# UNIVERSITY OF LONDON THESIS

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# The Application of the Design Building Block Approach to Innovative Ship Design

By

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*Doctor of Philosophy*

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# Declaration

I, Richard George Pawling, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Signed:

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Date: 2007-07-20

# Abstract

The ship design process is complex and strongly influenced by both the inherent technical complexity and interactions of subsystems. These arise from within ships and from external influences, such as the design environment and the capabilities provided by the available tools. These difficulties are particularly found in the design of service vessels, such as warships. Both requirements and performance of the ship are multi-faceted and some aspects may not be readily amenable to numerical description and assessment, particularly in the early stages of the design process. Preliminary ship design is characterised by exploration of options and the investigation of design drivers and relationships, with great variability in the design definition adopted by designers. This provides significant potential for investigation of alternative and innovative design solutions. A wide range of broad approaches and detail procedures for the application of computers to preliminary ship design have been proposed, including an architecturally centred approach to preliminary ship design. The latter has been previously proposed as a method for the integration of the technical and stylistic aspects. The most recent implementation of the Design Building Block approach is as a module within the PARAMARINE ship design software, known as SURFCON.

This research commenced with evaluating and demonstrating this implementation fit for use in preliminary ship design by modelling of a conventional vessel. A detailed procedure for using the tool was developed and this procedure was demonstrated by the development of a similar design. The Design Building Block approach was subsequently applied to a range of innovative preliminary ship design studies. These covered a range of vessel types and also differed in their overall objectives, including the assessment of the feasibility of a new concept and the evaluation of the impact of specific capabilities on the overall ship design.

The research confirmed that the use of the integrated spatial and numerical model, with an interactive graphical display, increased transparency in modelling and analysis, while greatly enhancing the designer's understanding of the design drivers. The flexibility and relative ease with which major features of the design could be modified, encouraged the exploration of alternatives and led to a ship design process akin to the sketching processes in product and architectural design. Further research is proposed in the areas of interface design to support innovate design, incorporation of further simulation and numerical approaches, together with the integration of systems engineering aspects into innovative preliminary ship design.

# Acknowledgements

I would like to express my thanks to the staff in the Department of Mechanical Engineering at UCL, and in particular to those staff and researchers who have been witness to the emotional rollercoaster that characterised the creation of this thesis. To my supervisor, Professor David Andrews I owe particular thanks for showing great patience in the face of what must have seemed like endless delays and constant vacillation. Without his enthusiasm and inspiration, none of this would have been possible. I would like to thank my friends and family for their support and robust encouragement to complete the write-up.

Finally I would like to dedicate this thesis and the effort embodied within it to my nieces and nephew, Lakisha, Lily and Jake, whom I have missed so very much.

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# Nomenclature

| | |
|---|---|
| 2D | 2 Dimensional |
| 3D | 3 Dimensional |
| AAMR | After Auxiliary Machinery Room |
| AAW | Anti Air Warfare |
| ADFPD | Assistant Director Future Projects Design (UK Ministry of Defence Senior Post) |
| AIM | Advanced Induction Motor |
| ANN | Artificial Neural Network |
| AShW | Anti Shipping Warfare |
| ASUW | Anti SUrface Warfare |
| ASW | Anti Submarine Warfare |
| BBDS | Building Block Design Stage |
| DBBa | Design Building Block approach |
| BMT DSL | British Maritime Technology, Defence Services Limited, Bath UK |
| $C_P$ | Prismatic Coefficient - a measure of the longitudinal distribution of the underwater volume of the hull |
| $C_M$ | Midship section Coefficient - a measure of the fullness of the centre part of the ship |
| CAD | Computer Aided Design |
| CAM | Computer Aided Manufacture |
| CFD | Computational Fluid Dynamics |
| CIWS | Close In Weapon System |
| CNC | Computer Numerical Control |
| CNGF | Common New Generation Frigate |
| DEC | Directorate of Equipment Capability (UK MoD) |
| DEFSTAN | Defence Standard (UK) |
| DXF | Drawing eXchange Format, a file format used for 3D and 2D models, limited to a faceted representation of 3D shapes |
| FAMR | Forward Auxiliary Machinery Room |
| FEA | Finite Element Analysis |

| | |
|---|---|
| FSC | Future Surface Combatant (UK 1990's future programme) |
| FSC IPT | Future Surface Combatant Integrated Project Team |
| GA | General Arrangement (drawing) |
| GRC | Graphics Research Corporation Ltd, Gosport, Hampshire, UK |
| GT | Gas Turbine |
| GTA | Gas Turbine Alternator |
| GUI | Graphical User Interface |
| GZ Curve | Line graph showing the change in righting lever (resisting an applied heeling force) with angle of heel - a measure of stability |
| ICR | InterCooled and Recuperated (Gas Turbine) |
| IFEP | Integrated Full Electric Propulsion |
| IGES | Initial Graphics Exchange Specification, a file format used for 3D models, which can describe complex curved surfaces |
| IMDC | International Marine Design Conference |
| INEC | International Naval Engineering Conference |
| ITMC | Integrated Technology for Marine Construction (UK research LINK programme sponsored by SSA) |
| KCL | Kernel Command Language |
| LCB | Longitudinal Centre of Buoyancy - The longitudinal position of the centre of the submerged volume of the hull |
| LCF | Longitudinal Centre of Flotation - The longitudinal position of the centre of the waterplane area |
| LCS | Littoral Combat Ship (US Navy 2000's project) |
| LPD(R) | Landing Platform Dock (Replacement) |
| MCDM | Multiple Criteria Decision Making |
| MCMV | Mine Counter-Measures Vessel |
| MFDS | Major Feature Design Stage |
| MMR | Main Machinery Room |
| MoD | Ministry of Defence, UK |
| MoD FBG | UK MoD Future Business Group |
| MW | MegaWatts |
| NES | Naval Engineering Standard (Now DEFSTAN) |

| | |
|---|---|
| NGS | Naval Gunfire Support |
| NICOP | Naval International Cooperative Opportunities in Science and Technology Program (US Navy ONR) |
| NSWCCD | (US) Naval Surface Warfare Centre Carderock Division |
| (USN) ONR | (US Navy) Office of Naval Research |
| PDM | Physical Data Model |
| PMM | Permanent Magnet Motor |
| PVF | Payload Volume Fraction - That fraction of the total internal volume of a ship that is occupied by payload (FIGHT) functional group |
| RCS | Radar Cross Section |
| RINA | (UK) Royal Institution of Naval Architects |
| RN | Royal Navy |
| SBBDS | Super Building Block Design Stage |
| SRD | Systems Requirement Document, UK MoD |
| SSA | Shipbuilders and Ship Repairers Association, UK |
| SSK | Non-nuclear propelled patrol or attack submarine |
| STEP | Standard for the Exchange of Product Data, a file format used for data exchange in a range of industries |
| SWATH | Small Waterplane Area Twin Hull ship |
| UCL DRC | University College London Design Research Centre |
| UCL NAME | UCL Naval Architecture and Marine Engineering course |
| UCL SDE | UCL Ship Design Exercise |
| VCG | Vertical Centre of Gravity |
| VR | Virtual Reality |
| VT | Vosper Thornycroft, Shipbuilder, Portsmouth, UK |

# Chapter 1: Introduction

## 1.1 Introduction

This thesis investigates the application of the Design Building Block approach to innovative ship design. This new approach to ship design, integrating architectural issues at the earliest stages, was first proposed by Andrews in 1981 [*Andrews, 1981*], developed in Andrews' subsequent thesis [*Andrews, 1984*] and summarised in a paper [*Andrews, 1986*]. The first practical implementation of the approach in the form of an integrated tool was the SUBCON (SUBmarine Concept design) software used within the UK MoD [*Andrews et al, 1996b*]. More recently, Dicks [*1999*] carried out research under Professor Andrews at UCL to demonstrate the utility of the approach for surface ships and to produce a functional specification for a future integrated software tool. This functional specification was then used by GRC to develop an additional module for their PARAMARINE ship design tool, which has been used by the candidate to design a range of preliminary ship studies.

Preliminary ship design, encompassing the terms defined by Andrews [*1994*] as Concept Exploration, Concept Studies, Concept Design and early Feasibility Design, is the earliest stage of ship design characterised by exploration of options and investigation of design drivers and relationships. Preliminary design has few resources and little cost, but has a very significant impact on the final configuration and cost of the vessel. Particularly in the case of warship preliminary design, the requirements themselves may be subject to investigation and change as the nature of possible solutions becomes known. The design is not rigidly defined and so a wide range of studies can be carried out, giving the opportunity for innovative and creative solutions to be investigated. Innovative solutions can arise in many aspects of ship design, such as:

- The overall topology of the vessel (e.g. SWATH and trimaran vessels);
- Advanced technologies (e.g. hydrofoil, Surface Effect Ships);
- New systems (e.g. Integrated Full Electric Propulsion).

## 1.2 SCOPE AND AIM OF THE THESIS

### Applicability of the Research

The research into computer aided ship design outlined in this thesis is focussed on the preliminary stages of the ship design process, when a wide ranging set of solutions may be investigated. This thesis does not encompass the downstream issues of contract design or detailed production design, where the selected design solution is developed to a very high level of detail. Furthermore, the general focus is on service vessels rather than transport vessels and, in particular, surface warships. Although the range of design studies presented encompasses vessels with conventional configurations and the issues subsequently highlighted may have applicability to preliminary design in general, the main area of interest is innovative ship design. This includes not only configurational and technical innovations, such as the trimaran or electric propulsion, but importantly the practical application of procedures intended to foster creativity and innovation in ship design. This thesis does not specify a future research programme or new software development, but rather highlights key areas of, and concepts within, the field of computer aided preliminary ship design that should be emphasised to enhance the effectiveness of the Design Building Block approach.

### Research Approach

The design studies described in Chapter 5 of this thesis were undertaken by the candidate, as a member of the UCL Design Research Centre, for a range of customers over a period of approximately three years. The studies themselves were not part of a single structured research programme, but each has explored a different type of preliminary ship design and contributed to the understanding and development of the Design Building Block approach to ship design. This thesis presents the results to date of this ongoing research and describes the lessons learnt from the wide range of design studies carried out.

### Thesis Aim

The overall aim of the thesis can be summarised in the following statement.

> ***The aim of this thesis is to investigate the application of the Design Building Block approach to innovative preliminary ship design, to describe the nature of the design process that results from this application and to propose directions for future development, in order to enhance the effectiveness of the Design Building Block approach in the elucidation of the problems presented by preliminary warship design and in developing the design solutions.***

## 1.3 STRUCTURE OF THE THESIS

The thesis is divided into seven chapters with separate appendices providing additional material relevant to specific sections, as shown in Figure 1.1. This includes, at Appendices 6, 8, 9 and 10, four published papers which the candidate co-authored with his supervisor. Figure 1.1 also shows the general flow and relationships between the chapters. Chapter 2 provides background and context for the thesis, considering the nature of ships and ship design and recent approaches to computer aided preliminary ship design. Chapter 3 outlines the development of the Design Building Block approach and its most recent implementation as SURFCON in the PARAMARINE ship design system developed by GRC [*GRC, 2003*]. This leads into Chapter 4, which outlines the initial work undertaken with the tool to develop a practical process for its use in design. The range of design studies carried out by the candidate using the tool are described in Chapter 5. The discussion in Chapter 6 brings together the approaches outlined in Chapter 2 with the procedure from Chapter 4 and experience of applying the tool described in Chapter 5. From these discussions, conclusions are drawn and presented in Chapter 7. Each of these chapters is described in more detail after Figure 1.1.

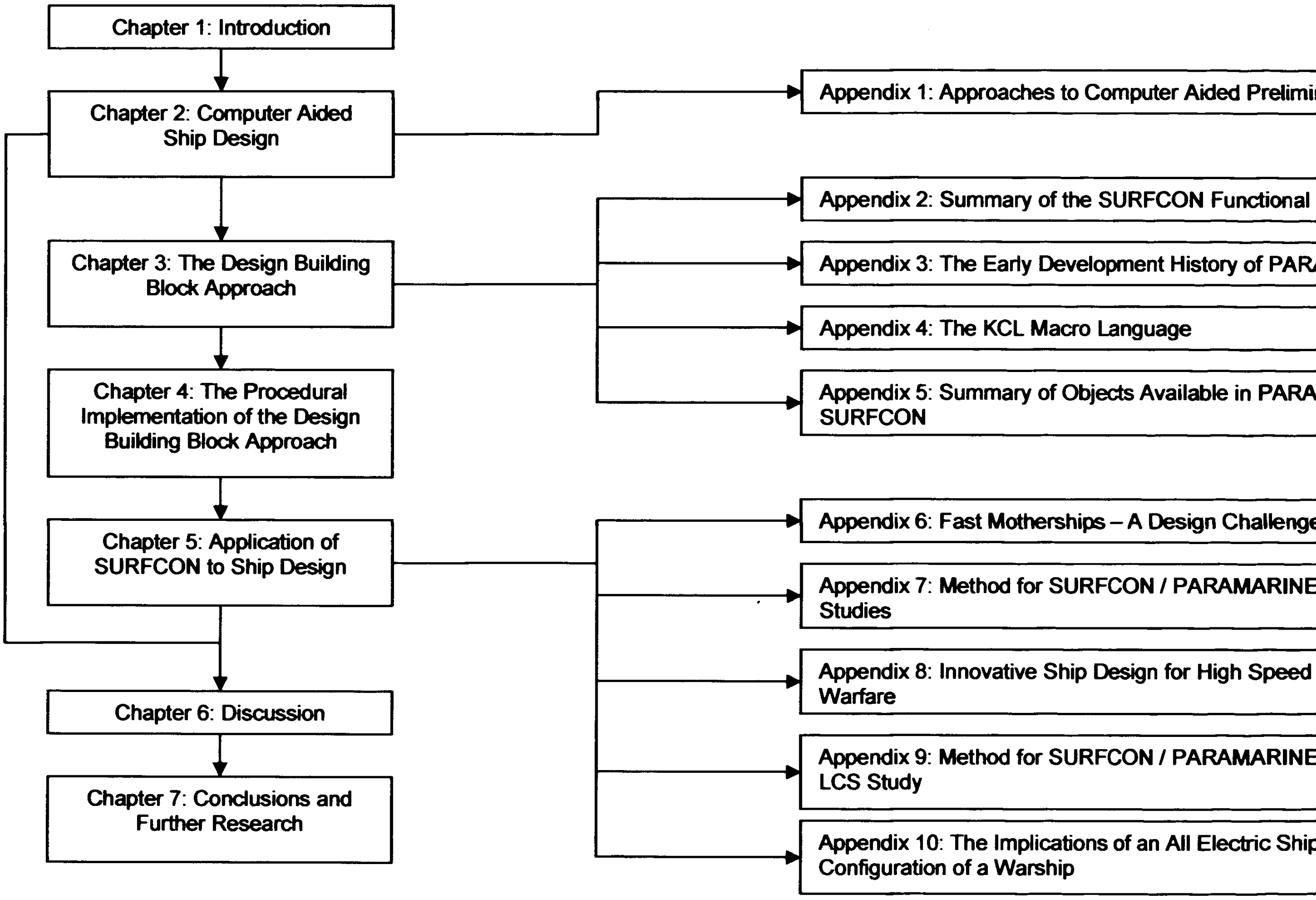



***Figure 1.1: Overall structure of the thesis***

## Chapter 2

This chapter outlines the characteristic qualities of ships that make ship design a complex process worthy of study in the field of design methodology. An overview of the ship design process is presented with particular emphasis on the position of preliminary design in the overall process, as the stage when innovative ideas should be investigated. A summary is presented of the application of computers to preliminary ship design and the approaches that have been most widely proposed and implemented are described and then discussed. More detailed reviews are given in Appendix 1. A short review of the importance of the human–computer interface is presented, the role of sketching in preliminary design discussed and recent research into the application of computers in this area summarised. From this, initial conclusions are drawn on the nature of computer aided preliminary ship design, providing the background to the recent development of the Design Building Block approach.

## Chapter 3

The Design Building Block approach is described as a holistic approach to ship design, featuring an architecturally–centred initial synthesis and utilising graphical computer aided design tools to incorporate stylistic issues and designer judgement into the design process. The historical development of software implementations of this new approach are outlined and finally GRC's "PARAMARINE" ship design system, used for the latest implementation, is described and the functionality provided by this software is compared with that achieved in earlier work on the approach. Key technical issues regarding the software are described in more detail in Appendices 2, 3, 4 and 5.

## Chapter 4

This chapter describes the development and demonstration of a practical procedure for the effective utilisation of the capabilities of the tool over three early stage ship design studies. The chapter concludes with an outline of the initial procedure that was developed for synthesising new designs in the PARAMARINE-SURFCON implementation of the Design Building Block approach. This procedure then provided the complete design toolset required to generate the early-stage designs outlined in Chapter 5.

