

# STATE OF THE ART REPORT

## DESIGN FOR LAYOUT

David Andrews<sup>1</sup>, Etienne Duchateau<sup>2</sup>, Justin Gillespe<sup>3</sup>, Hans Hopman<sup>7</sup>, Richard Pawling<sup>6</sup>, David Singer<sup>8</sup>

### 1. INTRODUCTION

This is a new section under “Design for X” State of Art reports; however some of the background has been addressed in previous IMDC SoA reports particularly those addressing Design Methodology (Andrews et al 1997, 2006, 2009). Given that there is a new initiative underway that is combining research in three major marine design centres it was considered worthwhile both taking stock of the State of the Art in ship layout design particularly in regard to initial or preliminary ship design, where the new initiative is directed.

This section of this Design for X report commences with two review sections, firstly on preliminary ship design process and why it can benefit from an architecturally based approach, and secondly, a review of ship design approaches and research on layout methods applied to various ship types. This then provides a basis for the three current research programmes, now being brought together under a project funded by the US Navy Office of Naval Research (ONR). The separate research activities into ship architecture and layout undertaken to date by the three universities of University of Michigan (UMich), University College London (UCL) and Technical University Delft (TUDelft) are then described in order to appreciate how these might be developed to improve the preliminary design of future naval vessels by incorporating layout design early in the ship design process.

### 2. PRELIMINARY SHIP DESIGN

#### 2.1 The Preliminary Ship Design Context

It might seem there have been a lot of papers on preliminary ship design, however generally they are either describing a specific ship design or talking in general about different ways in which ships may be designed. In the former case, especially when the design may only have been completed at that stage to a preliminary design or concept level, then it is usually just the final design outcome, rather than a detailed step-by-step description of the evolution of the design, for which a level of technical description is provided (Eddison & Summers 1995, Eddison & Groom 1997). If the description is of a completed design for a built ship then some detail of the early evolution is usually provided, as this is crucial and records major design choices, but these details are not sufficiently comprehensive to understand how the preliminary design itself evolved. (See for example Honnor & Andrews (1982) for the Royal Navy’s INVINCIBLE Class, Bryson (1984) for R.N. Type 23 Frigate and Leopold & Reuter (1971) for the U.S. Navy SPURANCE and TAIWAN Classes.) When it comes to generic expositions on ship design, if covering the whole ship design process, insufficient detail is provided to outline the preliminary steps beyond, at best, a few technical examples of the concept design effort (Gale (2003), Ferreiro & Stonehouse (1994)).

Most discussion of ship design in general and preliminary design in particular has focused on what might be considered to be design managerial, organisational and process perspectives. An example of this is Andrews’ (1994) paper on preliminary warship design, which spelt out the stages in preliminary design that had been adopted by the UK Ministry of Defence’s Future Projects Design Group that he headed up in the early 1990s. In particular it laid down a graduated process, appropriate to a major new warship concept, with three overlapping stages within the overall concept phase. Example projects that were being addressed were the next escort (which subsequently became the R.N. Future Surface Combatant (Andrews 2000)) and the Future Carrier (CVF) (Eddison & Groom 1997), both of which were commencing concept consideration at that time. The three stages were denoted as:

- Concept exploration;
- Concept studies;
- Concept design.

Each stage had a distinct objective in ensuring by the end of the overall concept phase, what the UK MoD now denotes as Initial Gate (MoD 1999), that a comprehensive exploration of the solution space, a comprehensive study of the main parameters and style issues, and a comprehensive investigated trade off study have been preformed. This approach was intended to result in a single preferred option, which matched the emergent (and affordable) operational requirements and was the basis for proceeding into Feasibility (now designated Assessment by UK MoD (MoD 1999)), This exposition

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<sup>1</sup>Design Research Centre, Department of Mechanical Engineering, University College London, UK

<sup>2</sup> Department of Marine Transport and Technology, Delft University of Technology, The Netherlands

<sup>3</sup> Department of Naval Architecture and Marine Engineering, University of Michigan, USA

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was done with design examples but not showing the intermediate steps to each of those concept designs, described in the Andrews & Pawling (2008) paper.

Two earlier papers by Andrews (1986, 1987) described the overall and the preliminary ship design process as part of that author's particular approach to ship design that culminated in the general exposition of his "Architectural" approach to ship design in (Andrews 2003a). Several examples of applying this approach to preliminary design tasks, for actual "real world" design investigations, are summarised in Andrews & Pawling (2006) and these outputs can be compared to purely academic exercises using the approach, such as those early cases described in Andrews (1986, 1987).

It has been acknowledged, by many eminent practitioners, that PSD is a complex process (see Turner 1994, Graham 1982, Rydill 2003). Andrews (1998) at Table 4 in that paper distinguished between a range of types of ship design in terms of their degree of novelty, from a stretch version of an existing design to the extreme of a radically new technology, typified by the U.S. Navy's 1970s 3KSES combatant (Lavis et al 1990). Neither the least or the most novel of this design spectrum would be appropriate examples on which to base consideration of the PSD process, nor, indeed, would the type ship or evolutionary design approaches, since they are heavily constrained by the specific designs they draw upon. We are thus left with essentially new or *ab initio* designs, which might be designs conventionally produced by the methods discussed below, or designs produced by such as the "architecturally integrated approach" (see (Andrews 2003a) and (Andrews & Pawling 2006) and outlined further in the later parts of this section on Design for Layout.

It is taken as axiomatic that the main motivation for preliminary ship design should be the elucidation of the initial requirement perception of the operational or naval staff and to thus inform that dialogue between the naval staff and the concept designer with a trade off process that balances the operational needs with what is perceived to be affordable (Andrews 2003b). Thus presentation of case studies, such as that in Andrews & Pawling (2008), is primarily to provide a detailed sequencing of the technical evolution of what would (probably) be just one option among several. In that instance a trimaran solution to a U.S. Littoral Combatant Ship requirement was the example chosen. Furthermore any requirement for a new ship concept would be far less clear at design commencement than this specific case, with the eventual "preferred option" at Initial Gate usually emerging from a difficult and often protracted trade off exercise, where affordability looms large. So the lack of the "requirement elucidation" element in this 2008 case study had the advantage of not complicating the main objective of that paper in presenting a technical case study showing a preliminary ship design evolution. With this proviso it is now appropriate to briefly review the general process of preliminary design.

## 2.2 The Preliminary Ship Design Process

Given the overriding importance of the initial ship design process in creating a new ship design by setting the "skeleton" on which the subsequent design is built, it can be considered surprising that there has been little direct discussion, over the years, on the specifically technical nature of that process. This is considered to be due, at least in part, to the fact that the vast majority of ships are evolved directly from specific previous designs. However, it is also in part due to the sensitivity of individual preliminary design organisations in not revealing the commercial or security aspects of their "Intellectual Property". The clearest exposition on the preliminary design of mercantile ships is that by Watson & Gilfillin (1977), now more than 30 years old. Perhaps the nearest equivalent from the naval ship design field is, surprisingly, from the highly sensitive world of submarine design. This is the three page "submarine design procedure" presented by Burcher & Rydill (1990) in their classic text book on concepts in submarine design. Unlike Watson & Gilfillin this does not give specific algorithms, though much of the book provides the basis for populating the various steps in the sizing procedure. However neither of these submarine or mercantile expositions takes a particular example and shows its stepwise development through the initial design process, hence the intention behind Andrews & Pawling (2006) was to provide such a description.

Lest it be thought there have been few publications on the nature of preliminary ship design, attention is specifically directed to the first State of the Art Report on Design Methodology (Andrews et al 1997) which included sections on Preliminary Ship Design Methodology and on Naval Ships and Submarine Design Methodology. These two sections are considered, with their 33 and 64 references respectively, to provide a comprehensive review to that date of the literature in the field. An update on the mercantile and naval ship design methodology was provided in the 2006 IMDC SoA report on Design Methodology (Andrews et al 2006). A further "state of the art" overview was provided by Gale in Chapter 5 of "Ship Design and Construction" and which is entitled "Ship Design Process" (Gale 2003). However, like most of the publications reviewed in these IMDC State of Art reports, this focuses largely on procedures and issues related to the environment in which ship design is practiced, rather than specifically on the progressive technical steps.

The use of computers to undertake a range of design explorations has also been characterised by presentations of a general nature with usually one or two example design outputs from the end of the concept process, rather than detailed expositions of the technical process including specific intermediate design solutions, as is presented in Andrews & Pawling (2008). An early naval ship design example of the general type, somewhat akin to Watson & Gilfillan (1977), was due to Eames & Drummond (1977). There have also been examples of a range of comparative design studies being presented, notably by Garske & Kerr (1981) and Mistree et al (1990), which give insights into the nature of concept

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exploration through altering various input parameters. An early computer supported investigation by Andrews (1984) varied both inputs and hull form parameters and this has been greatly extended by more recent work at UCL by MacDonald et al (2004) and, specifically using genetic algorithms, by Vasudevan & Rusling (2007). What all these studies reveal is the nature of specific worked up and balanced design studies as options or variants in exploring, either specific requirement impacts (e.g. speed, margins, payload) or form or dimension choices, in terms of ship performance or affordability. What they do not specifically reveal is the manner in which a given design option is both chosen and then developed to a given level of definition through a set sequence of intermediate balanced design steps, as presented in Andrews & Pawling (2008).

Because so many real designs evolve in response to the dialogue with the requirements owner, the technical nature of the preliminary design development is often obscured, or at best the major design choices are recorded for posterity. Thus for example, Bryson (1984) shows three intermediate design studies in the case of the Type 23 Frigate evolution from a 100 m light frigate to the 123 m final medium sized frigate design. However, aside from the completed design, little in the way of detail is given for each intermediate study, apart from profile drawings. In this case of the Type 23, significantly more information is provided in a Ministry of Defence produced schedule history of the full process of that design's development from 1979 to 1983 in a four page bar chart, which has been reproduced in a UCL internal publication handed out to the Naval Architecture MSc Course students (Brown 1984). However even this comprehensive design history only records major design decisions and specific design related activities rather than comprehensive technical descriptions of the intermediate design steps.

The most comprehensive design evolution description provided in open literature on a US Navy design, at an equivalent level to this Type 23 design history, was provided by Leopold & Reuter (1971). This largely describes the specific separate design processes for the SPRUANCE Class Destroyers in terms of the general arrangement, envelope definition, subdivision (and stability), structural design and subsystem design to a level more appropriate to the UK definition of the Feasibility phase than just initial concept design. That is to say at a level that is normally required at the conclusion of preliminary design leading up to contract definition. Leopold and Reuter do show four alternative cut away profiles from what are said to be at least nine "alternative (configurational) concepts" that the Littons team examined. However, again no technical detail is given on these alternative design studies or, indeed, any earlier concept studies that led to these configurational design options from which the final design was developed.

