other compartments and which have a clearly defined overall position.

(*b*) Locate the compartment with the highest association with that already positioned.

(*c*) Continue in order of association scores.

This simple approach has obvious limitations, one of which is that the significance of distance is not quantified. A more fundamental problem is that described in FIG. 3—peace/war, sea/harbour. The association will differ in each of the four cases. It is also difficult to balance a minor association in the primary role (ASW) against a more important association in a secondary role.

More refined approaches to association are given by Andrews[3]; the circles of influence are particularly useful for expressing indeterminate relationships, whilst different networks can be used to quantify several parameters. A network based on length may well be the best starting point for sizing a frigate.

TABLE VI—*Association matrix—a specific score of frigate compartment adjacencies*

		Galley	JR	SR	Offices	Workshops	Officers	Bridge	Ops	MCO	Radar	EW 1	CO/NO	Fwd Wpns	Hangar	Fwd Stores	Aft Stores	SCC/NBCD	NBCD Fwd	NBCD Aft	Machinery
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Galley + Dining Hall	1		4	4	3	1	3	2	3	3	2	2	3	2	2	1	1	3	2	2	3
JR Accommodation	2	H		2	2	2	2	2	3	3	3	3	2	3	3	3	3	3	2	2	3
SR Accommodation	3	H	A		3	2	2	3	3	3	3	3	2	2	2	2	2	3	2	2	3
Offices	4	L	L	A		3	3	2	2	2	2	2	3	1	1	4	4	3	1	1	3
Workshops	5	L	L	H	A		2	1	3	4	4	4	2	4	3	2	1	3	1	1	4
Officers' Accommodation	6	L	L	L	A	L		4	4	4	2	2	3	2	2	1	1	3	2	2	3
Bridge	7	L	L	L	L	L	H		4	4	4	3	4	2	2	1	1	3	2	2	2
Ops Room	8	L	A	A	L	L	H	A		5	4	4	4	2	3	1	1	4	3	2	2
MCO	9	L	L	L	L	A	H	A	H		2	3	3	2	3	2	1	4	2	2	2
Radar Offices	10	L	A	L	L	H	L	A	H	A		3	2	2	2	2	1	3	2	2	1
EW Offices	11	L	A	A	A	A	L	L	H	H	A		2	2	3	3	1	2	2	2	1
CO and NO Accom	12	L	VL	VL	H	L	H	A	H	H	L	L		2	3	1	1	2	2	1	2
Fwd Weapons	13	L	A	A	A	L	L	L	L	L	L	L	L		2	3	1	2	3	1	1
Hangar & FD etc	14	L	L	L	VL	A	L	L	A	A	L	L	L	L		2	4	2	1	3	1
Fwd Stores	15	VL	VL	H	A	A	L	L	L	A	A	A	L	A	A		1	2	2	1	2
Aft Stores	16	H	L	L	L	A	L	L	L	L	L	L	VL	VL	A	VL		2	2	3	3
SCC/NBCD HQ	17	H	L	H	A	A	A	A	A	A	L	L	L	L	L	VL	VL		3	3	4
NBCD Post Fwd	18	L	L	L	L	L	L	L	A	A	L	L	L	A	L	A	VL	A		2	2
NBCD Post Aft	19	A	L	L	L	L	L	A	A	A	L	L	L	L	A	VL	A	A	L		4
Machinery Spaces	20	L	L	A	L	A	A	A	L	VL	VL	VL	VL	VL	VL	VL	A	H	L	L	

The lower left-hand half of the matrix shows the designer's aim as high, medium (A), low or very low; whilst the opposite half gives the numerical score when the specific layout is marked for achievement.

In the earliest stages (Level 1), the associations are so simple that formal disciplines are unnecessary. Level 2, the arrangement of major blocks, is sufficiently complicated to justify a quantified approach whilst Level 3 may be too complicated.

Once a tentative layout is produced and, even more, when two competing layouts are available, it becomes important to quantify the relative advantages and disadvantages even if only on a subjective basis.