## Chapter 5

Chapter 5 covers the ship designs produced by the candidate using the Design Building Block approach and SURFCON-PARAMARINE. This chapter shows how for each design the approach and tool was applied to a different type of early stage ship design. Each section contains summaries of the work carried out and the main issues, with the more detailed descriptions of the designs given in Appendices 6, 7, 8, 9 and 10.

## Chapter 6

The discussion presented in Chapter 6 is organised into four main aspects;

- General issues regarding the application of the Design Building Block approach to the preliminary design of innovative ships,
- Issues highlighted regarding the interaction of the designer and the design,
- The integration of the Design Building Block approach with advanced numerical analysis of designs,
- The process model used in the studies.

# Chapter 2: Computer Aided Ship Design

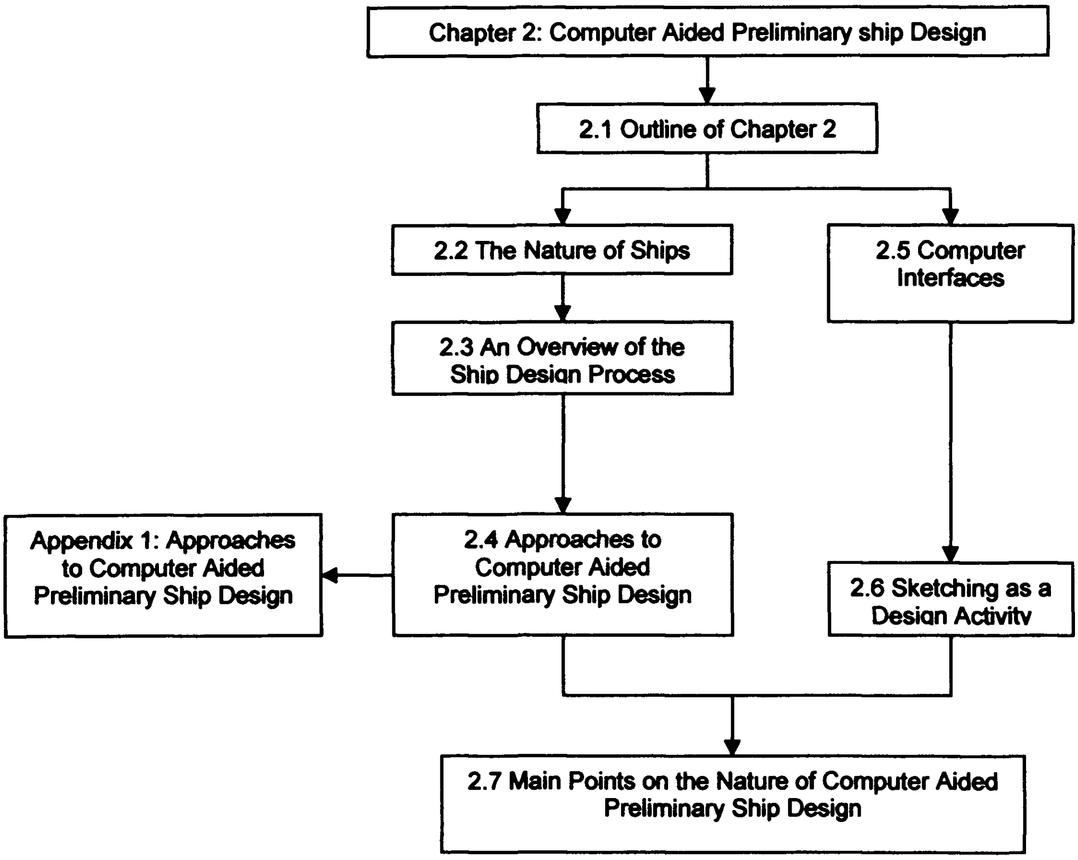



***Figure 2.1 Schematic of Chapter 2***

## 2.1 OUTLINE OF CHAPTER 2

This chapter provides the background and context for the thesis on the application of the Design Building Block approach to innovative ship design. The first two sections outline the characteristic qualities of ships that make ship design a complex process worthy of study in the field of design methodology, by reviewing the many published papers covering ships and ship design. This broad summary provides the background for a survey of the ways in which computers have been applied to preliminary ship design. In addition, the importance of the human computer interface is discussed and the role of sketching in preliminary design together with recent research into the application of computers in this area is summarised. In addition to illustrating the need for ongoing research in the field of preliminary design, this chapter also provides a wide survey of the subject which is used to inform the discussions in Chapter 6.

## 2.2 THE NATURE OF SHIPS

Ship design has been presented as a paradigm of the design of complex products [*Andrews, 1998*] and they have been described as the most complex artefacts designed and assembled by man on a regular basis [*Graham, quoted in Gates & Rusling, 1982*]. The level of complexity required can vary greatly when the complete range of marine vehicles is considered, from small ferries operating in sheltered waters, through to ocean-going cruise liners, warships and nuclear submarines. The main focus of this thesis is on ships, as opposed to submarines and specifically service vessels, with an emphasis on warships. Watson [*1998*] presents a graphical overview of the different types of vessel design, as shown in Figure 2.2. Merchant vessels are clearly delineated as those vessels that that use the sea as a medium to move cargo from one location to another and, in systems terms, could be considered as part of a transport system [*Erichsen, 1989*]. Watson differentiates warships from other service vessels by the complexities of the procurement process and by the need to consider the capabilities provided by the warship as part of a fleet.

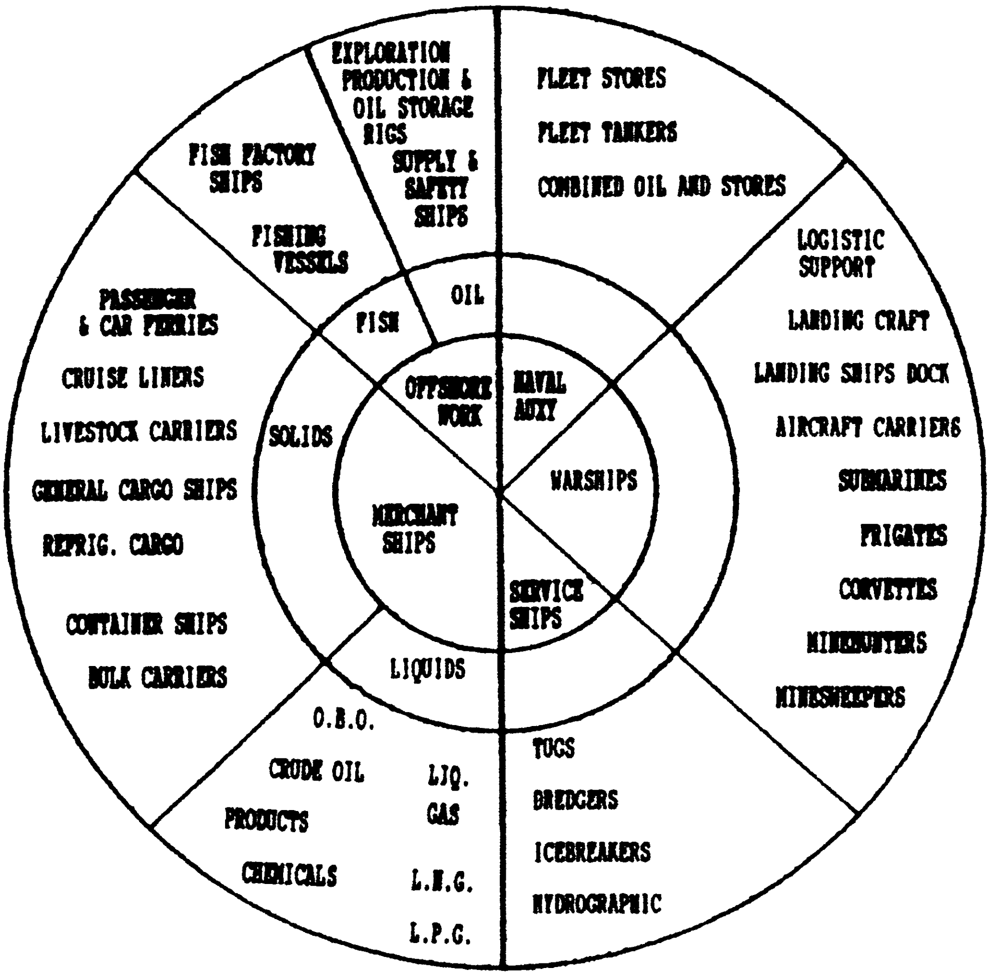



***Figure 2.2: Main ship types and their purposes [Watson, 1998]***

Compared with aircraft, Andrews has argued that warships can be seen to be more complex as the former are primarily a weapons delivery system, whereas warships must carry command and control and a full range of support systems with them. They must also be self supporting for the considerable duration of their mission and are inhabited by humans who are not just operators but occupants, requiring further accommodation and support systems [*Andrews, 2004a*]. In addition, the environment in which they operate is an interface between two domains, is hostile and ever changing.

The main areas of ship performance of primary concern to the naval architect were summarised by Brown and Andrews [*1981*] as "$S^5$":

- Speed
- Seakeeping
- Strength
- Stability
- Style

The first four areas are characterised by the technical aspects of the ship design. In each of these cases the vessel's performance can be predicted to an acceptable degree of accuracy using analytical tools. These can range from intact stability calculations using volumetric modellers, such as PARAMARINE [*GRC, 2003*], through resistance predictions, using historical series data for similar ships (for example the Series 64 high-speed hullforms [*Yeh, 1965*]) or numerical methods [*Andersen & Guldhammer, 1986*], to time domain simulations for seakeeping. However, the final performance of the completed ship in each one of these areas will still have a degree of uncertainty. This may be due to scaling effects, between model tests and reality, or, in the case of seakeeping, due to the dynamic and random nature of the operating environment greatly complicating the task of making detailed performance predictions [*Lloyd, 1989*].

Numerical processes of optimisation can be used to improve aspects of the performance of the design. These can be applied to limited areas of the design within a constrained solution space, such as the hullform shape [*Boulougouris & Papanikolaou, 2006*] or the design of structural scantlings [*Richir, Karr & Rigo, 2006*]. The overall design can also be optimised to improve performance in one of the areas listed above. However, this may be at the cost of other areas of performance. Examples of radical solutions with both advantages and disadvantages include:

- The Small Waterplane Area Twin Hull (SWATH) vessel offers improved seakeeping performance, but has increased resistance in calm water and requires a greater structural weight fraction than an "equivalent" monohull plus maintenance of draught and trim [*Kennell, 1992*].
- The high-speed catamaran offers increased deck area when compared to a monohull of the same displacement and less resistance at speed, but poorer motions in rough seas [*Armstrong, 2004a*].
- The trimaran offers reduced resistance at high speed, reduced speed loss in waves and increased deck area on No 2 deck, but has greater resistance at lower speeds and increased structural weight compared to its equivalent monohull [*Skarda & Walker, 2004*], [*Andrews, 2004b*]
- The foil-assisted planing trimaran design provides deck area appropriate to an increased number of passengers on a low displacement vessel and high speed. The trimaran configuration provides the former, while the use of lifting foils and a planing hull reduces the resistance sufficiently to achieve the required speed [*Tulk & Quigley, 2004*].

The final entry in the $S^5$ list, "Style", encompasses a wide range of issues not all of which are amenable to numerical investigation, particularly in the early stages of design. Examples of stylistic choices, each with its own complexity were given by Andrews [*1984*] and include the margin philosophy, survivability standards or the overall architecture of propulsive machinery, with possibilities including geared gas turbines or more recently, electric propulsion [*Apriainen et al, 1993*], [*Doerry & Fireman, 2006*].

There are many possible specifications that can be set for a new design, covering all of the $S^5$ areas. These can include simple performance goals, such as a speed to be achieved in a specified load condition, hull fouling and sea state and more complicated requirements, such as compliance with regulations or standards [*Ferreiro & Stonehouse, 1994*]. In some cases, the performance requirements are specific enough to drive the design to a particular solution, as in the case of the Ocean Survey Vessel H.M.S. Scott [*Wakeling et al, 1999*], where the low noise level and deep draught, required by the hull-mounted sonar, led to a large vessel with many empty compartments. More typically, however, the performance requirements themselves will not specify a single solution and a range of different configurations will be evaluated, as described by Leopold and Reuter [*1971*] for US Navy destroyers and amphibious ships and more recently by Skarda and Walker [*2004*] and Roy et al [*2004*], both comparing monohull and multihull designs against the same performance requirements.

Most service vessels must perform in a variety of roles and a range of functions. For its overall performance to be acceptable, the ship, composed of a wide range of sub-systems, must as a whole perform well in apparently disparate areas. These component systems originate in a wide variety of engineering disciplines, each with their own constraints, objectives and performance criteria. Although the performance of individual items of equipment may be accurately known at an early stage of design (if using existing equipment), the interactions, between the many different systems in the design are very important and the consequences of assembling them as part of a discrete system or their impact on the whole ship, may not be known with sufficient certainty early in the design when the choice is being made. These interactions can occur at all levels of the design, from the detail of specific systems to the overall configuration. Gates and Rusling [*1982*] show how the combat system has both internal relationships and interactions with the rest of the vessel, while Brown [*1993*] provides a wider view often linked to the spatial configuration.

Given many of these interactions are driven by the spatial configuration (layout or architecture) of the vessel, Brown [*1987*] illustrates this by means of concentric rings of problem areas and solutions that can be incorporated into the overall layout of the vessel, see Figure 2.3.

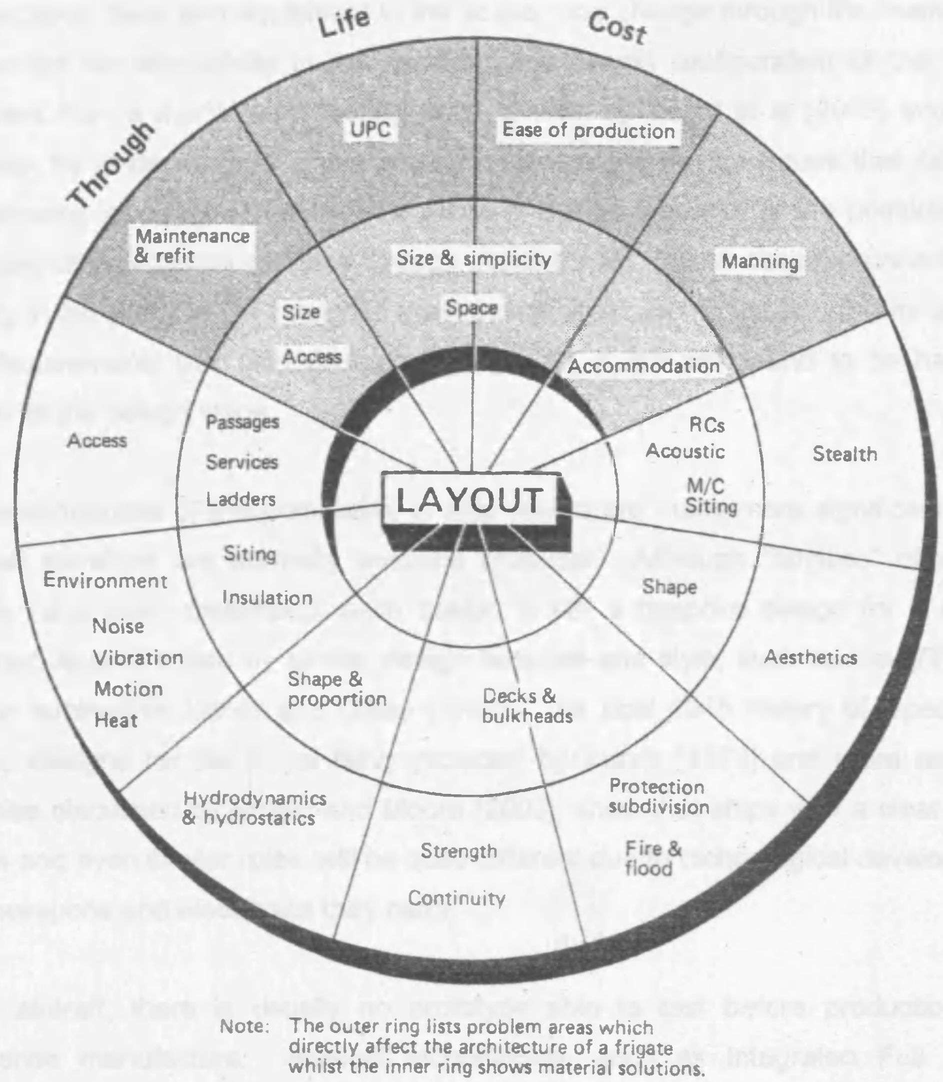



***Figure 2.3: Diagram of design constraints on layout showing how ship architecture is related to all aspects of ship performance [Brown, 1987]***

The overall architecture of the vessel encompasses many areas of configuration which strongly influence the performance of the vessel and have interactions with each other. Van Griethuysen [*1992*], [*1993*] describes the many complex interrelationships in monohull hullform design, while Andrews [*2004b*] provides a more detailed overview of the many architectural issues introduced by the use of multihulls and the provision of aircraft facilities [*Andrews, 2003a*]. MacCallum outlines how configurational relationships can change during the design process, with additional links between parameters becoming clear after evaluation of earlier concepts, [*MacCallum, 1982*], and Brown and Moore [*2003*] describe, from a historical perspective, how the aspects of the overall configuration, that are seen to be of most importance in the design, can change as the design develops.