Before Section 3 outlines the issue of ship layout in preliminary ship design, it is considered sensible to spell out, in a little more detail, the overall concept process in terms of three initial design stages listed at the beginning of this section. These were comprehensively presented in Andrews (1994) considering the preliminary design of warships:-

## a) Concept Exploration

This initial design phase can be said to comprise a wide ranging exploration, which starts at the initiation of investigations for a new ship design. It should be an extensive investigation of all possible options and typically include modernising existing ships, modifying existing designs and exploring the full range of, for example:

- (i) packaging of the primary function (e.g. aircraft, weapons or sensors for a combatant; cargo/passengers for auxiliaries or merchant ship equivalents);
- (ii) capability of the ship to deliver the functions (e.g. speed, endurance, standards);
- (iii) technology options to achieve the functions and capability (e.g. existing technologies, enhanced materials and systems, enhanced technological/ configurational options, reduced technology levels).

These explorations may well be cursory or may show the need to pursue several distinct options and may require research programmes or revisiting (not for the last time) the operational concept.

## b) Concept Studies

Assuming only one or two options are to be taken forward, the wide ranging but cursory nature of the initial exploratory stage is unlikely to have investigated in any depth the perceived design drivers and the impact of various choices on function, capability and technology. This stage is dependent on the type of vessel (i.e. combatant, aircraft carrier) and degree of novelty (e.g. conventional monohull, unconventional configuration), as well as a range of issues to be addressed from payload demands through speed and endurance to style issues, such as those associated with design life, signatures, survivability and complement standards. All these issues normally merit investigation before the design is too fixed. They can also significantly influence the downstream design but, more importantly, they need to be debated with the requirements owner, since their impact on the ship's performance and affordability should be part of the requirements elucidation dialogue before the form and style of the solution is too precisely fixed.

## c) Concept Design

This final stage prior to approval to commit to a more substantial design effort (i.e. in UK MoD terms, prior to Initial Gate decision) is primarily focused on the design (and costing) information necessary to ensure that the approval to proceed is based on sufficient information and the process beyond that approval can proceed coherently. Typically the

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stage is dominated by cost capability trade-off studies and the interaction with any associated operational analysis. It can be appreciated that to enter into this last concept stage with inadequate exploration of the solution space or of the style and performance issues, is unwise as any submission to proceed is likely to be vulnerable to probing by approval authorities of the decisions on such issues. This just emphasises the inherently “political” nature of naval ship acquisition at the front end of the process and why it is often protracted and seen to be unsuccessful and apparently costly, as is well addressed in US Navy organisational papers (such as Tibbitts & Keane (1995)).

Alongside the specific technical design development task in preliminary ship design is the political and process procedure. The wider procedural issues, which have been addressed in numerous generic papers (see Andrews (1994), Tibbitts and Keane (1995)) and indeed in papers on specific ship designs, should be seen together with the detailed technical design evolution, as they strongly interact.

## 2.3 The Need for the PSD Process to be Architectural

Betts (2000) in a keynote paper to the 2000 IMDC discussed, in terms of warship design, the needs for tools to be used in preliminary design. These were listed at Table 5.2 of Andrews (2003a) (and reproduced at Table 1) where Betts “Needs” are compared to a summary of the types of CAD tools available for Preliminary Warship Design.

**Table 1: A Listing of Betts (2000) Analysis of Preliminary Warship Design Tools Needs With the Current Range of Types of Tools Available (Andrews 2003a)**

Needs for Preliminary Warship Design Tools	Current Types of Preliminary Warship Design CAD Tools
1. Utilise data for assessment of performance, risk and Through Life cost.	1. Optimisation – black box, fuzzy methods, Genetic algorithms, neural networks.
2. Useable by knowledgeable design team.	2. Expert systems, knowledge based.
3. Deal comparably with conventional and unconventional ship concepts.	3. Decision Based Design and MCDM.
4. Provide reasonable (preliminary) solutions.	4. Configuration based, including Design Building Block approach.
5. Assist communications with design team and <u>all</u> stakeholders, especially those evolving the operational requirement.	5. Simulation Based Design and Virtual Prototyping.

In justifying the adoption of a configuration based approach (item 4 of Table 1) (Andrews 2003) went on to list the features required of a preliminary ship design approach. Thus these should provide:

- Believable solutions, i.e. solutions which are both technically balanced (Hyde & Andrews 1992) and sufficiently descriptive (Andrews & Pawling 2003);
- Coherent solutions, which mean that the dialogue with the customer should be more than merely a focus on numerical measures of performance and cost, by including a comprehensive visual representation.
- Open methods, in other words the opposite of a ‘black box’ or a rigid/mechanistic decision system, which means that the description is responsive to those issues that matter to the customer, or are capable of being elucidated from customer/user teams;
- Revelatory insights, in particular those identifying, early in the design process, likely design drivers to aid design exploration in initial design and beyond;
- A creative approach, not just as a “clear box” but actually encouraging “outside the envelope” radical solutions and a wide design exploration.

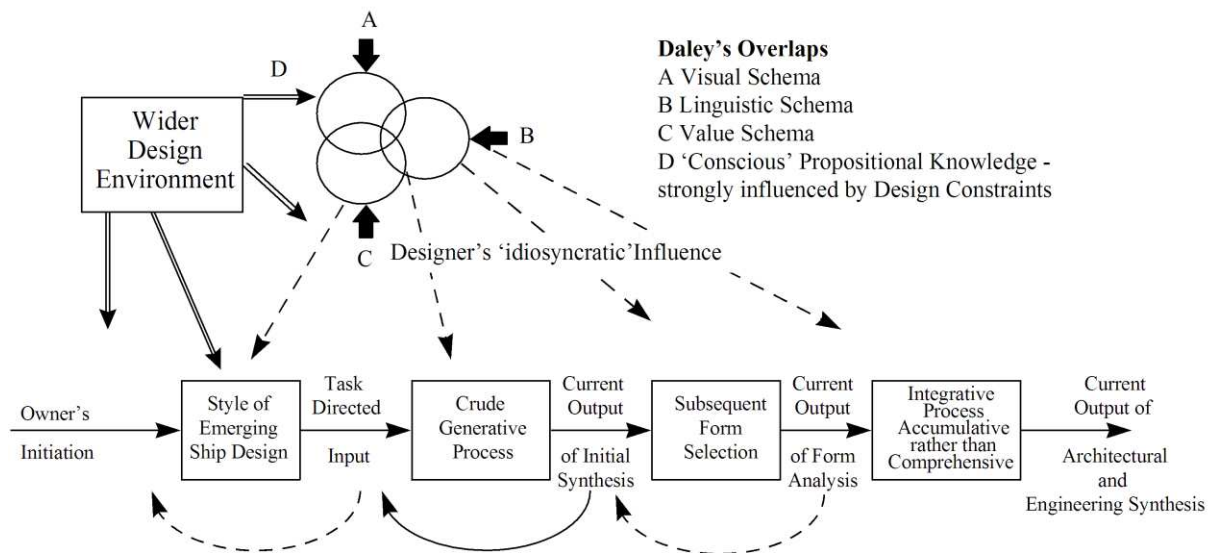
## 3. THE ARCHITECTURALLY BASED APPROACH TO SHIP DESCRIPTION

### 3.1 Motivation for an Architecturally Based Approach to Ship Description

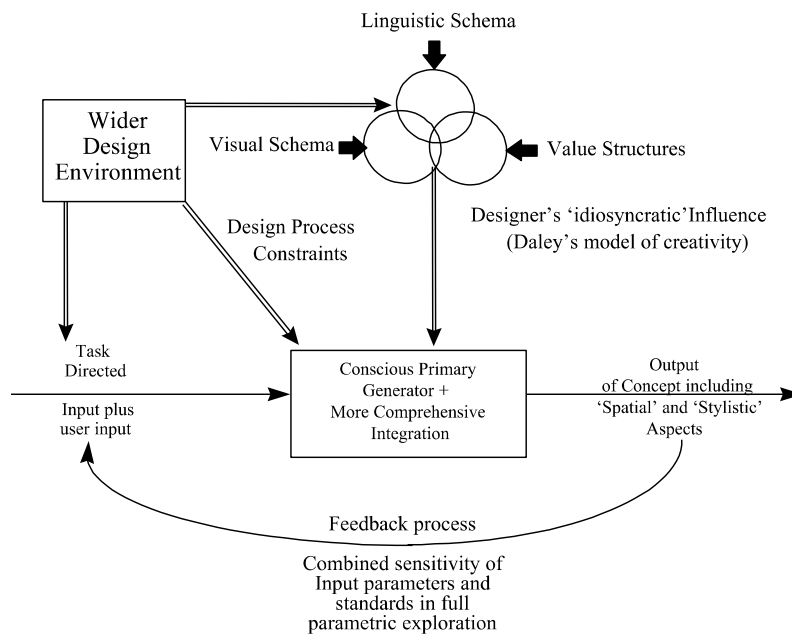
A 1980 paper entitled “Creative Ship Design” (Andrews 1980) concluded that creativity in ship design would be fostered by an approach to the initial ship synthesis which placed greater emphasis on the physical description of the ship's layout. A subsequent justification for, and initial demonstration of this approach to initial ship sizing was given in 'An Integrated Approach to Ship Synthesis' (Andrews 1986). That contrasted the sequential process of gross ship sizing, followed by hull parameter determination and then architectural and engineering development, summarised in Figure 3, - with the all in one or concurrent synthesis - summarised in Figure 4. That paper showed that this combination of the architectural and balanced numerical description enabled the ship designer to develop *ab initio* design options, which through the architectural representation could take into account many of the ship’s main requirement drivers.



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**Figure 3: A Summary Representation of Current Sequential Synthesis (Andrews 1986)**



**Figure 4: A Summary Representation of a More “Holistic” Approach to a Fully Integrated Ship Synthesis (Andrews 1986)**

With an architecturally based description at the preliminary stage of a design it becomes possible to explore many of the issues which are of direct interest to the naval staff. Such issues - ranging from those concerned with the ship's fighting capabilities and crew evolutions on board, to the sustainability and supportability of the vessel on mission - are best investigated for their impact on the overall design at the earliest exploratory stages of the design. Thus, for example, layout for weapons effectiveness is a function of topside disposition (Andrews & Bayliss 1998) and also of internal arrangement and zone logic (Andrews, Piperakis & Pawling 2012), both of which are more readily explored through the ship's architecture. The logic adopted for routing ship systems also affect producibility and constructional building block considerations. Also the initial configuration is able to reflect not just the traditional focus of the naval architect on the aspects of Speed, Seakeeping, Stability and Strength as performance drivers but also Style issues (Andrews 2012), including through life supportability considerations and adaptability for changing roles and technology upgrading. Without this architecturally based approach, the alternative of a simple recourse to the use of margins on the numerical values of space, weight and mass centres would not adequately reflect the configurational and associated ship service demands so as to provide genuine adaptability through the life of a given design.