The most important 'flow' activity is replenishment at sea (RAS). During this operation the frigate is off station and vulnerable and the time required must be minimized. A clear RAS area with good routes to store rooms etc. is important. Philosophically, the problem is a simple one even though there may be problems in a real ship. A secondary requirement is that there should

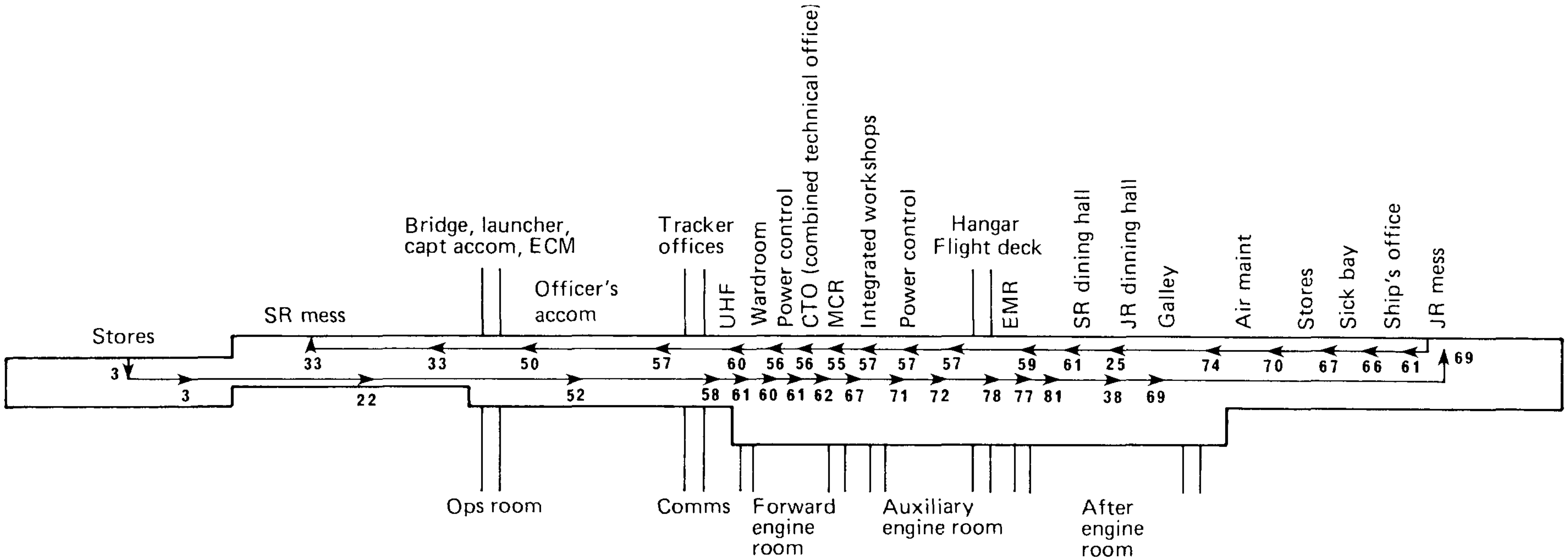

FIG. 8—PERSONNEL FLOW FOR A CHANGE OF WATCH IN CRUISE CONDITION

be quick and easy access from the store rooms to the point at which the stores are used, e.g. provisions to galley.

Another evolution worth numerical consideration is the movement of the crew from cruising watch to action stations.

At such a moment, when attacks may be imminent, all doors and hatches are opened for access. Obviously time is vital. A simple personnel flow analysis is a useful first step in which numbers of man movements are recorded on a line diagram (FIG. 8). This will be a first step to sizing passages, access routes, etc. Given two or more tentative solutions a full circulation analysis can be performed. In a large ship, or if the problem appears difficult, a dynamic simulation of the movements can be used.

A regular activity worth study is queueing for service in the dining hall. A simple flow chart may be adequate but queueing theory can be used if the problem is difficult. Some thought is needed should the ship have to go to action stations during a mealtime. Use of washplaces before breakfast is another difficult activity.

Vulnerability Assessments

The details of vulnerability assessment fall outside the scope of this article but it is clear that vulnerability considerations will have a major impact on layout. Computer-based systems exist which, given details of a ship and missile performance, can predict the point at which the explosion will take place and the damage area due to blast, splinters and flooding. Spread of fire is being added to such systems. Such a program can be used in single shot mode to study areas which are considered, by inspection, to be unduly vulnerable and changes made to layout. Used in random mode (Monte Carlo), overall assessments of ship's vulnerability can be made. Confidence in such systems is growing but, perhaps, the most useful outcome is to make clear to the user the extent of his own prejudices.

The conventional damage stability/floodable length calculation is a simple and, within its limits, reliable form of vulnerability assessment. Such calculations are essential in studying the number and location of watertight bulkheads and the effect of moving them to improve layout.

Layout—Level 3

The remaining spaces are less demanding in that many, such as messes, bathrooms, offices etc. can be broken down into smaller units if necessary. Mess decks are less flexible than of old since bunks have size and shape whereas hammocks could be regarded as compressible.