The functions, roles and equipment in the vessel may change through life, leading to a requirement for adaptability in the systems and overall configuration of the vessel. Examined from a marine engineering point of view by Abbot et al [*2003*] and, more generally, by Andrews [*2001*], adaptability concerns the design issues that can arise from allowing insufficient margins in a range of design features for the possibility of a significant change in role part-way through the ship's life. In this case the uncertainty is not only in the ability of the design to meet the initial requirements, but also its ability to meet requirements that may develop through life, which are bound to be harder to quantify at the design stage.

The consequences of this complexity in ship design are made more significant by the fact that warships are normally bespoke products. Although "families" of warship designs have been developed, each design is still a bespoke design for a specific customer, even if linked by similar design features and style, such as the VT export designs outlined by Usher and Dorey [*1982*]. The post 1945 history of, specifically, warship designs for the Royal Navy provided by Purvis [*1974*] and more extensive examples discussed by Brown and Moore [*2003*], show that ships with a clear design lineage and even similar roles, will be quite different due to technological developments in the weapons and electronics they carry.

Unlike aircraft, there is usually no prototype ship to test before production units commence manufacture. Radical technologies, such as Integrated Full Electric Propulsion (IFEP) will be tested at a shore establishment [*Gerrard & Eaton, 2004*] or introduced into service in a lower risk lower performance configuration (for example, electric propulsion was introduced into the RN in the LPD(R) using existing equipment, before being adopted with new equipment for the Type 45 destroyer [*Newell & Curlewis, 2004*], [*Gerrard & Eaton, 2004*]). Similarly a new combat system can be tested on a trials vessel or shore development facility. Demonstrator craft have also been used to evaluate new hullform types, such as the trimaran RV Triton [*Pattison & Searle, 2000*] and the hydrofoil HMS Speedy [*Brown et al, 1984*]. However, until the first of class is complete all the new technologies and equipment will not have been operated together. Extensive testing is thus required of the First of Class to ensure the performance of the design. This is largely, but not exclusively focussed on the propulsive machinery and the combat systems [*Harris, 1980*], [*Yarrow Shipbuilders Limited, 1989*]. Alterations may be required to meet the performance specifications but obviously will be heavily constrained.

Naval vessels in particular are strongly affected by the political, social and economic environment in which they are designed and procured. In the latter half of the twentieth century, the main influences have been issues of cost and maintenance of the ship building industrial base [*Brown & Moore, 2003*] with additional concerns, such as the potential for exports, if a design is adopted by the national navy [*Skolnick & Skolnick, 1991*] [*Brown & Moore, 2003*] and the potential for international co-operative projects, such as the British-French-Italian "Common New Generation Frigate" (CNGF). The latter can greatly complicate all aspects of the design, from the selection of equipment to management procedures [*George et al, 1999*]. More recent influences include the concept of risk [*Gates, 2004*] and the impact on the environment [*Breslin & Wang, 2004*].

## 2.3 An Overview of the Ship Design Process

### The Overall Process

The complex nature of ships outlined in the previous section has had a strong effect on the processes used to design them and many approaches and procedures have been adopted. The ship design process has been discussed in detail by Brown [*1993*] and Andrews [*1981*] [*1984*] [*1993*] [*1994*], primarily from the UK perspective and by Tibbitts & Keane [*1995*] from the perspective of the USA. Andrews [*1984*], Dicks [*1999*] and Lamb [*2004*] present extensive overviews of the approaches and more formal summaries of the different methods of design have been presented in the Design Methodology State of the Art Reports of IMDC 1997 [*Andrews et al, 1997*] and IMDC 2006 [*Andrews et al, 2006*].

The overall ship design process has been characterised as one of increasing detail and confidence in the design. Although the terminology used to describe the stages in this process vary, a general outline is provided by Andrews [*1994*].

- Concept Exploration
    - A wide-ranging divergent phase of exploration in which initial ideas on solutions to meet the initial outline requirements are explored;
- Concept Studies
    - Investigations on issues which are likely to be significant size or cost drivers in the design;
- Concept Design
    - A baseline design is produced and studies of options undertaken;
- Feasibility

  - o Usually one solution is developed to a level sufficient to assess its technical viability, addressing all major technical issues;
- Ship Design and Contract Definition
  - o The design is developed to sufficient detail to form the technical content of a contract;
- Detailed Design
  - o Overlapping with the construction, this involves producing the working definition (drawings etc).

Preliminary design is concerned with the first three stages; Concept Exploration, Concept Studies and Concept Design and also to some extent with early Feasibility Design. Figure 2.4 illustrates the importance of the early stages of ship design, with few resources and little cost, but a very significant impact on the final cost of the vessel.

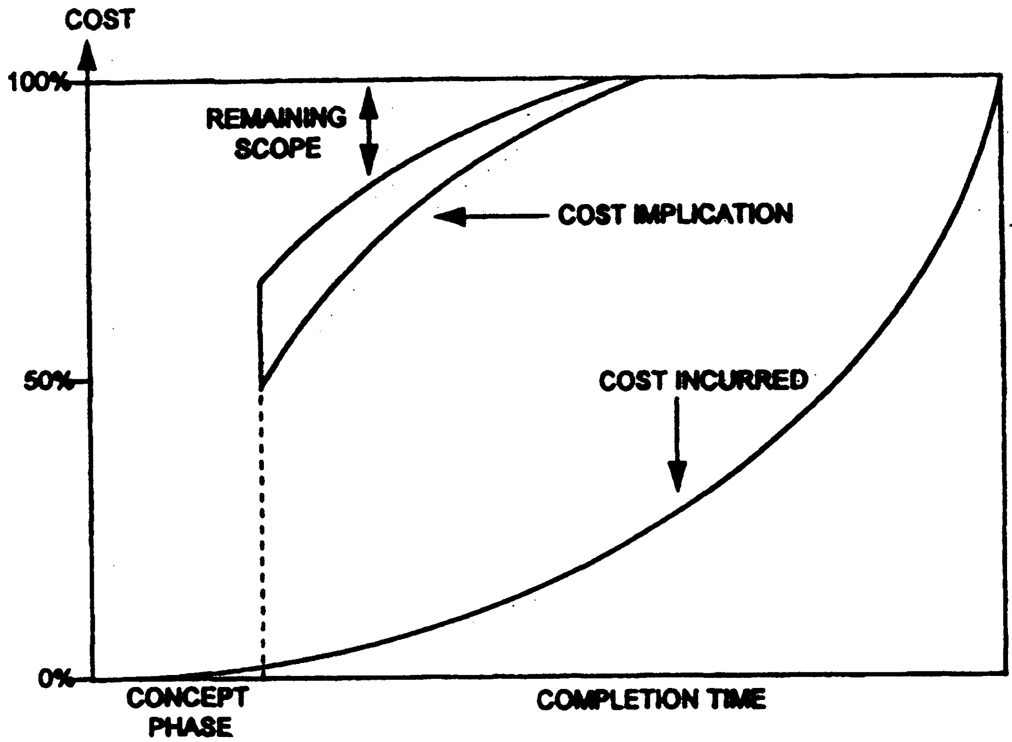



***Figure 2.4: Representation of the importance of preliminary ship design [Andrews et al, 1996b]***

Although the list above shows the requirements as an input to the process, Andrews [*1984*], [*1998*] has presented preliminary ship design as an example of a "wicked problem", in that the difficulty lies not in producing solutions to meet operational requirements, but rather in formulating the problem itself and bounding the solution space within constraints. The objective of preliminary design is then not to produce solutions to meet the requirements, but to explore and determine the requirements themselves. This relationship between statements of required capability and the preliminary stages of warship design has been discussed by Andrews [*2003b*]. Typified by the extensive consideration of requirements for the Royal Navy's Future Surface Combatant (FSC) [*Finlayson & Johnstone, 2002*] this type of requirements engineering can be seen as largely a judgement exercise in overall military capability. In contrast Andrews concludes that the requirements should be arrived at through the use of rapid, architecturally centred preliminary design tools to aid in requirements elucidation [*Andrews, 2003b*].

Andrews [*1998*] has presented a range of types of ship design, from a naval perspective, in terms of increasing design complexity, as shown in Table 2.1. Merchant ships are usually of the first three types, outlined by Watson and Gilfilan [*1976*] and Lamb [*2004*]. However, as discussed in Section 2.2, radical designs can also be adopted for use in commercial vessels, particularly in fast passenger and car ferries, such as the foil-assisted trimaran [*Tulk & Quigley, 2004*] and displacement trimaran designs [*Armstrong, 2004b*].

| Type | Example |
|---|---|
| Second batch | Batch 2 Type 22 Frigate |
| Simple type ship | Many naval auxiliary vessels |
| Evolutionary design | A family of designs |
| Simple synthesis | UCL student designs |
| Architectural synthesis | UCL design studies |
| Radical configuration | SWATH, trimaran |
| Radical technology | US Navy Surface Effect Ship |

***Table 2.1: Types of ship design with examples from naval ship design [Andrews, 1998]***

For warships, the focus of this thesis, the overall process is complicated by the parallel development of the weapons and propulsion systems, as outlined by Bryson [*1984*] with regard to the Royal Navy Type 23 frigate, see Figure 2.5. This increases the uncertainty in the design process, as the equipment and its interfaces with the rest of the ship will be subject to change. This uncertainty has led to the adoption of structured margin philosophies, with separate allowances for uncertainty in the design and the addition of new equipment [*Andrews, 2001*].

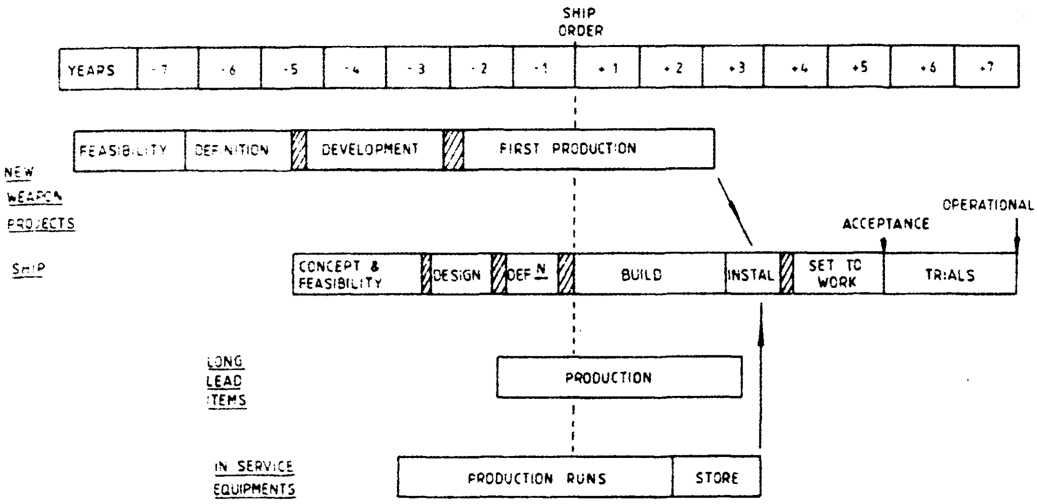



***Figure 2.5: Chronological relationship between ship design and procurement and that of its major equipment [Bryson, 1984]***

These interactions make the design of naval ships inherently complex and have been effectively illustrated by Brown [*1995*] as an "interaction mesh" of interlinked iterative loops, as shown in Figure 2.6. The complexity of the ship design combined with the possibly conflicting physical consequences of the requirements make ship design an example of "satisficing", as defined by Simon [*1981*]. The process of satisficing is contrasted with the process of optimising, where a design is configured to provide the maximum or minimum of a certain property. Instead the objective is to find *good* configurations, rather than the *best*.

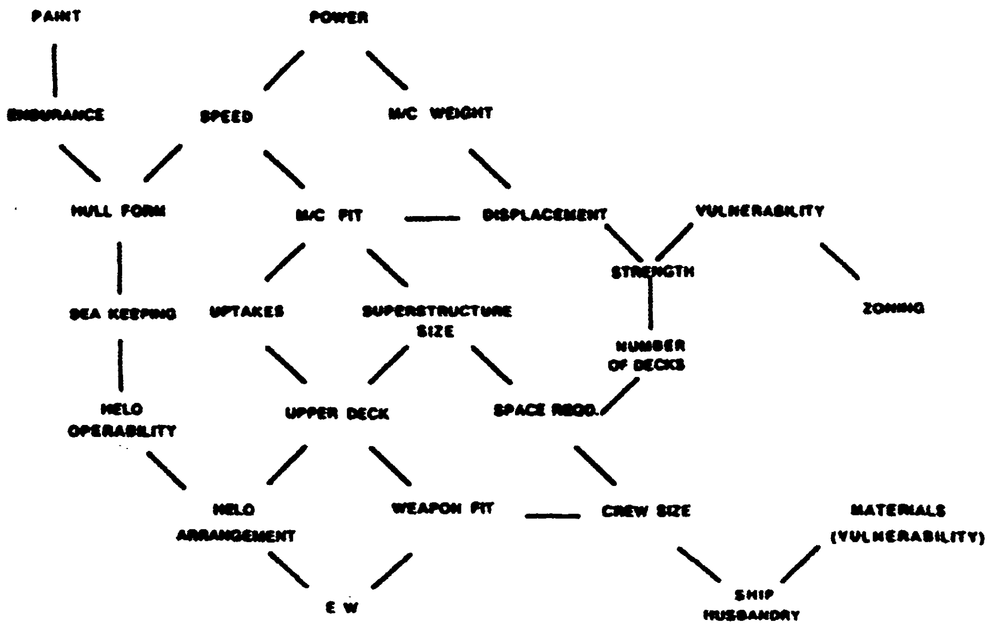



***Figure 2.6: Part of the "interaction mesh" of interlinked iterative loops [Brown, 1995]***

The complexity, uncertainty and interactions in the wider field of preliminary design have resulted in an iterative model being well established as a general approach and Lamb [*2004*] outlines several of the generic iterative approaches that have been used in design in general and ship design in particular. This iterative process allows the design definition to be corrected and improved, based on previous calculations and investigations. The iteration takes place at many levels from small cycles within each loop of Figure 2.6, an example of which is shown in Figure 2.7, through the iteration of a design to a numerical balance of weight and volume, to a much larger iteration of the design through the stages of the design process described above.

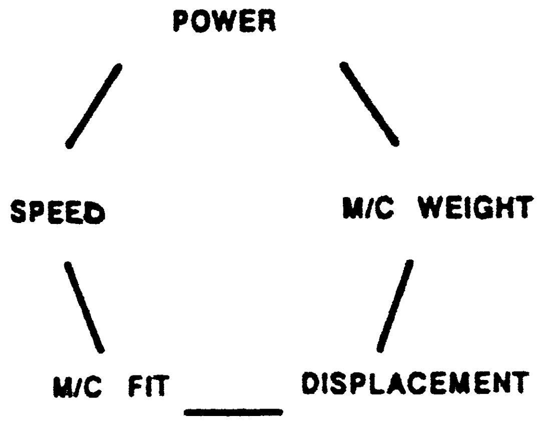



***Figure 2.7: An example of a simple iterative loop in ship design [Brown, 1995]***

Andrews [*1981*] presented this iterative process as a 3-dimensional design spiral, expanding on previous 2-dimensional representations to include the main constraints and additional influences outside the purely technical issues, as discussed in Section 2.2. This spiral description is illustrated in Figure 2.8.

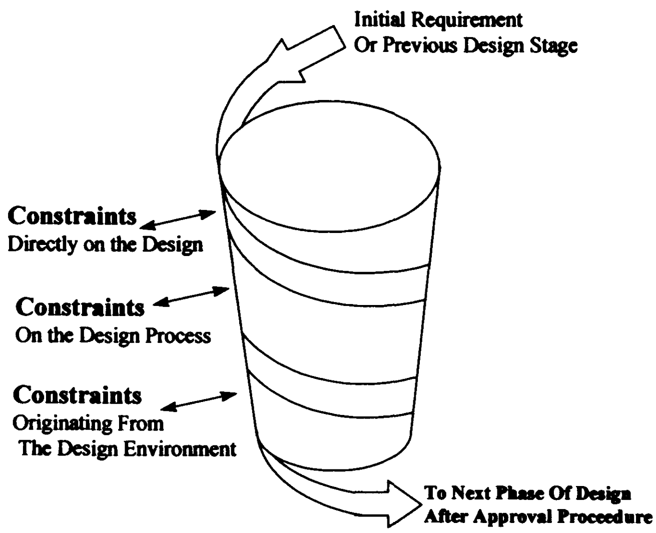



***Figure 2.8: The Design Spiral [Andrews, 1981]***

However, alternatives to the spiral description have been proposed. The two main alternatives are the bounding and set based approaches, outlined by Lamb [*2004*]. In the design bounding approach, a wide range of candidate variant designs is reduced by eliminating those that do not meet requirements or constraints (i.e. are outside defined bounds). In the set based approach, outlined by Parsons [*2003*], the design is developed by producing options that are within broad sets with competing requirements. This can then inform the designer as to potential trade-offs between the competing design aspects.