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## 3.2 A Review of Ship Architectural Design

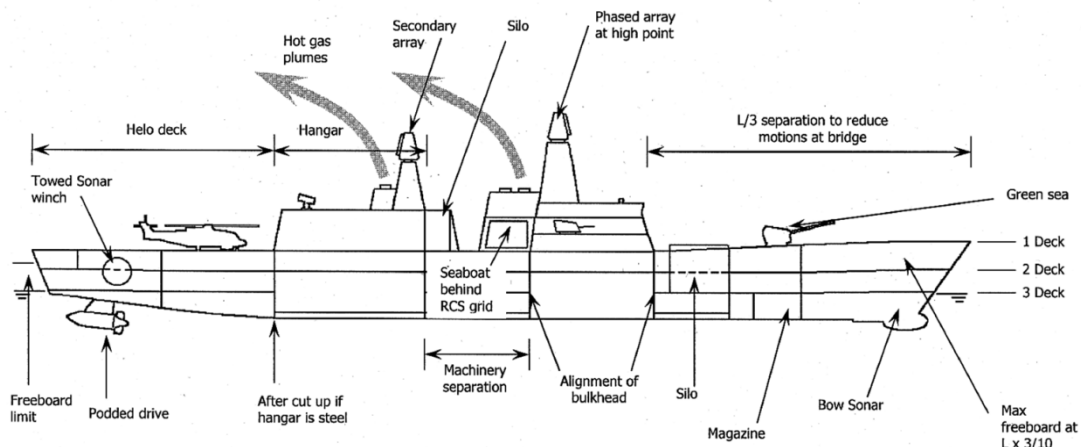
A major aspect of ship design, that of ship architecture and how it is produced as part of the evolution of a new ship design, has in general been somewhat neglected by the profession of naval architecture. The 1980 vision (Andrews 1980) was justified since:

- Many of the features and aspects of design could not be properly addressed with the traditional sizing approach but could be incorporated in initial design with the better design methods and tools becoming available;
- The enormous recent advances in computer aided graphical design, in its infancy in 1980, are available to every personal computer user.

The current section considers how the architectural aspects of ship concept design have been dealt with prior to approaches, such as the UCL DBB approach, reached their current maturity. Also summarised below are examples of research in ship and terrestrial architectural approaches to designing the internal configuration of large, complex constructions. Three ship layout types are now summarised:

### 3.2.1 The Example of a Frigate Architecture

A paper entitled “The Architecture of Frigates” (Brown 1987) drew on that author’s experience of preliminary warship design and on research undertaken by Andrews (1984) with various post graduate students at University College London (Hutchinson 1981, King 1985). Brown's paper was largely a comprehensive survey of many of the aspects and constraints impinging on frigate layout design through the various phases of design (termed levels by Brown), from initial design concept (Level 1) through to detailed General Arrangement (Level 3). The design constraints were indicated in his Figure 4, where an outer ring showed “problem areas” directly affecting a frigate's architecture (e.g. access, noise, vibration, hydrodynamics, structural continuity, survivability, stealth, aesthetics and through life issues), while his inner ring showed elements of the material solution (e.g. accommodation, decks & bulkheads, shape & proportions, passages, ladders, services & machinery seatings). In keeping with the last of the Brown and Andrews’ (1980) “S<sup>3</sup>” aspects in ship design, namely that of 'Style', Brown discussed the range of style-related issues relevant to the layout of a given design (i.e. ship role, modular/cellular features, margins, zoning). He emphasised how, for his Level 1 (for a frigate and similar combatant vessels), the key to the internal layout is the design of the upper or weatherdeck disposition of weapons, helicopter arrangements, radars, communications, bridge, boats, seamanship features, machinery uptakes and downtakes, and the access over the deck and into the ship and superstructure. Figure 5 shows Andrews’ (2003) updated version of Brown's frigate configuration.



**Figure 5: Frigate Layout Considerations (Updated By Andrews (2003) From Brown (1987))**

When considering Level 2 of layout evolution Brown discussed various numerical techniques under two categories, namely those intended to quantify the need for the layout feature and those used to analyse the performance of a stated function. This is shown in Table 2, where other techniques are also included beyond those taken into account in the 1980s UCL research programme (Andrews 1984).

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**Table 2: Numerical Techniques for Warship Layout (Andrews 2003)**

Category	Technique	Application	Source
Needs	Association matrix	Frigate layout preference	Andrews (1984)
Elucidation	Circles of Influence	Frigate Compartment relationship	Andrews (1986)
Layout Performance	Circulation	Adapted from CAAD	Buffa(1966), Hutchinson(1981)
	Multi criteria knowledge based	Ship layout to minimize size	Graves (1980), Hills (1993)
	Contact diagram	Merchant ship superstructure	Cain (1979)
	Mission evaluation	Overall layout	Hope (1981)
	Numerical analysis of spatial structure	Architecture applied to frigate layout	Hillier (1984), Andrews (1984)

Some of the techniques listed in Table 2 have been proposed for some time as a means of evaluating the layouts of buildings and ships but they have failed to be adopted in general design practice, largely because of the difficulty in assigning numerical values to layout options which provide valid bases for assessment. For example, the method used to investigate the circulation of personnel in frigate layouts, for watch changes in cruise and action states (Hutchinson 1981), did not constitute a believable measure because:

- The most “efficient” configuration (i.e. smallest value of circulation) in the designs investigated was actually the peacetime layout;
- Circulation did not take into account the fact that layouts are driven by cultural aspects (e.g. officers, petty officers and ratings are not accorded equal status);
- While personnel flow is readily quantifiable, it is not as important in determining a ship's layout as the juxtaposition of vital compartments driven by the need to fight the ship, survivability, maintenance etc.

Another approach proposed for looking at layout design is that of expert systems. These have been applied to layout design by Helvacioğlu and Insel (2003), who outline a container ship design tool where the ship is described at three levels of detail, with different rules bases and expert system engines applied to each level of decomposition. Of interest in this SoA report is the so-called “third level” of decomposition, representing the layout of individual decks of the container ship’s accommodation block. In common with most expert systems, this approach is primarily suited to “type ship” designs, where the overall topology and style are specified, and a relatively simple performance function can be used to determine the preferred arrangement – in this case the estimated evacuation time. Expert systems require a well-structured and populated rules database to function, and Helvacioğlu and Insel describe the methods they used to obtain layout preference information from human designers and the structures used to store this in a manner allowing it to be applied in new designs.

There would seem to be some difficulty in separately conducting a range of evaluations, beyond personnel circulation (because that is relatively easy to compute) and then additionally adding them together, when the aspects are so disparate that it makes it questionable that a layout can be “optimised”. However, this is not an excuse for the designer to revert to making arbitrary choices, rather to use numerical analysis where appropriate, so as to properly inform decisions, rather than questionable numbers being the sole basis for making a design decision.

### 3.2.2 Configuration Driven Design

Although it has been argued that the design of all warships (and most commercial service vessels) should be driven in large measure by their internal (and upper deck) configuration, it will be recognised that the concept design of certain ship types has to be approached by firstly configuring the spaces required to achieve the primary function(s) of that vessel. Thus, the physical description of a passenger, cruise or ferry ship can only be produced by commencing with the arrangement of the public spaces and cabins (Levander 2003). Similarly the configuration of certain large naval vessels, such as aircraft carriers and amphibious warfare vessels, are driven by the spaces required to accommodate the primary “cargo”, whether the hangar and flight deck or the well dock and vehicles decks in those specific cases. See Figure 6, which schematically shows personnel routes, equipment removal routes and stores routes around and directly below the primary decks, i.e. the flight deck and hangar deck. Honnor & Andrews (1981) discussed the need for access from the main through deck, below the hangar, and around the side of the hangar, taking into account the other needs for machinery inlets, outlets and removal routes, as well as features such as boat arrangements and ventilation. The paper also pointed out, however, that some important military features were deliberately omitted from this figure, such as:

- Magazines and weapon movement routes;
- Other important aircraft support spaces and stores;
- The location of ship and force command, control and communications;
- Damage control features.

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Although these would need to be included in order that the evolution of such a complex ship configuration could be properly appreciated, this example - and the previous frigate case - are considered to leave no doubt as to the centrality of a ship's architecture in the design process.

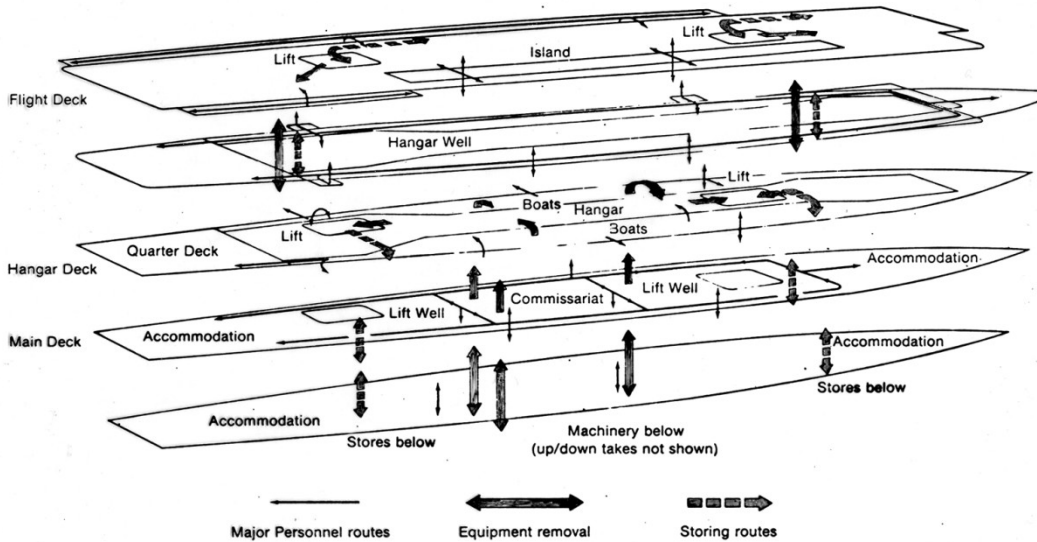


Figure 6: Schematic of INVINCIBLE Class Internal Arrangement (Honor & Andrews 1981)

### 3.2.3 Unconventional Hull Configurations

Unconventionally hulled vessels require a significantly distinct ship design process. In the case of displacement-borne multi-hulled configurations - like the catamaran, SWATH and trimaran - the architectural design is highly significant. The high speed advanced vehicles, like the ACV, hydrofoil, SES and various hybrid forms, on the other hand, are governed by a technology akin to aerospace, which has been the industry behind most of the current fast (coastally operated) craft in service. When the initial sizing of the larger multi-hulled vessels is considered, in terms of dimensions and form parameters, it is apparent that their sizing is not circumscribed by the relatively narrow range of parameters typical of monohulls. Consequently the designer, of say a SWATH or trimaran, has to size these vessels on the basis that it is the configuration of their major spaces which constitutes the main driver for determining the vessel's dimensions and principal form parameters (Andrews 2003). As can be seen from figure 7, the size and shape of the trimaran ship shown are determined by the arrangement of the major operational and habitable spaces.