TABLE VII—*Preferred location of spaces*

Space	*Area* m^2	*Deck*		*Longitudinal*	
		preferred	*alternative*	*preferred*	*alternative*
Ship's Office	12	2	1, 3	amidships	forward
Engineers Office	15	2	1, 3	amidships	aft

A suitable starting point is a matrix such as TABLE VII in which each space is listed together with its required area and a preferred location and acceptable alternatives.

Such a matrix can be used, together with the association matrix, to locate the remaining spaces. All too often, the less important compartments will have inadequate positions.

Production Considerations

Whilst Level 1 and many Level 2 decisions should have little effect on ease of production, it is clear that advanced outfitting methods must be fully considered at Level 3. A partnership between designer and builder is essential at this stage. Detailed consideration of the aspect is outside the scope of this article but a useful reference is that by Easton[13].

The designer can help to reduce production costs by minimizing the length of services and, in particular, by reducing the number of bulkhead penetrations, an aim consistent with zoning philosophy.

The Way Ahead

It is all too easy to assume that computer-aided design, followed by expert systems will solve layout problems. However, until it is possible to weight numerically the critical and conflicting operational requirements in peace and war, there is little prospect of obtaining valid figures of merit.

What can be hoped for is that computer generated and displayed solutions to specific problems may illuminate the nature of the more general problem. There seems little doubt that 'walk through' graphics will make layout more comprehensible to those unfamiliar with drawings and also assist the naval architect.

In these days structural and hydrodynamic considerations rarely dominate a frigate design and it may be that layout should be the starting point of the design, adjusted later to meet engineering essentials.

Reduced manning may reduce the magnitude of the problem whilst making it more important that an optimum solution is found.

The true figure of merit is cost and a form of design accounting in which an imputed rent is charged, increasing with the 'desirability' of the site, may be worth pursuing. The difficulties are great but if they can be overcome a true minimum cost solution becomes an achievable target.

Conclusions

The layout of a warship is an exceptionally difficult 'wicked problem' in that the way the ship is worked differs so much from time to time. Furthermore, layout is constrained by many other aspects of the ship.

Further study on the nature of the problem is needed. Computer-aided architecture is best seen as an aid to understanding the problem rather than as a tool for solution.

Those who go to sea are clear that some ships are better laid out than others. The naval architect should bear this in mind and rise to the challenge.

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References

1. Andrews, D. J.: Creative ship design; *Trans. Royal Institution of Naval Architects*, vol. 123, 1981, pp. 447-471.
2. Brown, D. K.: Defining a warship; *Naval Engineers Journal*, vol. 98, no. 2, March 1986, pp. 31-40.
3. Andrews, D. J.: An integrated approach to ship synthesis; *Trans. Royal Institution of Naval Architects*, vol. 127, 1985, pp. 73-102.

4. Ware, H. P.: Habitability in surface warships; *Trans. Royal Institution of Naval Architects*, vol. 128, to be published.
5. Donnelly, K.: Aesthetics in warship design; *The Naval Architect*, June 1985, pp. E282–285.
6. Anon.: MEKO frigates; *Defence*, vol. 12, no. 11, Nov. 1981, pp. 753–757.
7. Broome, W. B., Nelson, D. W., and Tootle, W. D.: The design of variable pay load ships; *Naval Engineers Journal*, vol. 94, no. 2, April 1982, pp. 147–178.
8. Gates, P. J.: Cellularity—an advanced weapon electronic integration technique; *Trans. Royal Institution of Naval Architects*, vol. 127, 1985, pp. 105–120.
9. Akhurst, R.: Hull subdivision in surface warships; *Journal of Naval Engineering*, vol. 30, no. 1, Dec. 1986, pp. 58-64.
10. Gates, P. J., and Rusling, S. C.: The impact of weapon electronics on modern warship design; *Trans. Royal Institution of Naval Architects*, vol. 124, 1982, pp. 341-355.
11. Lloyd, A. R. J. M., and Hanson, P. J.: The operational effectiveness of the shipborne naval helicopter; *Air Threat at Sea Symposium, Royal Institution of Naval Architects, 1985*.
12. Barrett, M.: Discussion, pp. 42-43 in Bryson, L.: The procurement of a warship; *Trans. Royal Institution of Naval Architects*, vol. 126, 1984, pp. 21-51.
13. Easton, R. W. S.: Modern warships, design & construction; *Trans. Institute of Marine Engineers*, vol. 96, 1984, paper 53.