A notable approach that has been applied to ship design, to manage the complexity and interrelationships, is Systems Engineering. This is not an approach to design itself, but rather an approach to organising the design and the design process. Figure 2.9 illustrates the simple outline life cycle used within Systems Engineering, showing the stages of requirements generation, the design of a solution at the overall (architectural) and detail (component) levels, integration of the solution and concluding with testing.

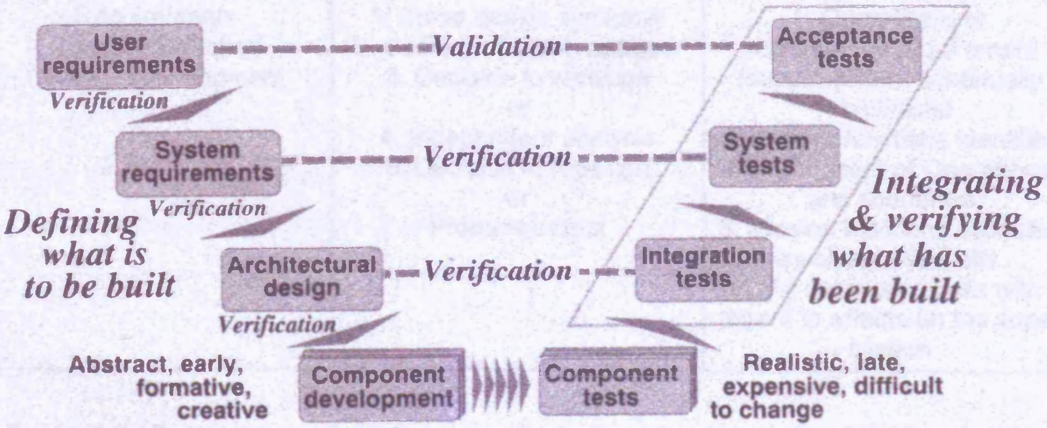



***Figure 2.9: The simple system life cycle [Stevens et al, 1998]***

Checkland [*1993*] identified the crucial characteristics of "systems thinking" as being the emergent properties of the whole system and defined four basic ideas in systems thinking:

- Emergence: The principle that the whole entity will exhibit properties which are attributable only to the whole and cannot be reduced to component parts;
- Hierarchy: The principle that any entity can be treated as a whole and also broken into component parts;
- Communication: The transfer of information between entities;

- Control: The means by which entities maintain their performance under changing circumstances.

Furthermore, Checkland [*1993*] highlighted two types of systems: Hard and Soft. The Hard Systems methodology, known as Systems Engineering, was defined as suitable for tackling problems where the objective is readily definable and the system's emergent properties are known. The Soft Systems methodology, however, was concerned with problems in which the objectives, relationships and emergent properties are unknown and the approach must then focus on understanding the problem to be solved.

Recent discussions on the use of Systems Engineering in warship design are summarised in Andrews et al [*1997*] and Andrews et al [*2006*]. Systems Engineering has been adopted as the model for US naval ship design and the main characteristics are shown in Table 2.2.

| **Elements of SE** | **Engineering the System** | **Systems Thinking** |
|---|---|---|
| • Requirements<br>• Concept Selection<br>• Concept Development | 1. Some design synthesis<br>2. Some (sufficient) analysis<br>3. Decision to redesign<br>or<br>4. Independent analysis<br>5. Decision to redesign<br>or<br>Produce output | 1. Operational or performance requirement (super system) continually scrutinised<br>2. System functions identified from Concept of Operations and scenarios<br>3. Mission functions allocated involving trade offs<br>4. All decisions made with regard to effects on the super system |

***Table 2.2: A summary of systems engineering characterising US Naval ship design [Andrews et al, 2006], from Calvano et al, [2000]***

Andrews et al [*2006*] summarising van Griethuysen [*2000*], notes that Systems Engineering does have advantages, such as emphasising integration in the design process and incorporating issues such as testing and acceptance. Systems Engineering is criticised, however, for being overly general, failing to recognise that different engineering products require different approaches to design and, in particular, some proponents suggest Systems Engineering allows requirements to be generated without any modelling of possible design solutions [*Andrews et al, 2006*]. This latter point has been discussed in more detail by Andrews [*2003b*], who suggests that the process of "requirements engineering" instead should be one of "requirements elucidation", where the designer has an ongoing dialogue with the requirements owner through the medium of early design studies.

## Approaches to Preliminary Ship Design

Returning to Table 2.1, the type of ship design being developed influences the preliminary design process used. Merchant ships are usually evolutionary designs or type ships and so can make use of sizing algorithms with a high degree of certainty, as outlined by Watson and Gilfillan [*1976*]. This is not always possible with warships, although in some cases a family of vessels can be developed by a single design house, with similar features, as presented by Usher and Dorey [*1982*].

In outlining the process of preliminary ship design in the 1950's, Brown [*1983*] describes the use of mathematical parametric models based on type ships for the preliminary design of new warships. Frequently presented in the form of graphs and used for calculation by hand, these were intended for evolutionary design and separate, more detailed, calculations were required where the new design deviated from the established configuration. Subsequent development of the design was more labour intensive and required the development of a hullform to meet the dimensions and hullform shape coefficients, which had been determined in the initial stages. Manning [*1956*] outlines a similar process and notes that the development of a hullform was vital to the investigation of the internal arrangements and thus was developed as early as possible. These approaches to preliminary ship design were characterised by a sequence of estimations of weights and development of detail, as follows [*Manning, 1956*]:

1. Select a parent ship;
2. Make first approximation of displacement;
3. Select trial displacements for making preliminary estimate of displacement;
4. Make preliminary estimate of displacement;
5. Check principal dimensions and coefficients of fineness;
6. Re-estimate displacement of design in accordance with principal dimensions and coefficients of fineness selected in step 5 and prepare weight statement;
7. Prepare curve of sectional areas;
8. Prepare preliminary line drawing;
9. Make buoyancy and stability calculations then prepare hydrostatic and stability curves;
10. Prepare preliminary general arrangement plans (for merchant ships, make computations of tonnage and capacity);

11. Send preliminary lines to ship model towing tank to check powering computation;
12. Prepare preliminary machinery general arrangement plans;
13. Prepare preliminary structural plan of midship section;
14. Make preliminary weight calculation, including estimate of longitudinal balance and stability for standard conditions of loading;
15. Prepare revised weight estimate showing preliminary design displacement;
16. Make a preliminary study of buoyancy and stability of ship in damaged condition.

The calculations required and time taken to develop such design descriptions as the curve of areas, limited the possibility of making significant changes to the design and thus the iterative process was constrained, as shown in Figure 2.8. The knowledge and skills of the individual designer were a vital component of these design processes, as described by Brown [*1983*] and by Brown and Moore [*2003*]. The difficulty in conducting a numerical analysis of the designs led to a reliance on designer creativity and judgement, so that in the early stages practical solutions had to be developed and the need for more detailed investigations identified. The next section provides an overview of the application of computers to this preliminary ship design process and the changes that resulted.

## 2.4 APPROACHES TO COMPUTER AIDED PRELIMINARY SHIP DESIGN

This section outlines the main ways in which computers have been applied to preliminary ship design. Firstly, an overview is presented of the three main tasks for which ship designers have used computers and how this usage has changed over time. Andrews [*2003c*] has summarised preliminary warship design tools and their roles (see Table 2.3).

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

***Table 2.3: Analysis of preliminary warship design tools [Andrews, 2003c]***

After an overview of the application of computers to preliminary ship design, the use of numerical models, concept exploration models and parametric design is considered, followed by Multi Criteria Decision making approaches. There are two "fuzzy logic" approaches that have been applied to preliminary ship design; Genetic Algorithms and Artificial Neural Networks, which are considered before the focus turns to expert and knowledge based systems. Finally, the use of Virtual Reality and Simulation Based Design is discussed. The main text contains summaries of each of the approaches, with more detail in Appendix 1.

### 2.4.1 An Overview of the Application of Computers to Ship Design

The application of computers to ship design has changed significantly over the latter part of the 20th Century, as related by MacCallum [*1982*], Andrews [*1984*] Tibbitts & Keane [*1995*], Jensen et al [*1997*] and Tan & Bligh [*1998*]. There are three main ways in which computers have been applied to ship design; analysis, modelling and synthesis.

#### Analysis

MacCullum [*1982*], in summarising the development of the applications of computers to ship design, notes that the initial applications involved the computerisation of conventional manual methods, for analyses of intact and damaged stability, estimation of resistance and structural design. These tools applied the same methods as the previous hand calculations to a simplified model of a particular feature of the design. Thus these calculations could be undertaken in less time, accelerated by the computational power of the machine [*Tibbitts & Keane, 1995*]. The interfaces to these tools were frequently purely numerical, although limited graphical representations of pre and post processed results were also developed over time [*Calkins, 1988*].

Approaches were also developed to algorithmically link the dimensions and form factors of the hullform, producing a mathematical model of the hull that could be investigated and optimised for certain aspects of performance [*Keane, 1987*], [*van Griethuysen, 1993*]. A significant development in the use of computers for analysis has been the implementation of non-linear numerical techniques, such as genetic algorithms and neural networks, and these are addressed separately in this chapter. (Sections 2.4.4 and 2.4.5)

A further use of computers for analysis is in rule-based structural design tools, such as Lloyd's Register's RulesCalc [*RINA, 2000*] These tools, focussed on type ships covered by the prescriptive rules of the classification societies, allow the rapid generation of structures and assessment of structural strength based on a relatively simple definition of the vessel (overall dimensions, cargo hold positions, etc).

### Modelling

Another important use of the computer has been through Computer Aided Draughting and Drawing tools. These store a description of the spatial configuration of the vessel. This description may then be interrogated in order to provide inputs for subsequent analysis of the vessel's performance or configuration. Although crude tools were developed relatively early on, the degree to which the ship definition could be stored electronically has increased with the increasing capabilities of the machines available [*Tibbitts & Keane, 1995*].

The early tools, such as the BRITSHIPS software [*Forrest & Parker, 1983*], were focussed on storing a definition of the structural design of the vessel for use in Computer Aided Manufacturing systems (CAM) and this remains an area of development, along with the generation of faired hull surfaces [*Couser, 2006a*], [*Couser, 2006b*]. Initially these systems consisted of several different tools with common information exchange file formats, such as the UK MoD Forward Design System (GODDESS) outlined by Yuille [*1978*], Holmes [*1981*], Pattison et al [*1982*] and Barratt et al, [*1994*]. Developed by the UK MoD for the design of future surface warships, this system was capable of both modelling and analysis of hullform, layout, structures, stability etc. Many current tools can represent the overall and detail configuration of the ship in three dimensions (3D) and can similarly interface with various analysis tools. Examples of this include AutoShip, which is a 3D development of the 2D drawing software AutoCad [*RINA, 2007*], TRIBON [*RINA, 2005a*], Foran [*RINA, 2006*] and PARAMARINE [*GRC, 2003*].

Another widespread application of electronic storage of complex designs is the "Integrated Product Model" (IPM) or "Integrated Product Data Environment" (IPDE), where the complete detailed configurational definition of the design is stored centrally and can be accessed simultaneously by many in the design team [*Ross, 2006*]. These tools are intended for the detailed stages of design leading to production. IPM / IPDE concepts have been applied to ship design in such tools as, IntelliShip [*Andersen & Piene, 2005*], Foran [*RINA, 2004b*] NAPA [*Juntunen & Kosomaa, 2002*], CATIA [*RINA, 2001*] [*RINA, 2004b*] and TRIBON [*RINA, 2005b*]. This also allows the use of an on-line database of equipment models, produced by the equipment manufacturers.

## Synthesis

The third main area of application of computers to ship design is the integration of analysis procedures into an overall design system. This has led to the development of integrated systems suitable for use in the creation of new designs. One example is the CONDES tool, developed for use prior to modelling the design in GODDESS [*Hyde & Andrews, 1992*]. This provided a simplified model of the hullform and analysis, but was more flexible and faster to use. It thus allowed a wider exploration of cost and capability options before a limited range of designs were chosen to be studied in more detail using GODDESS.

The more limited type of design synthesis implemented in CONDES, making use of historically derived algorithms and limited detailed analysis has been widely applied to early stage computer aided ship design. Examples include the US Navy's Destroyer design tool DESCA [*Robbins, 1983*], its successor system ASSET [*Heidenreich, 2002*] and the portfolio of tools for container ship design outlined by Schiller et al [*2001*]. The UCL MSc Ship Design Exercise procedure is an example of a primarily numerical process that, although intended for use with computers, is not integrated to a particular tool. The overall iterative synthesis procedure is shown in Figure 2.10. This process links the mathematical parametric models of the hullform, developed by van Griethuysen [*1993*], with historically derived weight and space estimation algorithms that scale from the overall size of the ship. This is a simple form of numerical synthesis, making use of typical values for Payload Volume Fraction (e.g. 0.3 for surface combatants), overall ship density and hullform coefficients to initiate the iterative process, but is flexible in that alternative methods of evaluating each of the weight and volume groups can be utilised.

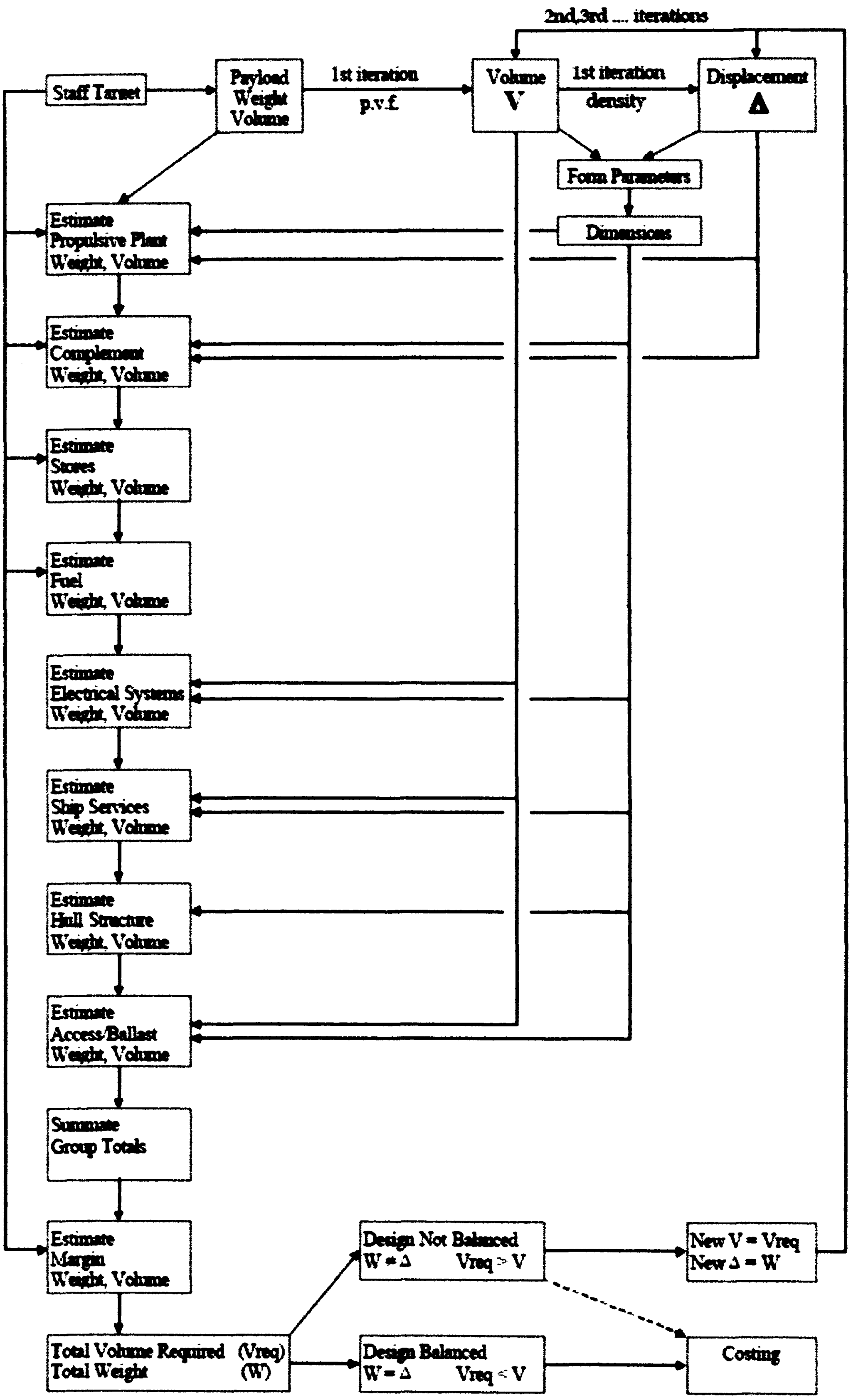



***Figure 2.10: UCL MSc Ship Design Exercise synthesis procedure [UCL, 2001a]***

However since the late 1990's software tools have become commercially available that integrate in a single software package (or a federated system, as in GODDESS), early stage design tools and capabilities together with more detailed naval architectural analysis. The US Navy's LEAPS programme [*Hurwitz, 2001*] seeks to achieve the same integration by providing a common data exchange system between separate early stage design programs within ASSET and specialist detailed modelling analysis software.