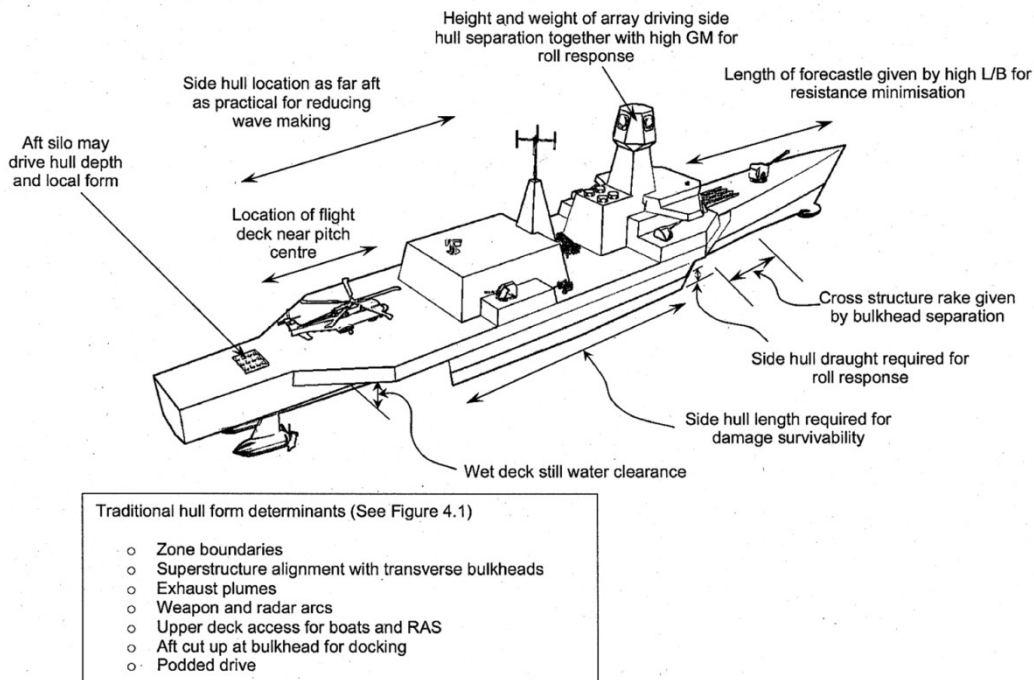


Figure 7: Trimaran Combatant Configuration Drivers (Andrews 2003)

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## 3.3 Architectural Design Methods for Ships

While the advent of computer aided design systems to naval ship design has led, specifically in US Navy practice, to formalised procedures for General Arrangement Design, the broad principles predate CAD technology in ship design (Carlson & Fireman 1987). The need for the naval architect, at the formative preliminary design stages of a ship design, to have a clear understanding of the issues affecting configuration has become more important, because of the risk that the readily available design tools enable the novice ship designer at his/her personal computer all-to-readily to produce what appear to be worked up ship design solutions.

An early approach to 'Functional Arrangement Design' was due to Barry (1961), for both large passenger ship conversions to troop ships and on cruiser gun disposition, while providing insights relevant to current ship design practice. For example, Barry proposed the juxtaposition of what were drafting tables, so that those designers working up the upper decks and superstructure could better interface with the outboard profile designer, while those responsible for the lower deck arrangements interfaced with the inboard profile design. In modern practice this approach translates to the necessity for the ship designer to ensure that 3-D models of compartment locations are considered not just in terms of a given deck arrangement but also of the relationships with adjacent decks and the topside, as indicated by Figures 3, 4 and 5. The second example, of a similar vintage (Baker 1956), was produced as a means of maintaining coherence in ship layout. Baker's 'stylised layout', designated areas of his 'St LAURENT' Canadian Destroyer design to the specific functions of machinery, living, working, payload (weapons), services and liquids, with the object of avoiding excessive interaction between functional areas which could lead subsequently to loss of design control. Leopold and Reuter (1972), in their comprehensive design history of the DD963, LHA and FDL classes for the US Navy, outlined, for their designations of five 'ship systems' (i.e. containment, mobility, ship support, mission support and human support), a basis for "logical selection of design configurations within boundaries of the feasibility envelope". Each arrangement was then individually evaluated for a range of parameters, such as ease of modernisation and conversion, modularity and minimisation of vulnerability and topside clutter.

Even when the move to computerisation of the ship design process was gathering momentum (see Carlson & Cebulski 1974, Holmes 1981), manual general arrangement procedures were still adopted and the computer used to present compartment attributes and to manage the auditing process. The allocation of space then took place within the defined overall ship envelope at what was termed, in UK practice of the day, the Feasibility Stage and involved an initial assignment of compartments to decks and watertight subdivision locations which was rarely changed subsequently – or, if so, in a minimal manner to avoid wholesale redesign- an approach which could result in the loss of the original layout logic. Carlson & Fireman (1987) stated that architectural layout programs were examined for their potential for application to ship layout, but could not deal with ship shape and space limitations; also, optimisation techniques were infeasible because of the large number of independent variables involved in ship layout. They provided an update of the US Navy's General Arrangement CAD system with an 'Arrangement Design Methodology', summarised in Figure 8, which shows a sequential approach constrained by the initial concept design output and hull form plus subdivision of the decks and bulkheads.

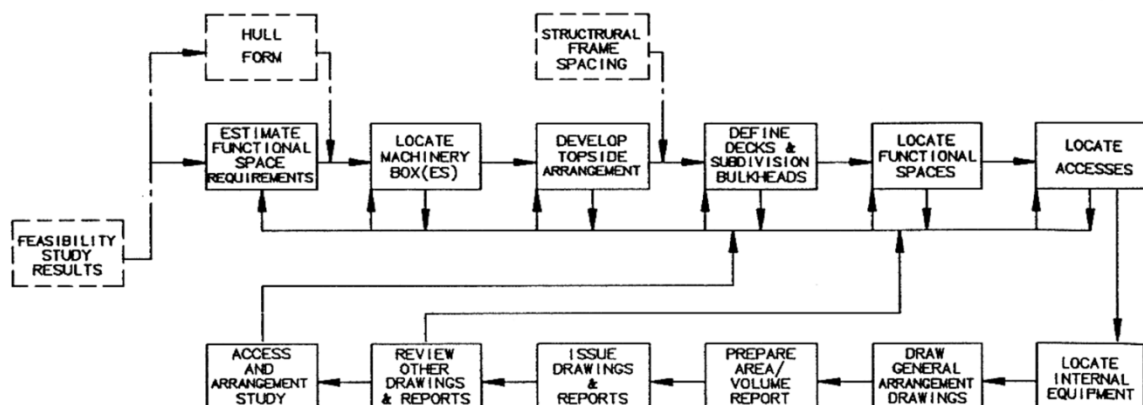


Figure 8: US Navy's General Arrangement Task Sequence (Carlson & Fireman 1987)

This background serves to demonstrate that General Arrangement design has continued to be a deliberately constrained process, and that decisions which constrain the architectural design are made at the preliminary or concept stage, where there is an apparently unavoidable and insufficient consideration of the consequences of the constraints being imposed on the layout. Furthermore, when the arrangement is subsequently developed, there is a momentum in evolving the total ship design, which massively inhibits any significant exploration of the constraints and any possibility of a radical readjustment of the architecture of the ship. This downstream tyranny of the schedule virtually eliminates any real ability to meet the aspirations of Concurrent Engineering.

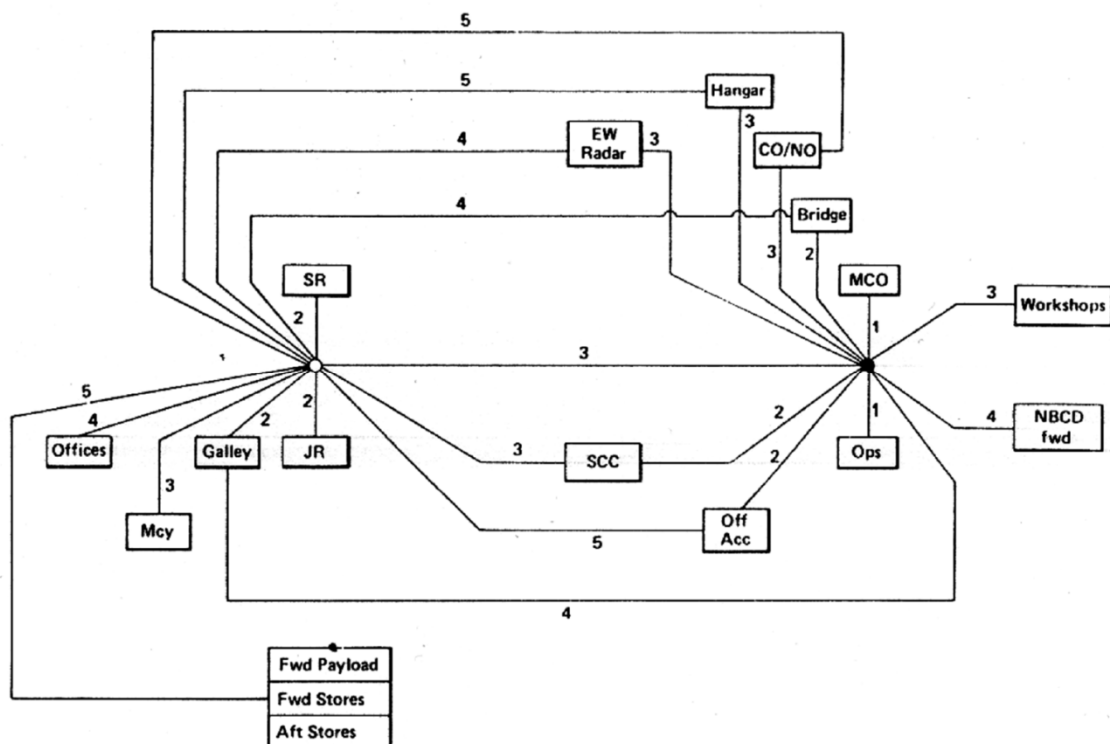
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## 3.4 An Integrated Architectural Synthesis

The approaches described in the foregoing contribute to, but also constrain, the challenging design problem of producing the general arrangement of a complex ship design. This is done by the well-established method of using damage stability and structural continuity considerations to determine main transverse bulkhead disposition and thereby controlling the evolution of the general arrangement, within a previously determined envelope of the hull form. An alternative logic, that of using the disposition of the principal spaces in the ship to determine both the initial sizing of the ship and the selection of hull dimensions and form parameters was proposed in Andrews (1980). The aim was to have a means of fostering 'creative ship design', which was then demonstrated in what was termed an 'integrated synthesis' (Andrews 1986). This gave an example of a sequence for allocating the various compartments in a frigate design. This sequence was not suggested as the recommended way of obtaining the layout, but rather as a suitable start point for an integrated synthesis to take and to utilise the ship arrangement, produced by such a sequence, to size, dimensionalise and select form parameters. It was also argued that with integration of the ship architecture with weight, space and form parameters, a better initial design solution could be achieved, since a more comprehensive initial design description:

- Would provide a better basis for initial cost tradeoffs and parametric selection;
- Could be used to explore alternative layouts, while the hull form and dimensions were still fluid;
- Could be readily altered, both as regards layout disposition and the consequent hull dimensions and form impact.