GRC's PARAMARINE [*GRC, 2003*], developed as the successor to GODDESS, is an example of an integrated software package. Its modelling tools are suitable for the early stages of design and its numerical analysis tools are accessible through a single software interface using a single model of the design. Some systems developed for detail design, such as TRIBON [*Tribon Solutions, 2004*] and CATIA [*RINA, 2004b*], offer initial design tools the outputs of which are used as the basis of more detailed design development. However, they are primarily focussed on preliminary structural design and weight estimation, intact and damaged stability and on equipment selection. The ship models used reflect this, representing the vessel as a hullform subdivided by bulkheads and decks. The increasing capabilities of commonly available software have permitted the creation of bespoke preliminary ship design tools, as described by Couser [*2005*]. These use features of Microsoft's' Excel spreadsheet to interface with specialist analysis tools, allowing an early stage design to rapidly be generated. However, these numerical tools feature crude definitions of the configuration of the vessel and so are only suitable for constrained type-ships.

Another significant development in the application of computers to ship design, particularly for preliminary ship design, has concerned required hardware. As described by Tan & Bligh [*1998*], computer ship design systems of the 1970s required expensive, specialist hardware and Yuille [*1978*] describes how this limitation on the number of available machines restricted the usage of the tool. The rapid developments in the power of computer hardware, with the associated reductions in computer cost, mean that more advanced tools, such as PARAMARINE and TRIBON, do not require specialist hardware and can be run on the ubiquitous, low cost Personal Computers (PCs).

### 2.4.2 Preliminary Numerical Models (Section A1.1 in Appendix 1)

Numerical ship models, also known as parametric models, have been used in a range of preliminary ship design investigations. The overall approach is that the vessel design is described through a series of parametric relationships, examples of which are given by Parsons [*2003*]. Parsons defines two main types of numerical models; point-based and set-based.

In point based parametric design methods, the designer is required to make decisions regarding the configuration of the design, within the limits imposed by the model and algorithms used. This process leads to the development of a single design solution and limited studies can be carried out to assess the impact on the design of changing the detail choices made. Examples include the US Navy's ASSET [*Heidenreich, 2002*], the CONDES tool, formerly used by the UK MoD [*Hyde & Andrews, 1992*], and the specialised tools for assessing Surface Effect Ships described by Reeves [*1983*].

Set based parametric design methods, however, use these numerical models and approaches such as Genetic Algorithms, to produce a very wide range of variants of a basis design configuration. Each of these variants is assessed for performance and numerical methods, such as Multi Criteria Decision Making (MCDM) and Simulated Annealing [*Hills et al, 1993*], are used to evaluate the resulting densely populated solution space. Examples of set based approaches include the SWATH design tool, described by Nethercote and Schmitke [*1982*], and the container ship tool, outlined by Lamb and Kotinis [*2003*].

Although these numerical models can permit either the very rapid development of a single design solution or the conduct of a numerical search of a large solution space, they suffer from a significant drawback in that they are limited to a single overall configuration of the design. This, combined with limited designer interaction with the model of the design may limit their applicability to innovative preliminary ship design.

### 2.4.3 Multiple Criteria Decision Making (Section A1.2 in Appendix 1)

In Multiple Criteria Decision Making (MCDM) the optimal solution is not immediately clear from the problem and a trade-off must be made between possibly conflicting criteria. A summary of MCDM was presented by Andrews et al [*1997*]. The approach requires the development of a large set of candidate designs to be evaluated and these are typically produced using a parametric model of the ship. A key issue in MCDM is that of how to perform the effectiveness evaluation of the design alternatives, where many areas of technical performance must be integrated into a figure of merit to describe the overall performance of the design. Whitcomb [*1998*] describes the use of hierarchical weighting to aggregate the performance in many disparate areas, including the more subjective issue of risk. This is examined in more detail by Brown and Mierzwicki [*2004*].

There have been several applications of MCDM to ship design, one of the earliest being Nowacki et al [*1970*], who considered the selection of tanker overall characteristics based on economic measures. More recently Mistree et al, [*1990*] considered a corvette and the demonstration by Brown and Mierzwicki [*2004*] used an aircraft carrier operating Unmanned Combat Air Vehicles (UCAV).

The effectiveness of mathematical methods in finding the optimum point, as defined by some measure of effectiveness, in a numerical solution space, is long established and the use of hierarchical weighting systems allows the incorporation of a wider range of performance aspects than just speed and payload capacity. However, in order to generate the large number of alternatives required for an effective search of the solution space, a configurationally constrained parametric model must be used, so limiting the range of solutions that can be considered. This limits the application of such methods to preliminary innovative design, as emergent relationships and novel solutions arising from explorations of the design are less likely to be discovered.

### 2.4.4 Genetic Algorithms (Section A1.3 in Appendix 1)

Genetic Algorithms are sometimes referred to as Evolutionary Algorithms and are a method of solving search and optimisation problems based upon the principles of natural evolution [*Sommersel, 1997*]. The approach can be summarised in the following stages:

a) The design phenotype (physical design) must be mapped to the genotype (collection of chromosomes) by describing the design as genes (design parameters) and arranging these genes as chromosomes (collection of design parameters).
b) The fitness of each chromosome (set of design parameters) must be evaluated, by evaluating the fitness of the corresponding phenotype (physical design).
c) The chromosomes (set of design parameters) are then ranked according to the fitness evaluations.
d) A new population of chromosomes (collection of design parameters) is created by both combining the characteristics of the highest ranked chromosomes and by introducing small random changes to the chromosomes themselves.

The application of Genetic Algorithms to the ship design process has several difficulties as summarised by Sommersel [*1997*]:

- The design of the ship model such that it can be represented in the form of a chromosome;
- Finding a suitable evaluation function that can be used to rank the designs;

- Construction of a Genetic Algorithm that can be applied on the chromosome.

The design (phenotype) must be expressed as a finite number of parameters (genes), which must be independent of one another, to allow the process of random mutation to occur [*Sommersel, 1997*]. This limitation has been addressed in the studies discussed in Appendix 1 by either focussing on a single constrained detail aspect of ship design, or by using a simple model of the overall ship configuration.

The second issue of how to evaluate the fitness of the chromosomes and is potentially more significant. Firstly, each aspect of the overall performance of the design, controlled by the Genetic Algorithm, must be analysed. In the case of stability or resistance, this can be performed using established methods. However, for more complex issues, such as the correct position for spaces in the general arrangement, as outlined by Sommersel [*1997*], Kyu-Yeul et al, [*2002*] and Nick, Parsons and Nehrling [*2006*], large databases of required adjacencies and locations are required. The development of such databases from past designs could be difficult and also they will only indicate how ships *have been* laid out, not necessarily how they *should be*. The use of Genetic Algorithms for such layout problems is further complicated by the introduction of "ilities", such as producability and adaptability, which have subjective aspects and can require a higher level of detail in the model.

### 2.4.5 Artificial Neural Networks (Section A1.4 in Appendix 1)

Artificial Neural Network systems attempt to emulate the process of learning that it is believed to take place in the biological brain. Inputs are connected to outputs by several layers of neurons or nodes, each of which applies a simple mathematical transfer function to its input to generate an output [*Parsons, 2003*]. Weightings are applied to the links in between the nodes, to produce an overall function linking output to input. An ANN system undergoes a period of training, using a database of examples, to develop the appropriate weightings. Once this training is complete, the ANN can apply the same mathematical operations to a set of inputs that may be different from those used in the training. Although the resulting network can be used for rapid calculation, it is difficult to examine in detail [*Jensen et al, 1997*].

The main application of ANNs has so far been to the analysis of specific detail aspects of ship design, such as initial stability [*Alkan & Gülez, 2004*], and to the estimation of overall dimensions of specific types of ships, as described by Clausen et al [*2001*] and Parsons [*2003*]. This is a result of the requirement for a database for the training process, as these highly constrained analyses are more amenable to the collation of large databases. ANNs are essentially tools for extrapolation and interpolation of data sets, which raises the question of their suitability in assessing innovative and unconventional solutions, where data from previous designs would be lacking. However they could be used for interpolation purposes, as part of a larger portfolio of preliminary ship design tools.

### 2.4.6 Expert Systems and Knowledge Based Systems (Section A1.5 in Appendix 1)

Expert Systems and Knowledge Based Systems are two methods of utilising computers to draw upon past designs and design experience in the generation of new designs. The three fundamental components of an Expert System are the knowledge base, inference engine and user interface.

The Knowledge Base is a database of knowledge, which may or may not be relevant to the current design. This can be in the form of rules [*Halvacioğlu & İnsel, 2003*], numerical descriptions of previous designs [*Alkan & Gulez, 2004*] or relationships between design parameters [*van Hees* [*1992*], [*van der Nat, 1999*]. When the knowledge base consists of previous designs, problems arise concerning exactly which characteristics are to be recorded and how this information is to be effectively and explicitly represented. The inference engine recognises features in the new design and relates them to information in the database, presenting this information via the user interface. This imposes limitations on the configuration of the design, in that it must resemble the information in the database.

The Expert Systems approach has demonstrated potential for storing and applying large databases to new configuration. However, many of the systems developed to date use simplified design models or can only accommodate ships with known relationships within the design. This would seem to limit the applicability of the Expert System approach to the overall design of innovative vessels.

### 2.4.7 Virtual Reality and Simulation Based Design (Section A1.6 in Appendix 1)

Simulation has been defined by Clarke et al [*1986*], quoting Gagn'e [*1976*], as "an experiment using a computer model", and Simulation Based Design is being applied to many aspects of ship design. Virtual Reality (VR) technologies are differentiated from the wider field of SBD by the more realistic graphical representations used and the ability for the designer to move within the simulation environment [*Martin, 2002*]. The wide application of SBD, and the range of domain specific tools used, has led to the adoption of a federated approach where several tools communicate via a common environment, as demonstrated by Boudreaux [*1995*] and discussed by Anderson [*2000*].

Research into and application of VR and SBD has been surveyed by Andrews [*2005*], [*2006b*]. VR has been used for detailed design assessments, such as those described by Martin [*2002*], and for assessments of crane operator position in the preliminary design of dredgers [*Sonneveld & van Schothorst, 2003*]. Simulation has been applied to such varied problems as personnel movement and evacuation [*Galea et al, 2002*], [*Vassalos et al, 2002*], [*Andrews et al, 2007*], vehicle loading [*Zini et al, 2003b*] and technical issues, such as hydrodynamics [*van Oers & Stapersma, 2006*].

The main problems that have emerged, regarding the application of SBD to preliminary ship design, are the high level of detail required in the model and the need for the designer to perform extensive pre and post-processing of the data. VR technologies are more flexible, in that they provide an interface or display technology and so only require a spatial model of the vessel, even if at a very simple level of definition. However, a number of advantages have been proposed for the introduction of SBD into warship design, such as the ability to asses the whole ship impact of design changes [*Tibbitts et al, 1993*] and reductions in design process costs [*Boudreaux, 1995*].

### 2.4.8 Configuration Based Approaches

In summarising preliminary warship design tools, Andrews [*2003c*] mentions configuration based approaches in addition to the numerical methods described above and in Appendix 1. The Design Building Block approach is specifically mentioned and this is described in detail in Chapter 3. Apart from this approach, first described in detail by Andrews [*1984*], there have been limited investigations into the use of configuration or architecturally centred methods in preliminary warship design. La Rocca and van Tooren [*2005*] describe a configuration based approach to the design of aircraft and in surveying the development of feature-based approaches, prior to applying it to submarine design, Summers et al [*2001*] refer to research in the fields of part and mechanical system design.

Both of these last two developmental systems describe the design using discrete entities that contain numerical and geometric information. The multidisciplinary design system described by la Rocca and van Tooren [*2005*] illustrates the utility of a configurational based approach when generating inputs for specialist analyses tools (e.g. surface panels for CFD analysis or mass-and-beam descriptions for simple structural analysis). Summers et al [*2001*] note that a configurational model of the design, using features, provides a foundation for subsequent Virtual Reality analysis and that configurational models are an aid to designer understanding and interaction with the model.

An additional issue in configuration based design that has been addressed by both Summers et al [*2001*] and the much earlier paper by Nehrling [*1976*] is that of developing a suitable hierarchy for describing the configuration of the design. Summers et al note that the use of such a hierarchy in parametric configurational models is an advantage for the subsequent application of numerical automated analysis tools and propose a hybrid hierarchy containing both functional and configurational information – a concept previously applied to preliminary submarine design in Andrews et al [*1996b*] and described in Chapter 3. Nehrling [*1976*] however, focuses on the issue of hierarchy by developing a taxonomy of internal layout, based on a large number of standard detail layout elements, known as "patterns", which can be combined to create a symbolically described and parametrically scaled model of the ship. Although this allows a complete hierarchical description of the layout of the design, the use of an abstract non-functional descriptive method could limit the application of this particular approach.

## 2.5 Computer Interfaces

The issue of Human Computer Interaction (HCI), incorporates all aspects of the user interface; graphics, text, symbols, overall visual style and tool behaviour. This is a vital part of the software, as it is the environment in which the user works, and thus must be considered when reviewing such a software intensive topic as Computer Aided Preliminary Ship Design. The importance of the user interface in computer aided ship design tools has long been appreciated. Duffy and MacCallum [*1989*] quote:

> "Is it clear that what is needed, if the computer is to be of greater use in the creative process, is a more intimate and continuous interchange between man and machine. This interchange must be of such nature that all forms of thought that are congenial to man, whether verbal, symbolic, numerical, or even graphical, are also understood by the machine and are acted upon by the machine in ways that are appropriate to man's purpose." – [*Mann & Coons, 1965*]:

More recently Penn et al [*1995*], considering tools for architectural preliminary design, note that for computer tools to be used by creative designers, they must specifically address and reflect the pertinent issues in the problem domain. In the case of ship design, this would encompass the range of aspects discussed in Section 2.2.

An important aspect of user interfaces in general is the issue identified as the "Gulfs of Execution and Evaluation". These were first described by Norman [*1988*], who was primarily considering user interaction with machines, but also more domestic items such as doors, light switches etc. The Gulf of Execution refers to the degree of effort and abstraction that is involved in making a system perform a desired action. The Gulf of Evaluation, however refers to the level of effort that must be expended by the user in interpreting the current state of the system and deciding if the desired action has been carried out correctly.

Norman [*1988*] expands on this with the "Seven Stages of Action", where the user must not only perceive the state of the system and execute actions, but must interpret what they perceive, evaluate this relative to the goals and create a series of actions to be executed in order to achieve the goals. This is intended as an approximate generalisation of the process of interacting with any system ("The World"), be it organisational, mechanical or electronic.

### Interfaces in Computer Aided Preliminary Ship Design

The development of user interfaces in preliminary ship design software tools has been discussed by Calkins [*1988*], Jensen et al [*1997*] and Tan and Bligh [*1998*]. The development of naval architectural software interfaces was closely linked to the development of computer tools in general and can be summarised into three stages:

- Text only interfaces, presenting the designer information in a relatively abstract manner, such as the tanker preliminary sizing tool described by Nowacki et al [*1970*];
- Text interfaces with limited support for non-interactive graphical representation, such as the GODDESS tool described by Yuille [*1978*] and Holmes [*1980*];
- Graphical user interfaces featuring interactive, integrated graphical representations of the ship design, such as PARAMARINE, [*GRC, 2003*]. This tool is described in more detail in Chapter 3, as it provides the environment for the research presented.

However this general development path has not been applied universally. As has been discussed in the previous sections, some currently used ship design tools, such as

ASSET [*Heidenreich, 2002*], and still developing systems, such as the Submarine Concept Aid [*Biddell, 1998*], do not feature interactive graphical interfaces of the current configuration, rather text-based dialogue boxes within an overall windows interface are used. Where graphical representations are generated, these are only used to display the current configuration, as with the "features" based description of a ship configuration outlined by Summers et al [*2001*]. These more limited interfaces would appear to fail to satisfy the requirement for a more intimate and continuous exchange articulated by Mann and Coons [*1965*].

## 2.6 Sketching as a Design Activity

An important aspect of early stage design, particularly product design and most engineering design, is the use of sketching. In naval architecture, a "sketch design" has historically referred to a relatively early stage description of the design. [*Brown, 1983*] This was a formal outline of the design shown to the Board of the Admiralty for approval. Such a sketch design would include calculations of weight and space requirements based on historical data, hullform design (hydrostatics and powering estimates) and a basic general arrangement (profile section and upperdeck plan showing the arrangement of weapons, magazines and machinery). These sketch design submissions have also included an artist's impression of the ship at sea [*Andrews, 2006a*]. In a more modern early stage ship design process, such as the UCL SDE, this formal submission is retained in the form of design interviews and the Single Sheet Characteristics, which have a specified structure. [*UCL, 2001a*]

In this context, the "sketch" serves as a communication medium for conveying an outline description of the design between key individuals that the designer interfaces with. In more general usage, a "sketch design" is taken to mean any rough, early stage graphical description of the design, usually (but not always) produced with a pencil and paper. The use of such sketching in the early stage design process has historically been viewed as a process of externalisation, where the designer records ideas generated in their mind for subsequent recall. Recent research into Visuo-Spatial Working Memory (VSMM), as summarised by Bilda et al [*2006*], has suggested that the capacity of this working memory is limited and that sketching has an important role to play in reducing the mental load through the use of such external storage.

However, it has also been suggested that the act of sketching is itself a creative act [*Goldschmidt, 1991, Amheim, 1993*] and sketching has been presented as the archetypical design activity [*Fallman, 2003*]. Van der Lugt [*2005*] summarises three main types of sketches:

- The talking sketch, used for communication with other designers and non technical participants and re-interpretation of the ideas of other designers;
- The thinking sketch, used as part of the mental process of re-interpreting ideas and generating new ones;
- The storing sketch, used as external memory storage to enhance the accessibility of ideas.

Thinking sketches are part of a process of internalisation, distinct from the sketches for communication utilised later in the design development. This early sketching forms part of a reflective process featuring a design dialogue. This has been described by Goldschmidt as:

> "the oscillation of arguments which brings about gradual transformation of images ending when the designer judges that sufficient coherence has been achieved" [*Goldschmidt, 1991*]

Hence the sketch itself will never be a complete and identical image of the designer's conception of the design [*Arnheim, 1993*]. More recently, differentiation has been made between the creative process of combining ideas, concepts or designs and restructuring them. Based on observations of designers at work, Verstijnen et al [*1998*] proposed the overall structure shown in Figure 2.11, where sketches are most useful for the process of re-structuring, which is difficult to perform mentally. They proposed that combinatory design operations, however, can be performed mentally and so the sketches are used as a storage device. The "+" symbols indicating strong relationships and the "-" symbols weaker relationships.

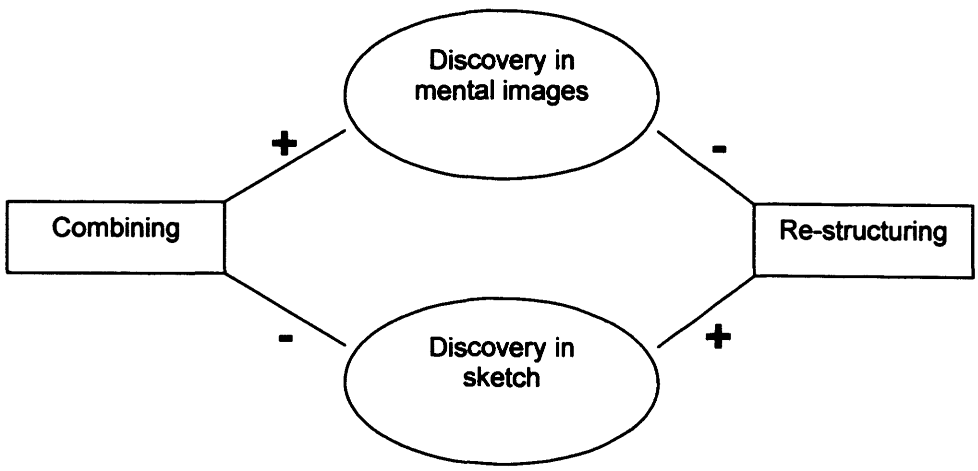



***Figure 2.11: The roles of combining, re-structuring and sketching in the design process [Verstijnen et al, 1998]***

In addition to forming a dialogue in the creation of new ideas, sketches also assist in familiarising the designer with the problem at hand [*Fallman, 2003*]. Arnheim [*1993*] observed that architects and designers draw on what they have seen of other designers work and Do & Gross [*1995*] explore how previously experienced visual forms are used as inspiration for new designs in architecture. The importance of visual stimuli on the creative process in design has more recently been studied by Goldschmidt and Smolov [*2006*], who examined problem solving with different types of visual stimulus available to the designer and concluded that, for ill-structured problems, the designer's environment strongly affects the nature of the design. This aspect of creativity was first identified by Darke [*1979*] as the "primary generator" in architectural design.

As in architecture and engineering design, traditional methods of sketching are widely used in the early stages of the design of yachts and pleasure craft [*Woods, 2006*] [*Ivanov, 2006*]. Woods illustrates the use of sketches in the design of yachts, both at the level of overall arrangement and external appearance and in the detailed layout of accommodation spaces. He draws attention to the importance of ambiguity in these sketches and considers that this ambiguity is vital to the generation of new and creative ideas.

## Properties of Sketches

Both Buxton [*2006*] and Gross [*2006*] have recently summarised the main properties of sketches, from the point of view of their use in the early stage design process. Table 2.4 below lists the main features of sketches they identify.

| | |
|---|---|
| **Quick** | Quick to make |
| **Timely** | Can be provided when need |
| **Inexpensive** | Cost must not inhibit concept exploration |
| **Disposable** | Investment in the sketch is the development concept represented, not the execution of the drawing |
| **Plentiful** | Meaning and utility of sketches is usually as part of a series of sketches |
| **Clear vocabulary** | Certain conventions are used to distinguish a sketch from other renderings |
| **Distinct gesture** | Open and free |
| **Constrained resolution** | Sketches do not go beyond "good enough" |
| **Appropriate degree of refinement** | The sketch does not suggest a greater degree of design refinement than actually exists at that point in the design |
| **Ambiguity** | Intentionally ambiguous, sketches gain value from being interpreted in different ways |
| **Suggest & explore rather than confirm** | Sketches provide a catalyst for further development |
| **Fluid** | The designer can easily move from sketches to more detailed schematics |
| **Forgiving** | Sketches can contain errors, or be under-specified |
| **Functional** | Sketches contain enough information to allow an evaluation of the design |

***Table 2.4: The distinguishing properties of sketches, summarised from Buxton [2006] and Gross [2006]***

These key properties revolve around central concepts of flexibility and simplicity. This is also noted by Pache et al [*2001*], who observe that despite the wide use of Computer Aided Design tools in early stage design, "classical" sketches using pencil and paper are still widely used to support development of the design in conjunction with CAD tools.

## Recent Research into Sketching and Computer Aided Design

The importance attached to sketching as a skill for engineering design has led to both philosophical discussions, such as Arnheim [*1993*], and practical investigations, most recently involving computers. However, this has mostly been limited to product, machine and architectural design. McGown and Green [*1998*] noted that the design research community had at that time moved away from developing automated design systems and moved instead to design support software, including sketching tools.

Do and Gross [*1995*] and Gross [*1996*] examine the use of sketching in developing designs for new buildings and in particular the use of sketching and visual analogies by the designer in a creative process. This combines reference material and previously experienced forms (which may not necessarily be buildings) to generate new ones. They present a CAD sketching system, the "electronic cocktail napkin", utilising shape recognition tools to extract geometric shapes from rough sketches. Importantly, the tool uses these shapes to form sketch based queries of an architectural database, visual dictionary etc and present these to the designer. This system aims to provide inspirational materials to the designer with visual and conceptual similarity to the new design.

Other approaches to linking sketching processes and CAD have been investigated. Alvarado & Davis [*2000*] describe a sketching tool with limited kinematic simulation capabilities for design of mechanical devices, allowing linkages, joints etc to be roughly defined and simple simulations of the resulting motion performed. van Dijk [*1995*] and Tovey [*1997*] describe tools which allow the designer to rapidly develop crude 3D CAD models based on their 2D sketches. These tools are essentially 3D modelling packages that can display the 2D sketches on-screen overlaid over the 3D workspace. Borg et al [*2001*] outline a developmental system using feature recognition to generate 3D CAD models (and subsequent CNC milled prototypes) from 2D sketches.

There have also been several investigations into the taxonomy of sketching in product design, in order to facilitate computer recognition and recording of sketching activities. Suwa et al [*1998*] developed an extensive scheme for describing designer activities during the sketching process. Kavakli et al [*1998*] investigate a more specific concept of breaking a design sketch for a product into distinct parts for digital storage, proposing that this type of hierarchy is an underlying part of human conceptual design processes. Pache et al [*2001*] describe an investigation into the design process utilising freehand sketches. Their study examined the use of sketches by several student and professional designers when addressing a representative design problem. They identify and record different types of interaction with the sketches, such as re-enforcing lines and simply looking at the sketches. Importantly from the point of view of computer aided design, Pache et al conclude that future sketching CAD tools must permit the designer to proceed in a range of ways, rather than constraining them, and that the tools must be able to support geometric, symbolic and textual definitions of the design. These definitions may also be at different levels of abstraction.

Sketching has also been examined as a means to better understanding the conceptual design process. These range from investigating the differences between novice and expert designers [*Kavakli & Gero, 2001*] to detailed examination of sketching processes leading to models of mental iteration [*Jin & Chusilp, 2006*].

In addition to the traditional fields where design sketching has been extensively used, such as architecture and product design, recent research has examined its used in a range of professions. Marchese [*2006*] describes the use of highly symbolised sketches by organic chemists when seeking to understand the mechanisms involved in organic chemical reactions, while Warr & O'Neill [*2006*] describe a developmental computer system applied to the problem of urban planning. In this case, the planning process is being carried out by a small group, working around a large-format interactive display screen and the process of sketching is seen as the externalisation of ideas and their communication between individuals in the group. Warr & O'Neill describe this type of highly interactive, small-group design work as "Public Social Private Design" (PSPD).

Fallman [*2003*] and Gross & Do [*2006*] describe the potential for use of sketching in the development of new Human-Computer Interfaces (HCI). Fallman notes that sketching activities have taken place in HCI design, but these have erroneously been referred to as prototyping and that there has been a tendency in HCI research to focus on the attributes of the sketch / prototype itself, rather than what it represents, as an early sketch of the design. Fallman notes that the use of sketching in HCI development is complicated by the involvement of additional non-visual aspects, such as interactivity and sounds, not well represented in pen-and-paper sketches. Gross & Do [*2006*] describe recent work in HCI development, using rapidly produced prototypes, to overcome the limitations of traditional sketching. They propose that the processes of hacking and tinkering with software code and the production of partially-functional prototypes are directly analogous to sketching in architecture and engineering design.

**Application to Preliminary Ship Design**

The concept of analogies to sketching is applied by Woods [*2006*] to the hullform coefficients and dimensions used to describe a hullform design at the earliest stages of larger yacht design. Woods proposes that these coefficients demonstrate the ambiguity required of early sketches and are thus functionally analogous. Woods also gives an example of sketching in marine design, which contains the multiple levels of abstraction referred to by Pache et al [*2001*]. In this case, a CAD generated image of part of the accommodation spaces of a yacht, modelled to a crude level of detail, is used as the basis of a sketch drawn by hand. This sketch contains the graphical, textual and symbolic features widely seen in traditional sketches.

However, this type of sketching is essentially the same pen-and-paper process used in engineering and product design. The concept of the "thinking" sketch, with the characteristics, outlined in Table 2.4, and the creative process of development and understanding it represents, has similarities to the early concept stages of ship design outlined in Section 2.3, particularly the Concept Exploration stage. However, the full exploitation of highly flexible sketch representations to explore and more fully understand the design space is limited in ship design by the greater technical complexity outlined in Section 2.2. To encourage a process more akin to sketching to be used, a flexible, visually rich tool with integrated technical analysis is required.

## 2.7 Main Points on the Nature of Computer Aided Preliminary Ship Design

This chapter has outlined the complexity in ship design, which arises both from the inherent technical complexity and interactions of subsystems within ships and from external influences, such as the design environment, and the capabilities provided by the available tools. Both ship performance and requirements are multi-faceted and some aspects may not be amenable to numerical description and assessment, particularly in the early stages of the design process. These difficulties are particularly found in the design of service vessels, especially warships, which are the focus of this thesis.

This complexity has led to a ship design process that is characterised by iteration through stages of increasing detail and de-risking of the design solution. The preliminary stages of design, considered in this thesis, are particularly important due to their significant impact on the overall configuration of the adopted solution, despite the small resources allocated in the early stages of design. In early stage design there is great variability in the design definition adopted by designers. This provides significant potential for investigation of alternative and innovative solutions.

Historical (manual) ship design processes were labour intensive and dominated by hullform considerations, with historical data and scaling used to a great extent. Computers have increasingly been applied to all aspects of ship design, in replicating and accelerating the manual processes, analysing detailed technical aspects of the design and, most recently, in synthesising new designs. A number of approaches to the use of computers in preliminary ship design have been described and discussed:

- Numerical Parametric Design models;
- Multiple Criteria Decision Making methods;
- Genetic Algorithms;
- Artificial Neural Networks;
- Expert Systems and Knowledge Based Systems;
- Virtual Reality and Simulation Based Design.

Each of these approaches was found to have individual advantages and disadvantages for its application to innovative preliminary ship design. The common disadvantage was an inherent difficulty when addressing innovative design configurations or new systems, whose interactions with the rest of the ship are not well understood. Although many of the numerical methods presented can perform rigorous searches of a defined solution space, they make use of simple parametric models of the design. Such models may contain advanced technical analysis of performance issues, such as resistance or seakeeping, but have a very simple configurational description, limited to a stereotypical configuration. Thus the potential for innovation and elucidation of design drivers could be limited. However, for each of the approaches considered, there remain areas of the preliminary ship design process that may be amenable to their use.

This chapter has also considered the topic of computer interfaces in ship design software, since these have advanced considerably through the increase in low-cost computing power and their ubiquity makes them potentially very important in enhancing the designer understanding of the preliminary design. A related subject covered in this chapter was sketching, which is seen as a central tenet of preliminary design for product design and architecture. The fundamental nature of sketches was outlined given they are part of the preliminary design process, being more than just a mechanism for storing information. In listing their basic features, their similarity to early stage ship design was observed and the important conclusion reached that ship design software tools and user interfaces must be suitable to encourage sketching processes as a creative act.

# Chapter 3: The Design Building Block Approach

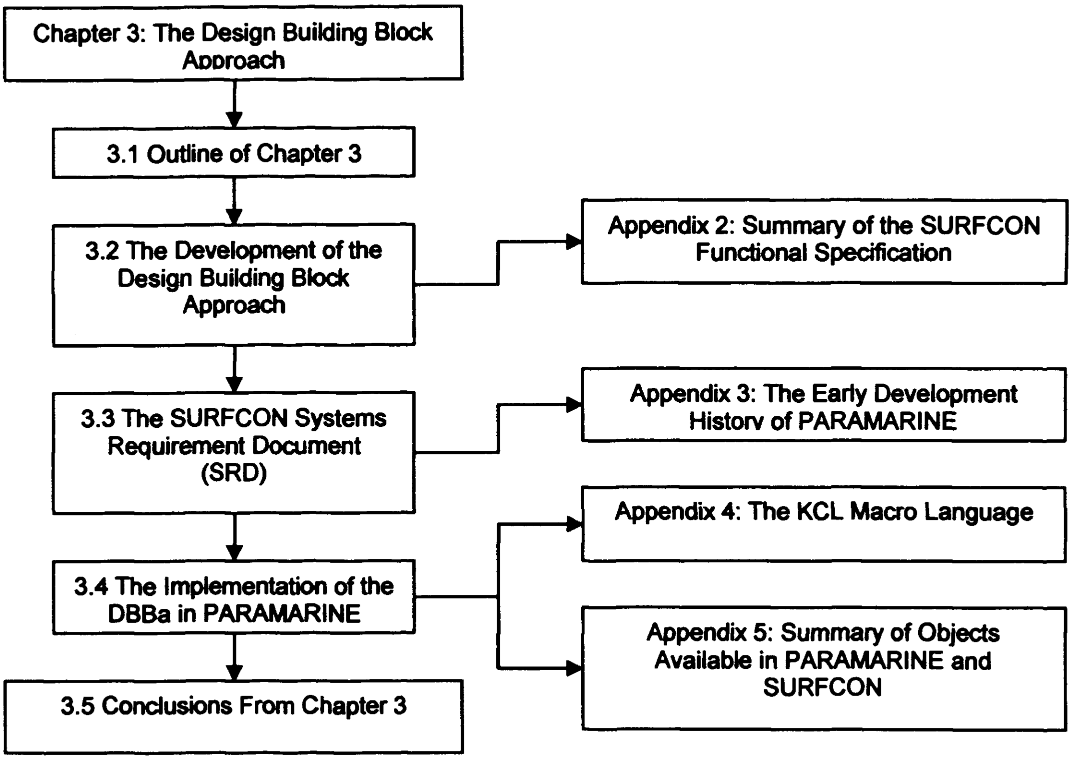



***Figure 3.1: Schematic of Chapter 3***

## 3.1 OUTLINE OF CHAPTER 3

This chapter describes the proposal of the Design Building Block approach, a holistic approach to ship design, featuring an architecturally – centred initial synthesis and utilising graphical computer aided design tools to incorporate stylistic issues and designer judgement into the design process. The historical development of software implementations of this new approach are outlined and, finally, GRC's "PARAMARINE" ship design system, used for the latest implementation, is described and the functionality, provided by this software, is compared with that described in earlier work on the approach.