The latter advantage was also justified the initial adoption of a conventional layout sequence, but only provided the ability to readily alter the layout and the initial sizing could then be exploited (rather than this layout being adopted and closing down the option of configuration exploration). Andrews (1986) also proposed that a layout could be synthesised by a progressive design approach of 'circles of influence' to address compartment relationships and thereby yield a 3-D block layout, around which a hull form could be "wrapped" (see Figure 9).



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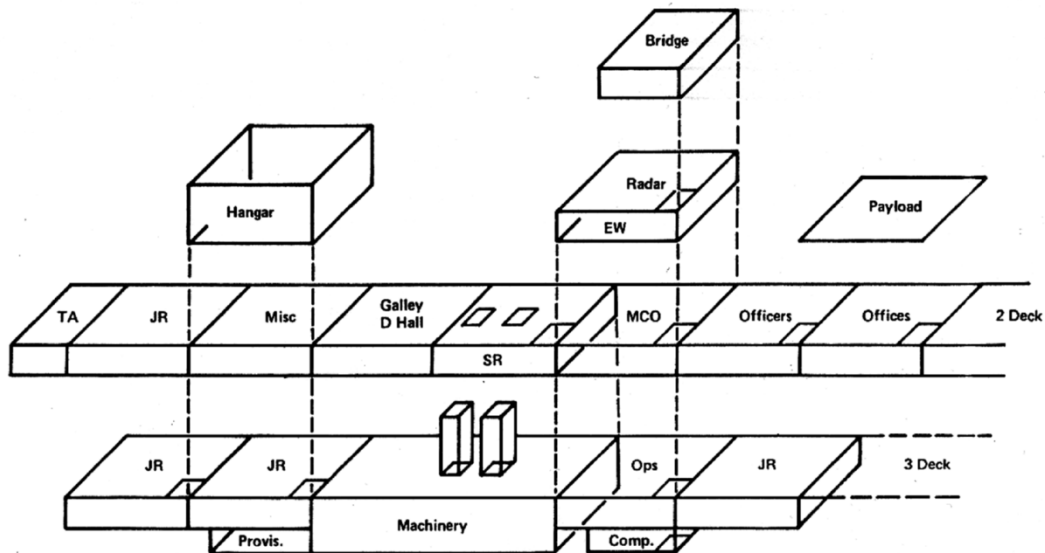


Figure 9: *Ab Initio* Frigate Compartment Block Synthesis (Andrews 1986)

While the integrated synthesis approach was demonstrated in the 1980s, it was not until computer graphics had advanced sufficiently in the early 1990s that the methodology outlined above could be adopted in a working design tool for submarines and then in 2001 for surface ships via the PARAMARINE ship design system (Andrews & Pawling 2003).

## 4. THE UNIVERSITY OF MICHIGAN (U-M) APPROACH

The research of U-M called “Intelligent Ship Arrangement (ISA)” published in Daniels and Parsons (2008), Daniels et al. (2008, 2009), Nick et al. ((2006)], Nick and Parsons (2007)], Nick (2008)], Parsons et al. (2008), focuses on arranging spaces into pre-defined structural zones. ISA was developed in the context of the U.S. Navy’s design process, which has influenced the scope, direction, and intended use of the method. The overarching objective is “to provide an optimization technology and design tool to assist the arrangements designer to create effective, rationally based surface ship arrangements with the maximum amount of intelligent decision making support” (Parsons et al. 2008). Secondary goals relate to the capture and application of Navy requirements and best practices and to the objective comparison of alternative layout configurations. ISA was developed to assist designers in creating layouts at the end of the conceptual design phase (Analysis of Alternatives, AoA) and at the beginning of preliminary ship design phase.

Due to the existing capabilities of U.S. Navy design tools and processes, ISA solves only the space arrangement part of the total ship design problem. ISA takes as key inputs: 1) a ship hull including structural subdivisions, 2) a list of spaces to be arranged, and 3) a collection of relative and absolute space location constraints and space-centric geometric constraints. These inputs can be specified beforehand using automated or manual synthesis tools. Currently, the U.S. Navy’s Advanced Ship Synthesis and Evaluation Tool (ASSET) (Beyer et al.(1990)) is the conceptual ship design synthesis tool used to determine, among other items, the main dimensions of a hull with its major structural subdivisions, a list of ship spaces appropriate for the given ship type, and the placement of major machinery. The automated/semi-automated approach employed by ISA was developed, in part, with the goal of incorporating general arrangements quantification into the larger ASSET synthesis, enabling a feedback loop of layout quality into total ship design at an early stage.

The ISA method works with a two-step process, Figure 10. The first step allocates the list of spaces to the structural zones of the vessel whilst the second step creates multiple arrangement (geometric) solutions for the allocation of the first step. This follows the methodology that each space allocation can have multiple geometrical arrangements, whilst each geometrical arrangement can be traced back to one unique space allocation. Thus multiple arrangements are needed for each allocation to find the “optimal” allocation/arrangement combination.

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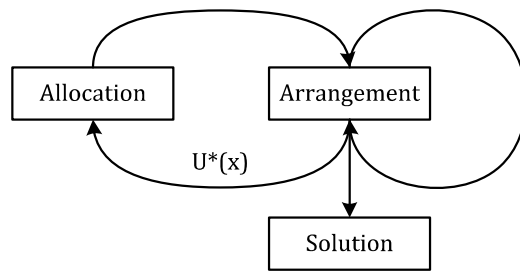


Figure 10: ISA Two Step Allocation/Arrangement Schematic, (Daniels Et Al. 2009)

## 4.1 Step 1: Allocation

The first step of the ISA method is the allocation of a pre-defined list of spaces to structural zones of the vessel. Each structural zone is subdivided by major bulkheads and decks and is fixed (i.e. the structural zone arrangement does not change during the ISA steps), see Figure 11. The spaces are allocated to the available structural zones by a Hybrid Genetic Algorithm - Multi Agent System (HGA-MAS). In this optimization scheme, the genetic algorithm is used to explore the design space by encouraging solution diversity, while the agents are used to provide intelligent search capabilities. Genetic algorithms are robust when used on highly multimodal problems with flat solution spaces, of which general arrangements is a prime example. The intelligence provided by the agents enables significant performance improvements over genetic algorithms alone.

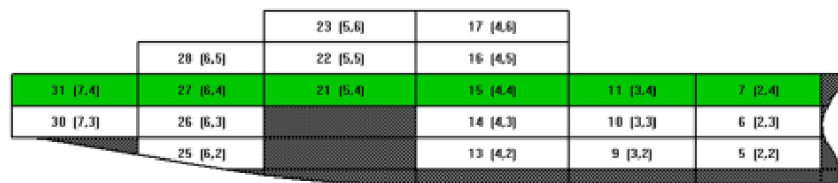


Figure 11: ISA Structural Zone Définition, , (Daniels Et Al. 2009)

The allocation of the spaces to the structural zones is driven by fuzzy constraints. The structural zones have a built in fuzzy constraint that tracks their area utilization. Spaces have built in global location preference and geometry constraints (required area, aspect ratio, etc.) as well as a collection of relational constraints with other spaces (adjacency, separation, etc.). The use of fuzzy logic to define the constraints allows the modelling of constraints such as; “close to”, “separated from”, or “more-or-less square”. These types of constraints are often encountered in the arrangement design rules.

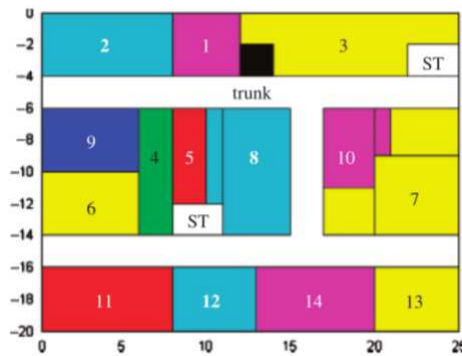
## 4.2 Step 2: Arrangement

After the space allocation to each structural zone has been defined the second step of the ISA method is activated. The arrangement algorithm maps the centroids of each space assigned to the current structural zone to an orthogonal grid which is a 2D description of the structural zone plan. This is done to ensure that each space has sufficient area available around it to achieve its final size. As shown in Figure 8, the arrangement algorithm is called several times to find the “optimal” arrangement of the current space allocation.

The arrangement step is also driven by fuzzy constraints. Spaces here have built in geometry constraints that address required area, aspect ratio, minimum dimensions, minimum segment width, and perimeter length. In addition they have the same collection of relational constraints between themselves and other spaces (adjacency, separation, etc.). The space geometry related criteria ensure that each space has its minimum required dimensions and that no unwanted irregular shapes are created whilst the other constraints control basic topology between spaces. The final result is a space arrangement of each structural zone according to their assigned topology, see Figure 12.



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**Figure 12: ISA Structural Zone Arrangement, (Parsons Et Al. 2008)**

The ISA tool is a 2D area driven design tool, this makes it suitable for arranging spaces/areas into a fixed positioning space (structural zone). Arrangement of weapon systems, sensors and the propulsion system, although theoretically possible, are not part of the arrangement process and are fixed prior to the ISA arrangement tool. As such ISA focuses on the arrangement design within the fixed envelope of the hull and topside.

### 4.3 Unique Features

- Hybrid Genetic Algorithm - Multi Agent System (HGA-MAS)
- Fuzzy Optimization
- Flexible fuzzy logic constraint system with customizable calculation objects

### 4.4 Recent and Ongoing Developments

There have been a number of improvements to the current working version of ISA. They include:

- Development of the ISA design tool is still under way, recently new studies have been made to improving the compartment and access networks. The new Passage Variable Lattice Network methodology (PVLN) allows for the generation of more complicated passage network configurations to better suit the access needs of all spaces in a zone-deck.
- Passage, Stair tower, and Deck templates applying commonly used compartment and access network patterns.
- The algorithms are now trimmed by the real ship geometry to improve accuracy.
- The objective functions were rewritten to increase performance of the search algorithm.
- Design Agent intelligence has been increased, allowing for more complicated design change requests.
- A new space projection system has been implemented to dramatically speed up compartment geometry generation. Spaces no longer have to take many iterations to “grow” to their final geometries
- Identifying networks and relations between spaces, this can be used to cluster spaces to allow for complex (group) moves.

## 5. The UNIVERSITY COLLEGE LONDON (UCL) APPROACH

The first paper on the UCL originated Design Building Block (DBB) approach to preliminary ship design was presented to IMDC in 1997 (Andrews & Dicks 1997). However that methodology for preliminary ship design originated in 1981 (Andrews 1981) and was then developed in the subsequent few years (Andrews 1986 and Andrews 1987) achieving its first working realisation, produced for the UK Ministry of Defence (MoD) in a classified version, for UK submarine design (Andrews et al 1996). This has since been developed in an unclassified form known as ESSD by GRC ([http://www2.quinetiq.com/home\\_grc.html](http://www2.quinetiq.com/home_grc.html)).

The 1997 IMDC paper, on SURFCON, outlined the procedure for preliminary ship design using the DBB approach, which was subsequently adopted in the working version of SURFCON as part of the GRC preliminary ship design tool PARAMARINE (see Munoz & Forrest 2003), and included the use of a functional breakdown.. That 1997 paper also showed an early application of the approach to both monohull and multihull (SWATH and Trimaran) design studies of frigate-sized combatants. The overall DBB methodology was presented to a wider technical audience in 1998 (Andrews 1998) when it was suggested that this constituted a new paradigm for the preliminary design of large complex products.

The 2003 IMDC paper (Andrews & Pawling 2003) spelt out the development of the practical PARAMARINE based DBB capability developed from the 1997 specification and the research demonstration presented to IMDC in 1997. A subsequent IMDC paper (Andrews & Pawling 2006) showed that in the intervening three years a considerable range of ship design studies were undertaken by the UCL Design Research Centre (DRC). Following the outlines of the design

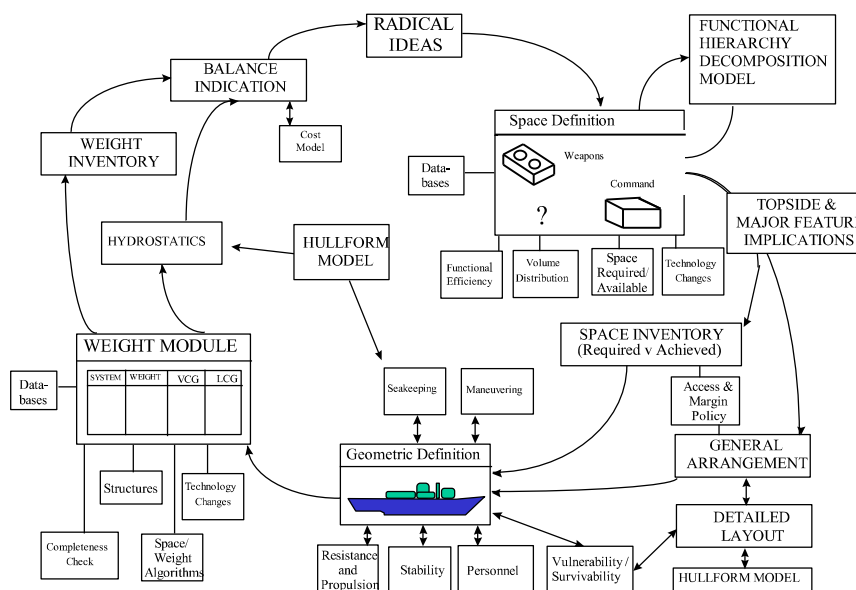
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applications of the DBB approach to ship design research, design for production, novel concept studies and simulation based design that paper concluded with a range of further issues that the computer aided graphical design approach to preliminary ship design could readily and usefully open up for consideration, while the design solution is still malleable. Thus, while ensuring the traditional naval architectural issues, such as stability, powering, weight and space balance, are still prominent in initial ship design, the designer can now give due weight to other aspects of major importance to potential owners and operators, which are best addressed through their interaction with ship layout and furthermore encourage creatively exploring innovation in ship design.

## 5.1 Summary of Design Building Block approach to preliminary ship design

The combination of modern computer graphics and interactive computer aided ship design tools was required to achieve an integrated CAD system readily available to practicing ship designers, since the design examples reported in the 1997 IMDC paper (Andrews & Dicks 1997) had only been achieved using a research “breadboard” demonstrator. With the setting up of the UCL Design Research Centre (DRC), within the UCL Marine Research Group, in 2001 the Design Building Block approach to integrating ship architecture into the initial ship synthesis could then be achieved at a practical level, as opposed to one restricted to a research level. This was done through its incorporation within an existing and established computer aided ship design system.

The PARAMARINE ship design system was produced by Graphics Research Corporation, a company initially set up to provide the UK Ministry of Defence naval ship design agency with a support and exploitation agent for its longstanding GODDESS ship design computer system (Barratt et al 1994). PARAMARINE took the essential naval architectural capabilities of the GODDESS system and reconfigured them into an object-oriented configuration, executable on modern personal computers (Munoz and Forrest 2002). This system was then able to accept a new module, known as SURFCON, which implemented the Design Building Block approach in a fully integrated manner. Thus the methodology, outlined in Andrews (1998) and summarised by Figure 13, can be said to be fully incorporated within a practical and available CAD system. The manner in which the SURFCON tool (as part of GRC’s PARAMARINE system) is structured and the demonstration of that, through the UCL DRC’s beta testing, was outlined at the 2003 IMDC (Andrews & Pawling 2003), detailed in (Pawling 2007) and summarised below.



**Figure 13: The Design Building Block Approach Applied To Surface Ship Design Synthesis**

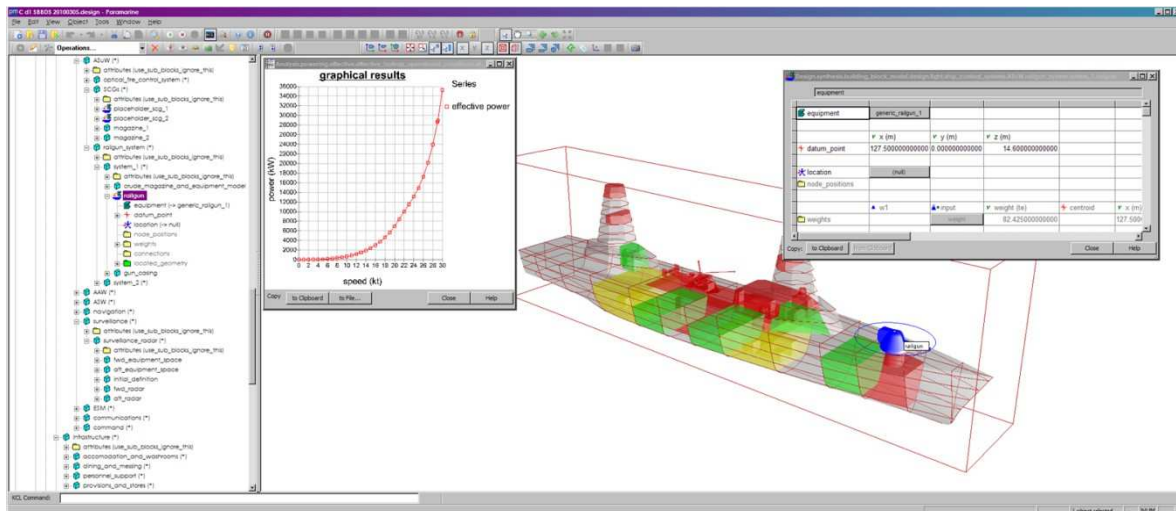
Two features incorporated in the PARAMARINE version of SURFCON that were part of the UCL prototype were:-

(1) A “Functional” breakdown of the design building blocks adopted for ship description. The categories of the building blocks (i.e. float, move, fight/operation and infrastructure) can be distinguished by their four characteristic colours in the example screen shot of the SURFCON system in Figure 12 and the subsequent examples. This breakdown of the DBBs was designed to foster the exploration of more innovative configurations and also to show the impact of additions or deletions of capability as part of the elucidation of requirements highlighted in the paper of that title to the 2003 IMDC (Andrews 2003).

(2) The term Master Building Block denotes how the overall aggregated attributes of the Design Building Blocks are brought together to provide the numerical description of the resultant ship design. The advantage of providing the Design Building Block capability of SURFCON as an adjunct to the already established ship design suite of PARAMARINE, means the audited building block attributes within the Master Building Block could be directly used by PARAMARINE.

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Thus the necessary naval architectural calculations can then be performed to ascertain the balance, or otherwise, of the architecturally based configuration just produced by the designer.



**Figure 14: An Example DBB Ship Description Using SURFCON and Showing the Graphical Screen, the Object-Oriented Hierarchy and an Example PARAMARINE Analysis**

The Design Building Block approach is both intended to foster innovative design solutions and is not "hard wired" or has set routines to achieve naval architecturally balanced ship solutions. It is required to be used by a capable ship designer, who can exploit the capabilities of the system and also produce coherent and balanced ship design studies. The system, in auditing a new configuration of design building blocks, will report to the designer the state of the design. Rather than automatically changing the dimensions and or the hull parameters, which might be the case in a "black box" system, SURFCON-PARAMARINE will tell the designer where the design is no longer balanced and the designer can make the decision that he or she considers appropriate to the design at that point in time, drawing on what are perceived to be the imperatives for the given study at that juncture.

The general procedure to be adopted in producing a new ship design study can be summarised as follows:

- (1) A very broad intent or "outline requirement" is identified and a design style proposed;
- (2) A series of Design Building Blocks are defined or selected (from a library or newly created), containing geometric and technical attributes;
- (3) The Design Building Blocks are located as required within a prospective or speculative configurational space;
- (4) An initial sizing and overall weight and space balance and performance (e.g. stability, powering) of the design is made, using the PARAMARINE naval architectural analysis routines;
- (5) The configuration is then manipulated until the designer is satisfied with both the configuration and the naval architectural balance;
- (6) Decomposition of the DBBs to ever greater levels of detail is undertaken as required, and balance / performance maintained at the required level that is seen to be appropriate for the particular study at its current level of definition.

Each Design Building Block, as the fundamental component of the SURFCON approach, can be regarded as an object in the design space and as a "placeholder" or "folder" containing all the information relating to a particular function within the functional hierarchy. The manner in which the design can be manipulated on the screen is spelt out in the 2003 IMDC SURFCON paper (Andrews & Pawling 2003). Importantly, the "block definition" object permits the designer to add whole ship margins and characteristics, such as accommodation demands, once the "block summary" object has summarised all the information in the top level block in the DBB hierarchy. In effect this is the Master Building Block object. The "design audit" object then allows the design description to be audited for any of the characteristics entered. Results can be displayed using the Functional Group hierarchy. This "design audit" object is then assessed both for a range of design infringements, by other objects in the design space, and for the balance of the overall ship design from the whole ship characteristics given by the Master Building Block.

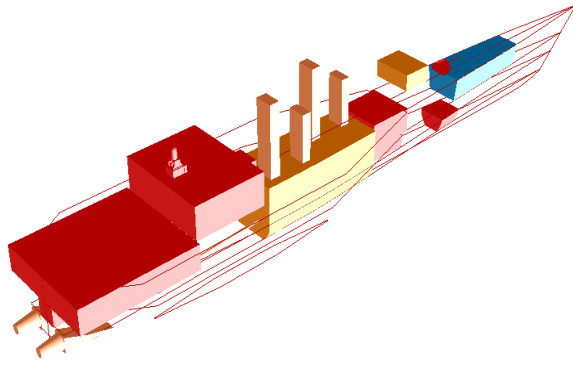
Table 3 shows the five main design stages for a typical DBB concept design study. The table also shows the main design decisions that were undertaken and indicates the number of DBBs at each of these stages, for a frigate example (Andrews & Pawling 2008). Thus an initial "super building block" definition of the principal architectural spaces finally works up to over three hundred DBBs for the fully naval architecturally balanced definition at the end of this particular concept design. Figure 15 shows each of the architectural definitions at the end of each stage in Table 3.