## 3.2 THE DEVELOPMENT OF THE DESIGN BUILDING BLOCK APPROACH

### 3.2.1 The Proposal for a New Approach to Ship Design

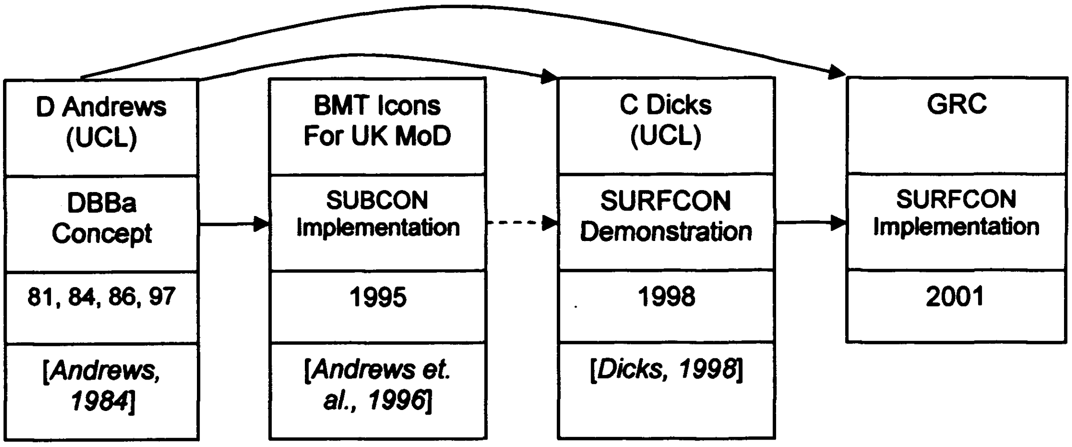



***Figure 3.2: The development and implementation of the Design Building Block approach***

Figure 3.2 shows a simplified history of the applications of the Design Building Block approach to design. The need for a new approach to ship design, integrating architectural issues at the earliest stages, was proposed by Andrews in 1981 [*Andrews, 1981*]. This proposal considered the wider issue of the philosophy of design and did not specifically outline a new approach. The philosophical and practical issues were discussed in much more detail in Andrews' subsequent thesis [*Andrews, 1984*] and summarised in a paper [*Andrews, 1986*]. In these, Andrews proposed a more holistic approach to ship design with a completely integrated architecturally centred synthesis process, including spatial layout, in the numerical balance process found in sequential ship design processes. The holistic model of ship synthesis, Figure 3.4 was contrasted with the schematic model of the sequential process, Figure 3.3.

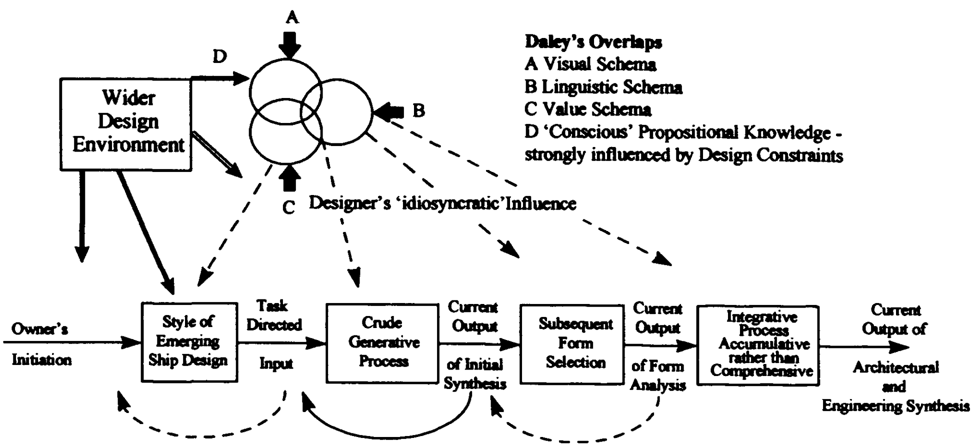



***Figure 3.3: The sequential synthesis process in ship design [Andrews 1986]***

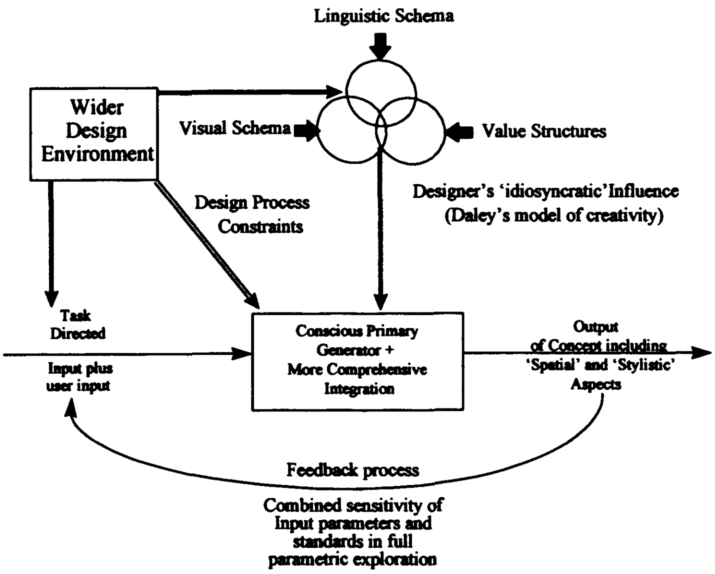



***Figure 3.4: The fully integrated ship synthesis logic [Andrews, 1986]***

The integration of a spatial model of the design, at the earliest stages of the design definition, was presented as a method to ensure the consideration of a wide range of "stylistic" issues, which would be missing in the sequential process, or would only occur later, when the design definition was fixed and less open to change. A broad range of issues were encompassed in the definition of the "style" of the design, including; personnel movement, ease of outfitting, functional flexibility (adaptability) and margin philosophy.

Andrews proposed that the new approach be implemented by the development of flexible graphically-oriented computer aided design tools for early stage ship design. These would not represent an automated system that attempted to iterate the design to a balanced solution, but rather an open and responsive system incorporating the designer's judgement in the design process. To encourage innovation, the system should provide flexibility in the definition of the design, the ability to reconfigure the spatial model and subsequently rebalance the design to permit exploration of solutions, generated through the application of the designer's creativity.

Andrews also presented a more detailed description of a practical application of the new integrated ship design process, shown as Figure 3.5. At this point in time several different tools were used to model the different aspects of the ship design at the earliest stages. These tools and their applications within the preliminary ship design process are summarised in Table 3.1.

| Tool | Use |
|---|---|
| WSVPROG [*Keane, 1981*] | Interactive weight and space estimation program, with resistance estimation |
| PARASURV [*Keane, 1981*] | Hullform parametric survey |
| HULLFORM [*Wray 1982*] | Hullform lines and decks generation |
| ROSTRA [*Lloyd 1983*] | Crude layout generation and assessment of area available |

***Table 3.1: Software tools used in the initial implementations of the Design Building Block Approach [Andrews, 1984]***

These tools were generated by UCL students in MSc and BSc projects. Data reflecting the current state of the design was transferred between them via simple text files containing input parameters, with user-editing to alter input values. Thus this did not represent an integrated system, but a series of tools that could be used within an overall process. These particular tools were intended to be widely applicable, but were based on the UCL Ship Design Exercise database and method, so were based on frigate and destroyer type vessels and so contained assumptions inherent to these ship types [*Andrews, 1984*].

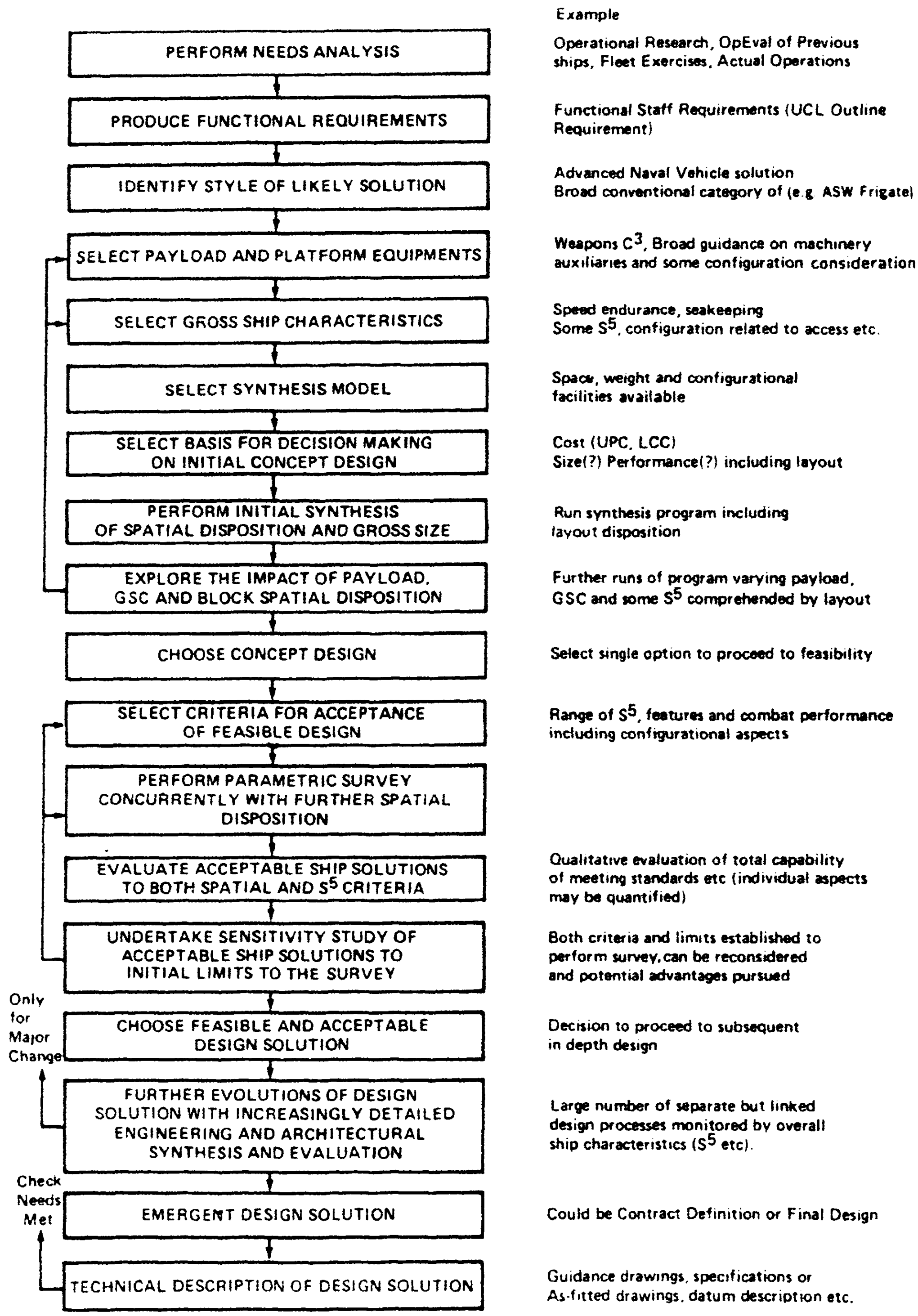



***Figure 3.5: Andrews' description of the ship design process showing major design decisions as well as process for the case of an integrated (spatial) initial synthesis [Andrews, 1986]***

The application of the approach to ship design and its implementation as a practical software tool was limited by the then-current computer graphics technology. However, the portfolio of software tools described in Table 3.1 was successfully used in the concept design of warships, including a generic ASW frigate [*Andrews, 1986*]. The ROSTRA arrangements tool and the WSVProg sizing programme were utilised in the early stages of the UCL Ship Design Exercise procedure [*UCL, 2001a*] by Lloyd and van Dinther [*1984*], to demonstrate the advantages of having such a tool available at the initial stage. These and other MSc dissertation studies outlined by Andrews [*1986*] indicated that it would not be possible to lay out a universally applicable mechanistic design procedure, the process shown in Figure 3.5 retaining a large degree of flexibility [*Andrews, 1986*]. An important differentiation noted by Andrews was Laming's [*1981*] distinguishing of genesis, defined as a "black box" process where ideas originate "out of the blue" and synthesis, a "glass box", where creativity originates from a holistic approach incorporating all design elements. This required a true Computer *Aided* Design tool, allowing the designer to make the judgements, where decisions made and algorithms used could be examined, rather than an automated design system, with often many choices made by the program originators and not revealed easily (if at all) to the designer using the system.

### 3.2.2 SUBCON

The first practical implementation of the approach in the form of an integrated tool was the SUBCON (SUBmarine CONcept design) software. This was developed for the Assistant Director of Future Project Design, MoD (Dr. Andrews) by BMT Icons (subsequently Tribon Solutions), to meet the needs of exploring radical configurational options for the Future Attack Submarine Programme [*Andrews et al, 1996b*]. SUBCON used a common Graphical User Interface (GUI) to access the modelling and analysis software, listed in Table 3.2. An example of the GUI is shown in Figure 3.6.

| Tool | Use |
|---|---|
| ORACLE | Relational database storing data for building blocks and completed designs |
| Integraph EMS | 3D modelling and spatial calculations |
| SUBDRAG<br>SUBDRIVS<br>MNSTRL | Analysis tools for resistance, manoeuvring, structures etc were those in use by the MoD at that time. |
| X-Windows / Motif | GUI, providing a menu and icon based interface with the design tools |
| Submarine Modelling System | Overall controlling system kernel |
| Microsoft Excel | Conversion of weights from NES weight groups to Building Blocks |