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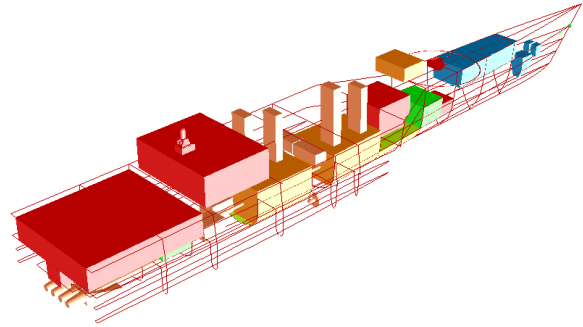
**Table 3 DBB Design Stages with Granularities for Each Stage for the LCS Study (Andrews & Pawling 2008)**

<b>Design Preparation</b>
Selection of Design Style
<b>Topside and Major Feature Design Phase (18-47)</b>
Design Space Creation
Weapons and Sensor Placement
Engine and Machinery Compartment Placement
Aircraft Systems Sizing and Placement
Superstructure Sizing and Placement
<b>Super Building Block Based Design Phase (110)</b>
Composition of Functional Super Building Blocks
Selection of Design Algorithms
Assessment of Margin Requirements
Placement of Super Building Blocks
Design Balance & Audit
Initial Performance Analysis for Master B.B.
<b>Building Block Based Design Phase (343)</b>
Decomposition of Super Building Blocks by function
Selection of Design Algorithms
Assessment of Margins and Access Policy
Placement of Building Blocks
Design Balance & Audit
Further Performance Analysis for Master B.B.
<b>General Arrangement Phase</b>
Drawing Preparation

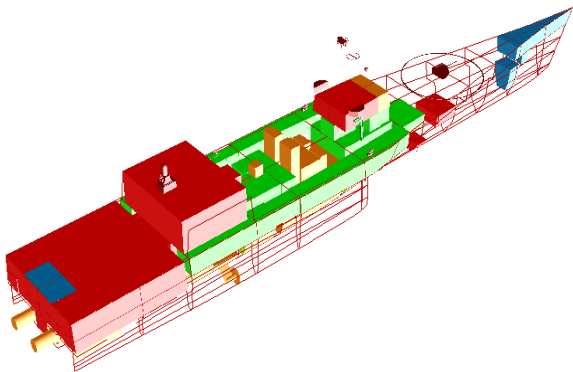
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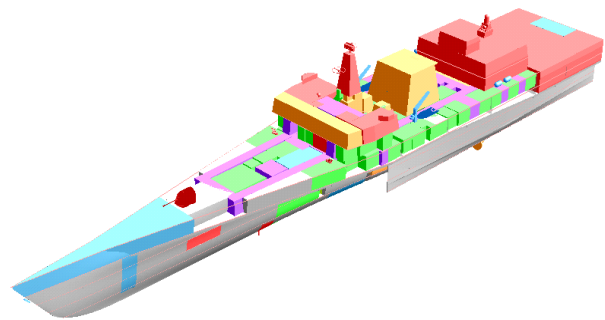
Topside and Major Feature Design Stage



Super Building Block Design Phase



Building Block Design Phase



General Arrangement Phase

**Figure 15 Architectural Representations for the LCS Study At the End of Each Design Stage in Table 3 (Andrews & Pawling 2008)**

While the instances of the use of SURFCON to date have largely, but not exclusively, been confined to warship design, the areas of design to which this manifestation of the DBB approach has been applied have been extensive. The following lists the four main areas of design studies undertaken by the DRC and detailed further in (Andrews & Pawling 2008).

- a) Studies related to ship design research, including a task for the UK MoD which looked at the impact of certain requirement drivers on the ship concept with regard to size, cost and configuration. The other two sets of research investigations were specific studies within the DRC; the first into the impact of the adoption of all electric machinery fit on a combatant and the second two discrete preliminary studies into naval aviation features on aviation capable vessels.
- b) Use of the DBB approach to investigate Design for Production (DfP) from the commencement of the design process for three distinct (naval and commercial) ship types, one of which explored DfP implications of adopting unconventional hull forms.
- c) Use of the DBB approach for the design of novel ship concepts under contracted design tasks for two major navies: one concept being that of a high speed and adaptable littoral combatant; the second a series of options for the fast transport of small fast combatants for littoral operations.
- d) Use of the DBB approach to facilitate exploration by simulation tools in preliminary ship design; the first a funded research programme into personnel movement on naval combatants and the second exploring the ship design implications of freight loading and unloading on to high speed short sea shipping.

As remarked in IMDC papers on SURFCON, the facility of an information rich three dimensional representation of a new ship concept, when integrated with a proper naval architectural numerical description, means the ship designer is able to explore many issues that traditionally were difficult to consider with a purely numerical description and, possibly, a separate sketch or profile. With this integrated representation, the concept designer is able to undertake a greater range of studies, better address innovative and novel options and investigate issues previously left until later in the design process. With such a tool the designer can produce concept descriptions that are able to move more smoothly into the later design phases when much more detailed graphical representations, such as Integrated Product Models (IPM) drive the design and production process.



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Due to its three dimensional representation SURFCON was said to be capable of investigating a large number of issues that are related to the ship’s configuration, as was spelt out in the 2003 IMDC paper (Andrews & Pawling 2003).:-

- Human factors. The simulation example was motivated by the pressures to reduce the number of people onboard. This can be facilitated by reconfiguring in preliminary design the arrangement of compartments and the main access routes, both through the ship and to the upper decks (Andrews et al 2008).
- Safety is a particular concern in modern ship design both for the crew and any passengers carried. Again the internal layout, not just to ease escape in emergencies but also for damage and fire fighting evolutions, can be reconfigured whilst the design is still fluid.
- Particular evolutions, specific to a given ship usage, such as helicopter operations from medium sized naval combatants or off shore support vessels right up to large scale aircraft or vehicle operations, from aircraft carriers or amphibious warfare vessels, can be investigated to make these critical evolutions more effective, as the two aircraft carrying studies referred to in item (a) above indicate
- For a naval vessel the topside configuration with launchers, directors, radar aerials, communications antenna, guns, helicopters, sonar gantries as well as the usual ship features of boats, access, navigation, anchors and cables etc, is a major design driver which is very hard to incorporate into usual ship concept studies. The graphical nature of SURFCON, because it is integrated into the numerical sizing, means that this aspect can be more readily influence the initial ship synthesis and earlier work on this could be readily incorporated in SURFCON (Andrews and Bayliss 1998).

## 6. THE DELFT UNIVERSITY OF TECHNOLOGY APPROACH

The method of the Delft University of Technology, published by (van Oers 2011; van Oers et al. 2008, 2009, 2010), is based on the Design Building Block approach, similar to UCL’s SURFCON. The intention of the tool is to increase the detail of a design in the conceptual design phase whilst maintaining a high level of design flexibility. This allows for more prediction tools to be used in this early stage increasing the knowledge about the concept designs.

In the tool objects and clusters of objects (systems, spaces, and components) are defined as building blocks which can be placed into a positioning space. By using different object types (i.e. envelope, subdivision, hard, soft, connection, and logical) van Oers is able to make a detailed parametric description of the vessel which a search algorithm can alter. The parametric model allows for large changes to the entire design (e.g. hull, superstructure, decks, bulkheads, object positions, etc.) thus maintaining the desired flexibility within the design.

The tools methodology is based on two simple steps; first create a large set of designs which are all feasible on a basic naval architectural level. Secondly have the designer (user) display and select designs out of this set based on characteristics and information which he/she deems important. The intent of this approach is to provide the naval architect with a diverse set of conceptual designs which all have sufficient detail to make relevant performance prediction. These performance predictions can be on the entire set of generated designs or only on those selected by the user as interesting subjects. The predictions can then support the further selection process of the “final” design.

Searching for alternatives is performed in a basic loop, see Figure 16. A search algorithm provides input to generate a parametric ship description which is then used to perform performance predictions. These provide a basis for rating the current ship arrangement and thereby direct the search algorithm towards better arrangements. A more detailed description of the TU Delft packing-based ship description is explained in the following subsections.

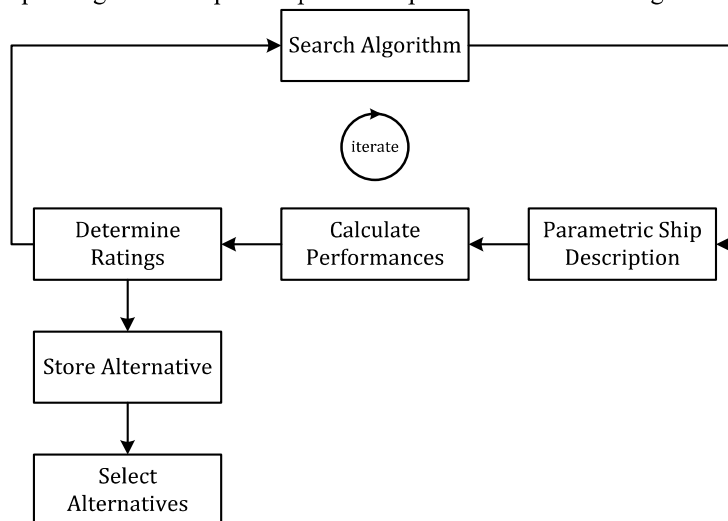


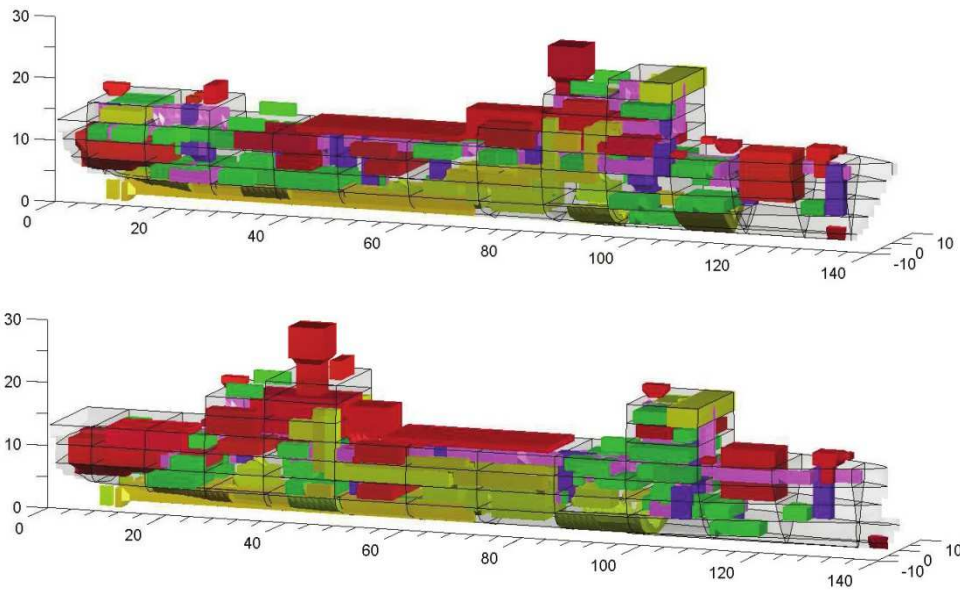
Figure 16: Searching, Storing and Selecting Alternative Ship Arrangements

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## 6.1 Parametric Ship Description

In order for a computer algorithm to be able to change the description of the ship, a parametric ship model is needed. This model allows the algorithm to change the entire arrangement of the ship by altering simple numerical values. The parametric model contains different object types represented by so called voxels (with the exception of the hull, decks, and bulkheads which are surfaces). The voxels are 3D blocks with a user defined dimensions (e.g. 1x1x1 meter) they can be placed on an orthogonal 3 dimensional grid. Clustering voxels into object allows the designer to create any type of system, space, or object (e.g. diesel engine, fuel tank, and bridge).

The parametric model takes the packing sequence (i.e. the order in which the systems are placed on/in the ship) and vectors with initial positions for each object as input. By using overlap management and different object types the placement, shape, and size of objects is regulated. The result is a fully packed and detailed 3D configuration of the concept design which can be easily changed in subsequent designs by a search algorithm, see Figure 17. Searching for alternative design configurations is covered in the next section.



**Figure 17: Example of a Parametric Model of a Frigate with Two Different Arrangements, (Van Oers 2011)**

## 6.2 Searching for Alternatives

Searching for alternative ship arrangements is done by a NSGA-II algorithm (Non-dominated Sorting Genetic Algorithm), see (Deb et al. 2002). The algorithm provides new input parameters to alter the parametric ship description (e.g. hull main dimensions, and object initial positions), see Figure . Using several performance prediction tools the search process is directed and constrained ensuring the generation of feasible designs. In this application feasible refers to compliancy with non-negotiable requirements such as the ability to float, sufficient initial (and damage) stability, and sufficient space to place all the objects. Included performance predictions are; ship weight, centre of gravity, hydrostatics, intact stability, reserve buoyancy, ballasting, resistance & propulsion (endurance), packing density, and diversity of the configuration. Depending on the ship type other performance measures can be added or removed, refer to (Wagner et al. 2010) for a drillship application.

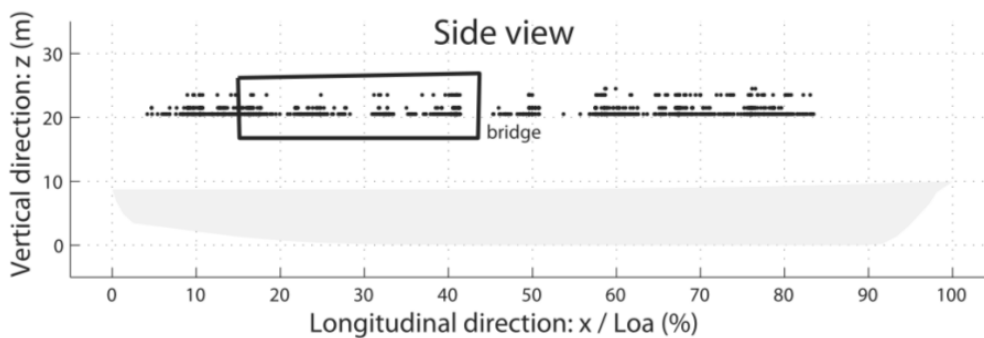
The packing density (i.e. the ratio between the sum volume of objects and total volume enclosed by the hull) is used as the objective function in the algorithm to be maximised. Other objective functions can be used to suit the needs of the ship type under consideration or the preferences of the user/designer. The goal however is to keep the number of objective functions used in the algorithm to a minimal to maintain the generation of diverse designs (Figure ) which gives the possibility to identify and study trade-offs. The selection of the final design(s) is thus left to a later stage where extra criteria are used to select the most promising alternatives.

## 6.3 Selecting Alternatives

The results of the search algorithm are a large number of feasible designs which are stored into a database. Using a selection process the user selects/discards designs according to decisions. This selection approach is meant to increase the designers' acceptance of the resulting configuration and to find out why this configuration is preferred. The approach follows a few simple steps:

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1. Determine which characteristics are important for selecting the design, these follow from design requirements which can be negotiable or non-negotiable. The characteristics selected are then ordered according to their importance.
2. The configurations generated by the search and packing algorithm are filtered and visualised according to the characteristic under consideration in a 2D scatter plot (e.g. position of the bridge relative to the envelope hull).
3. Selection of the relevant configuration is made “by hand” by drawing a selection polygon enclosing the desired configurations in the scatter plot, see 8. The non-selected configurations are discarded from further selection in subsequent characteristic decisions/selections.
4. By changing the sequence of analysing characteristics trade-off decisions can be made by visualising the influence of two different sequences on the final configuration.



**Figure 18: Selection of Preferred Bridge Positions (Van Oers 2011)**

The novel feature of the selection approach is that visualization is used to trigger the expression of human engineering judgement, rather than having an algorithm select the “best” design based on a numerical value (e.g. objective function).

## 6.4 Unique Features

The packing approach used by van Oers, allows for large changes within the parametric ship description. Objects are placed sequentially according to an initial position. After each object is placed at its initial position overlap between the current object and all previous objects is removed. The large changes are possible by changing the initial position of each object by an algorithm. The result is a detailed but flexible parametric ship description which can be used to explore the design space.

As mentioned the selection of ship configuration is done in a post-processing step, by interactively confronting the user with choices for certain characteristics. This approach is meant to increase the sense of acceptance for the final selected design (i.e. the user is in control for important decisions made) and to allow for expression of human engineering judgement in the design.

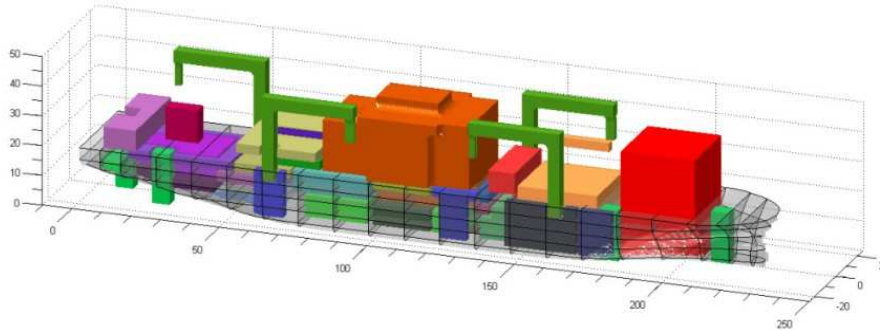
## 6.5 Practical Applications

The TU Delft emphasizes that its tool is not limited to naval applications. Research into practical non-naval applications by (den Hamer 2011; van Bruinessen 2010; Wagner 2009; Wagner et al. 2010) show that the configuration optimization routine can be used for different types of complex vessels. Examples are the application for the general arrangement of a deepwater drillship design (see Figure 19), and the deck layout of an offshore wind turbine installation jack-up.

During these practical applications the tool’s input was modified to incorporate ship type and problem type specific performance predictions, objects and constraints. This show the value of the generic parametric model set up by *van Oers*. By defining a library of ship specific systems and objects, using the generic object types, the arrangements of multiple vessel types can be explored.



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**Figure 19: Application of the TU Delft Tool to the Configuration of a Deepwater Drilling Vessel Design (Wagner 2009; Wagner Et Al. 2010)**

## 6.6 Recent and Ongoing Developments

Recent research, by (DeNucci 2012; DeNucci et al. 2009), focuses on the capture of design rationale, i.e., implicit reasoning and justification, behind configuration decisions, see Section 0. In their research, an integrated Rationale Capture Tool is presented which includes a novel elicitation approach (Reactive Knowledge Capturing), dedicated ontology for the structure of configuration rationale and an optimization-based feedback mechanism designed to increase the breadth of the database and improve the efficiency of the capture process. Analysis and results of a comprehensive test case performed with this tool are presented in this conference. The rationale database supports the decision-making process inherent in configuration design and shows promise in complementing any of the arrangement approaches described previously.

Feedback of captured knowledge during the design process is essential. This calls for a more dynamic and interactive design approach in which the user is constantly interacting with the design tool to identify and select promising design features and alternatives. This allows for gradual decision making regarding trade-offs throughout the design process. In this interactive approach a search algorithm would first generate an initial set of designs using only few systems and constraints. From this set the user identifies and selects promising designs for use in the next iteration. This process should give designers the opportunity to immediately see the effect of adding, removing or changing; systems, constraints, and requirements.

Current research being performed by Peter de Vos focuses on component selection, system functioning and matching steps for energy systems in the preliminary design stage. Due to limited resources (e.g. time, money, adequate personnel), these steps are often taken at a later stage in the ship design process when actual system selection has already taken place, often based on re-used information from previous similar designs. This may result in ill-estimated system dimension, sub-optimal system functioning and component matching, and limited creativity in the system design. The proposed solution is to automatically generate system (topology) models which can be used to analyse system dimensions, matching, operational modes, redundancy, and performance through simulation. This gives valuable information and input for use in the configuration optimization model, in which currently the systems are assumed available and decided upon.

The generic design and engineering process can be visualised by a Vee model, based on the model used in systems engineering, as shown in Figure 20. The developments by van Oers and DeNucci focus both on the design of ship configurations at the right side of this Vee model and assume that initial decisions on required systems and components have been made. However, these decisions also require a design process to select the most promising system solutions and are very much dependent on the knowledge available within the design team. In addition, the selection of system solutions is based on the required functions and related performance requirements which themselves are a result of a selection process to fulfil stakeholder's needs to execute a mission in an effective way. New developments will focus on additional tools to support these decision making processes and the capturing of the related knowledge in the left side of this Vee model.

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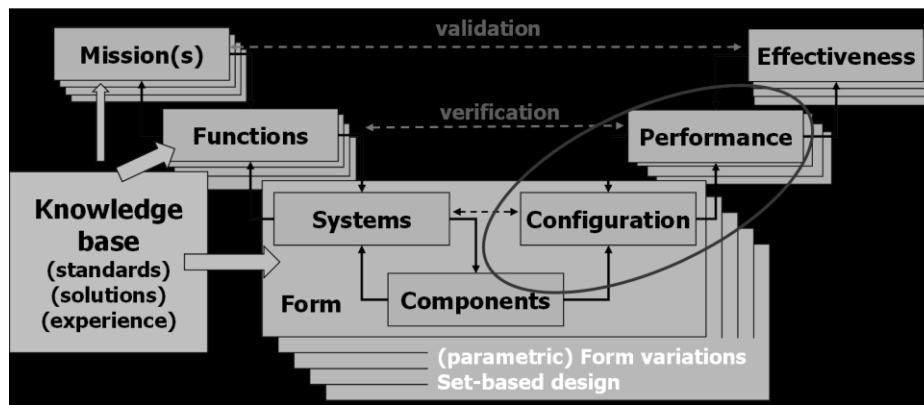


Figure 20: Vee Model Of Generic Design And Engineering Process (Based On *Systems Engineering*)

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