***Table 3.2: Components of the SUBCON system [Summary of Andrews et al, 1996b]***

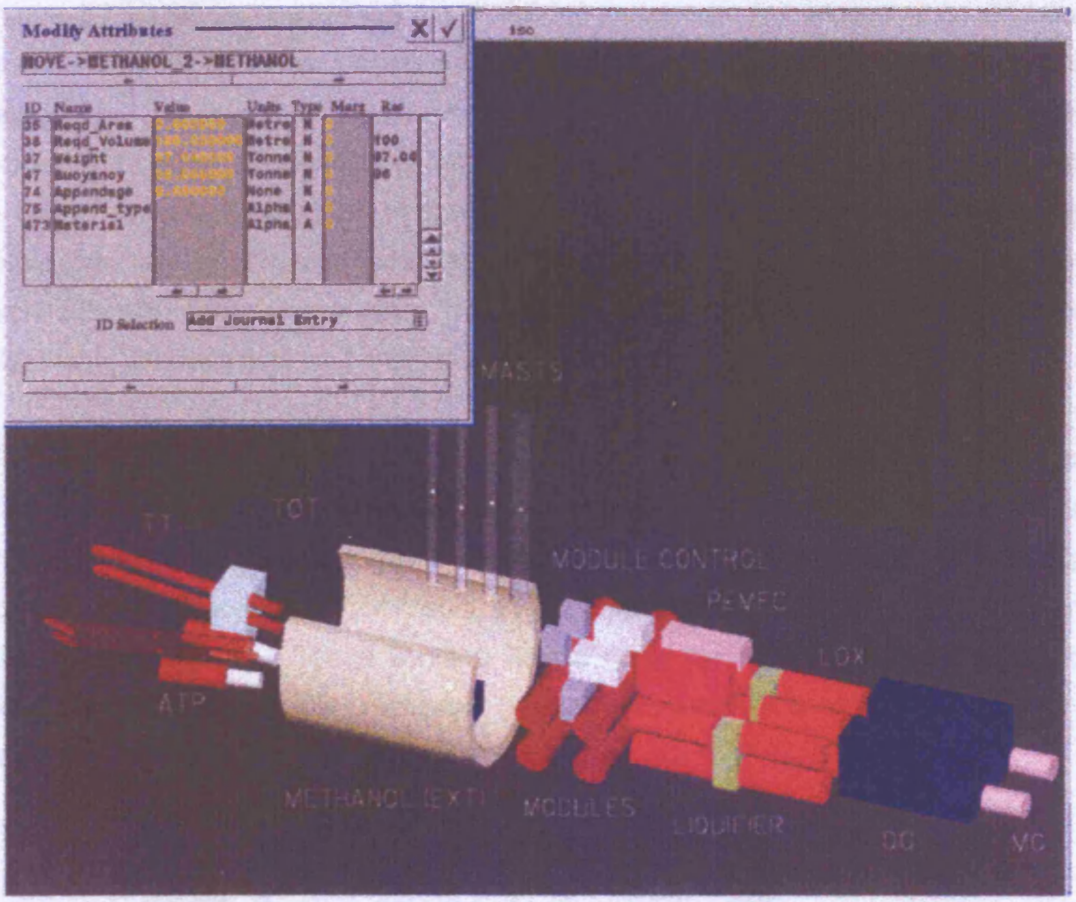



*Figure 3.6: SUBCON user interface [Andrews et al, 1996b]*

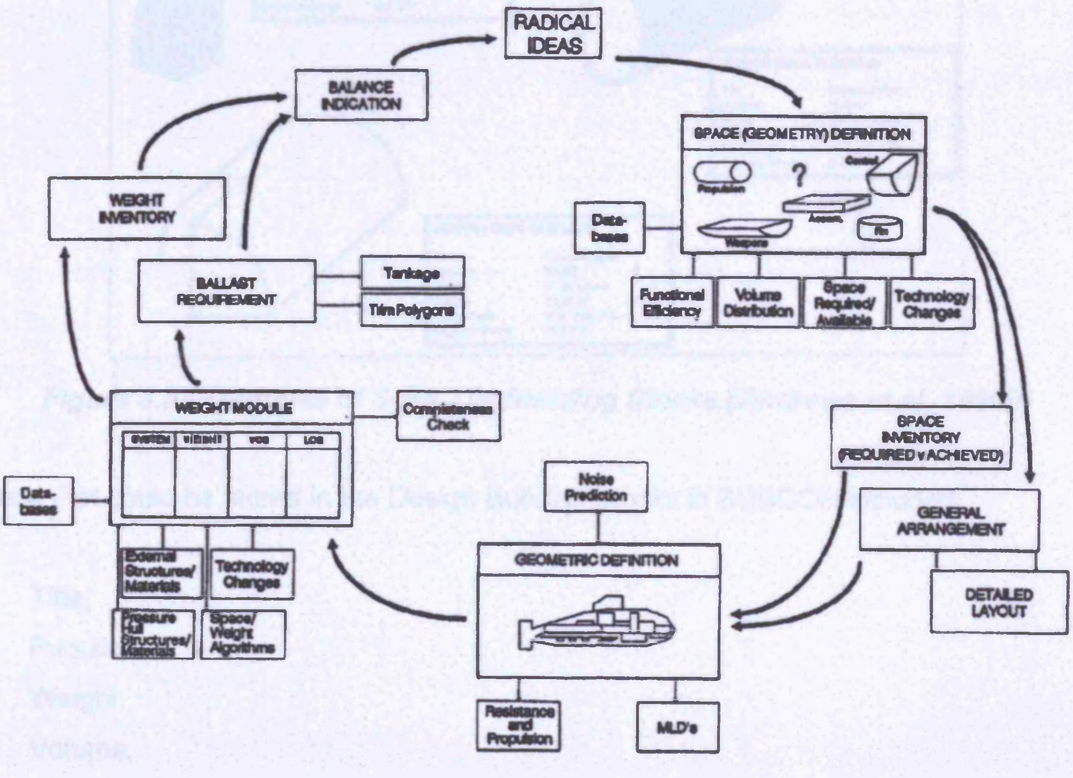



*Figure 3.7: The SUBCON process [Andrews et al, 1996b]*

Figure 3.7 shows an overview of the SUBCON process as first presented by Andrews et al [*1996b*]. SUBCON was the first full implementation of the holistic approach to ship (submarine) synthesis. The software developed was not a single integrated entity, however but rather a federation of tools with data management software to ensure that a single consistent definition of the design was in use at any time. This paper introduced two of the concepts central to software implementations of the new architecturally centred approach; the Design Building Block and the Functional Hierarchy, although both had previously been alluded to in Andrews [*1986*].

**The Design Building Block** should be thought of as a placeholder or folder in the design space containing all information needed to describe a particular function. Thus they differ from the Constructional Building Blocks that are a feature of modern 'design for production' processes. [*Storch et al, 1995*] Examples of Design Building Blocks are shown in Figure 3.8. These Building Blocks could have different combinations of properties; a geometric and numerical (weight) definition for a control console, or a weight and location definition only for a distributed system.

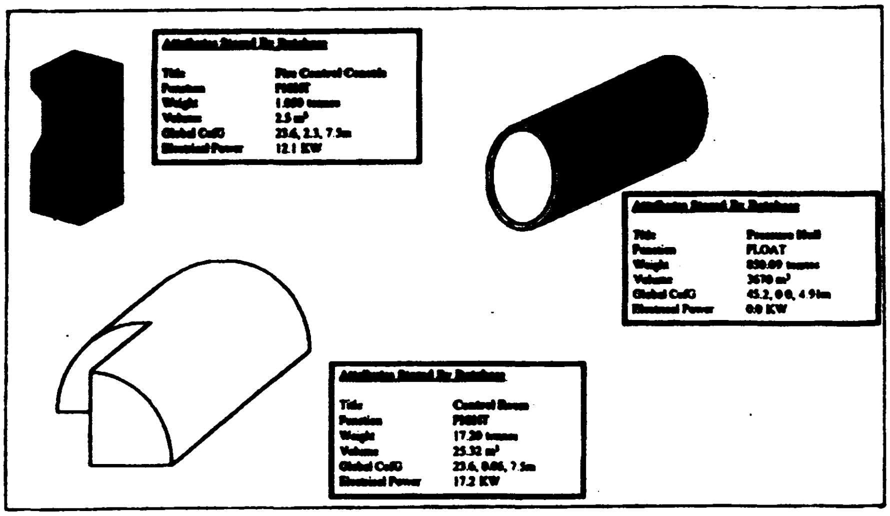


***Figure 3.8: Examples of SUBCON Building Blocks [Andrews et al, 1996b]***

Data that could be stored in the Design Building Blocks in SUBCON included;

- Title,
- Function,
- Weight,
- Volume,
- Location (centre of gravity position),
- Electrical power requirement.

The Functional Hierarchy runs through the SUBCON designs from the upper level of four main groups to more detailed groups. Andrews et al [*1996b*] contrast this with the traditional submarine weight grouping system used in the MoD, NES 163 [*MoD, 1989*], which is based on the historical breakdown of skills and tasks in ship construction. Table 3.3 compares these two weight grouping systems.

| Weight Group No | Weight Group Title |
|---|---|
| 1 | Hull Structure |
| 2 | Propulsion |
| 3 | Electrical Services |
| 4 | Control and Communications |
| 5 | Ship Services |
| 6 | Outfit and Furnishings |
| 7 | Armament and Pyrotechnics |
| 8 | Fixed Ballast |
| 9 | Variable Load |

| Functional Group Title | Major Elements |
|---|---|
| Float | Structure, Trim and Ballast |
| Move | Propulsion and Manoeuvring |
| Fight | Weapon Stowage and Launch, Sonar, Command, Control and Communications |
| Infrastructure | Accommodation, Life Support, Logistics, Services |

***Table 3.3: Comparison of conventional and functional weight breakdowns for submarine design (after [Andrews et al, 1996b])***

This change in breakdown system was promoted as encouraging innovative solutions, by removing the conservative assumptions of traditional systems and structures implied by the previous weight breakdown hierarchy. This drive to find innovative solutions was further enhanced by the adoption of an "open" approach to design. The SUBCON implementation did not utilise the "black box" approach, as cautioned against by Andrews [*1984, 1986*]. Rather than allowing the software tool to make changes to the design, to achieve a balance of requirements and performance, the tool would alert the designer to the presence of imbalance in the numerical demands and supplies of audited characteristics and then the designer would choose how to achieve a balanced design.

### 3.2.3 Work at UCL on the Integration of Architecture into Early Stage Design

Parallel with the development of the SUBCON tool by BMT Icons, at the behest of MoD ADFPD (Andrews), UCL undertook the development of an improved layout modelling and analysis tool for the Future Projects Group of the MoD. The resulting tool was CAESAR, developed by Zhang [*1994*]. This utilised the commonly used AutoCAD drafting software, with pre- and post-processors providing ship design functionality and compatibility with deck plans generated by CONDES. The AutoLISP scripting language was used to provide an interface to the AutoCAD, which featured specialised functions to assist in the early stage layout of the vessel. The basic element of the design in CAESAR was the compartment and this could have assigned a volume or deck area demand, which was audited against that supplied by the current layout.

CAESAR was not capable of any automated synthesis operations and did not perform any other naval architectural assessments, such as stability or resistance. Instead, it focussed on providing a tool to assist in the early stage layout of vessels, when data is scarce or uncertain. CAESAR was also intended to be used as an educational tool, the rapid generation of general arrangements allowing designers to gain experience and knowledge about ship layout. Figure 3.9 shows the representation of the ship design used within CAESAR, with decks shown separately.

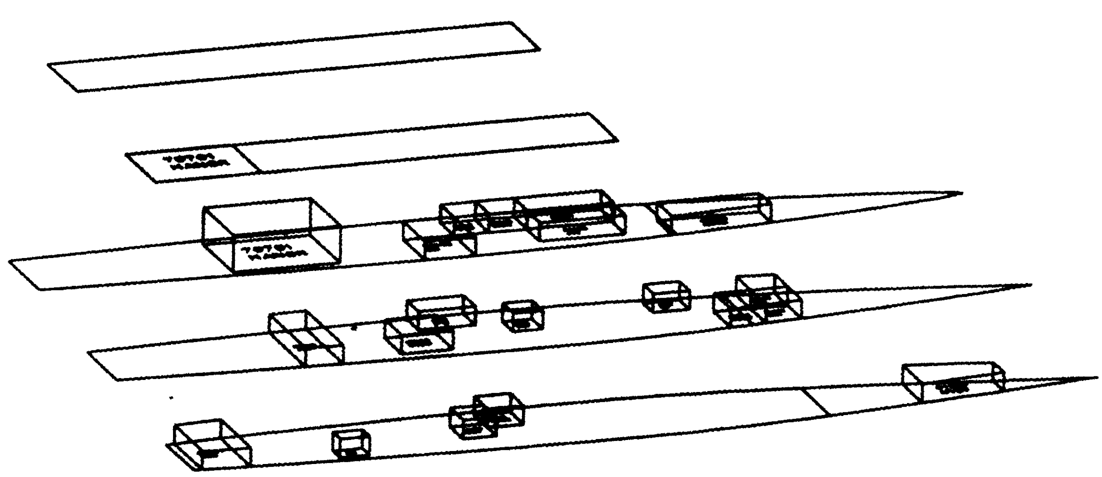


***Figure 3.9: Ship design configuration representation provided by the CAESAR software [Zhang, 1994]***

### 3.2.4 The Breadboard SURFCON System

Following the earlier research and development into the implementation of the Design Building Block approach for submarine design (SUBCON), Dicks [*1999*] carried out research, under Professor Andrews at UCL, to demonstrate the utility of the approach for surface ships (SURFCON) and to define a functional specification for a future integrated software tool.

Dicks outlined the philosophy of the Design Building Block approach with the following statements: [*Dicks, 1999*]

- A need for a new conceptual design is conceived and an idea of the likely design style to meet that requirement suggested.
- Drawing on novel ideas or historical data a series of Building Blocks are defined. Each Building Block contains geometric and technical attributes regarding the functions of that block.
- A design space is generated and Building Blocks configured as required (or desired) within the design space.
- Overall balance and design performance are investigated using simple and flexible algorithms and, as necessary, using analysis programs.
- Features of the design, such as size and configuration, are then manipulated until the designer is satisfied.
- Decomposition of the building blocks to greater levels of detail is undertaken, as necessary to increase confidence in the design solution.

Dicks represented the SURFCON process with a similar diagram to that shown in Figure 3.8, see Figure 3.10.

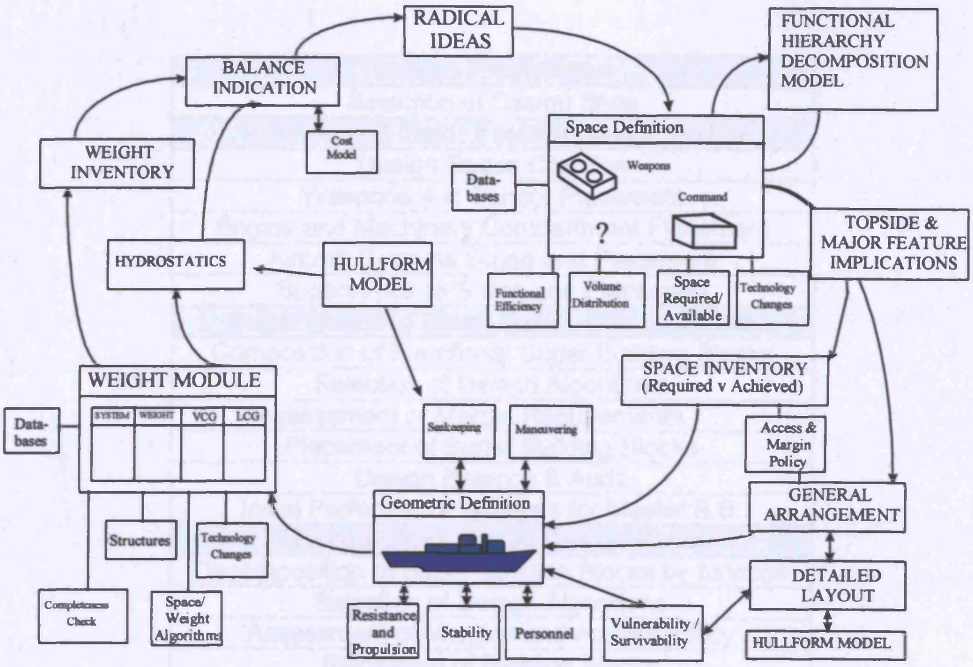



***Figure 3.10: The SURFCON process [Andrews & Dicks, 1997]***

In addition to this diagrammatic representation, Dicks presented a tabular description of the process of developing designs using the Design Building Block approach. This is shown as Table 3.4. This table, focussing on preliminary ship design, updated the description of the initial ship design process previously proposed by Andrews (Figure 3.5) and divided the process of design into a series of stages of increasing detail, with clearly defined activities occurring at each stage.

| |
|---|
| **Design Preparation** |
| Selection of Design Style |
| **Topside and Major Feature Design Phase** |
| Design Space Creation |
| Weapons and Sensor Placement |
| Engine and Machinery Compartment Placement |
| Aircraft Systems Sizing and Placement |
| Superstructure Sizing and Placement |
| **Super Building Block Based Design Phase** |
| 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. |
| **Building Block Based Design Phase** |
| 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. |
| **General Arrangement Phase** |
| Drawing Preparation |

***Table 3.4: Building Block design phases [Andrews & Dicks, 1997]***

The demonstration of the approach was achieved using a portfolio of design tools, which together with a suitable procedure for transferring data and prioritising analysis, formed a "breadboard" system. The software used for each task is summarised in Table 3.5.

| Tool | Use |
|---|---|
| HYDSTAT for GODDESS | Stability assessment |
| POWERING for GODDESS<br>POWSD for GODDESS | Resistance estimation |
| HULLFORM<br>Autosurf | Hullform generation |
| Excel | Weight and space estimation, hullform parametric survey, data storage |
| Autodesk Mechanical Desktop 1.2 (with solid modelling) | Layout generation and assessment of area available |

***Table 3.5: Software tools used in the functional demonstration of the Design Building Block Approach [Summarised from Dicks, 1999]***

This prototype Computer Aided Preliminary Ship Design system was used to create conventional (Monohull) and unconventional (Trimaran and SWATH) designs for surface warships. Although the computer tools did not necessarily represent those that would be used in a later SURFCON system, they allowed the incorporation of realistic assessments of the design at the pertinent stages of the procedure. This validated the overall concept of the Design Building Block approach for the early stage design of warships and illustrated how the approach could practically be used. Dicks was able to demonstrate using a series of related small surface combatants and larger Landing Ship, Logistic (LSL) designs, how the design was initiated with a small number of relatively simple Super Building Blocks and gradually increased in complexity, detail and certainty through the phases of Table 3.4 [*Dicks, 1999*].

### 3.2.5 The SURFCON Functional Specification

The functional specification for SURFCON was presented to the UK Ministry of Defence as a proposal for a new Computer Aided Preliminary Ship Design System [*Dicks, 1998*]. A summary of the main features of this functional specification is included here, with a more detailed description of key technical issues in Appendix 2.

The functional specification outlined three types of requirements for the overall system; technical requirements, relating to the capabilities required of the SURFCON tool; computational requirements, which covered the more detail requirements of the structure of the new tool; and other requirements, relating to the procedure by which the tool would be used in the environment of a typical MoD Future Projects (Naval) ship design project. Hardware requirements and solutions were not covered in the functional specification, as no hardware development was to take place. The only consideration of this issue was a requirement that the computer hardware should be sufficiently capable to allow design operations and calculations to be carried out in real time. A simple outline specification of likely minimum hardware requirements was given.

The main technical requirement of the new tool was to remove the 'housekeeping' tasks of recalculation and updating, previously carried out by the designer, so allowing him or her more time to concentrate on solving problems of the design itself. However, the functional specification made it clear that the intention was not to develop an automated system;

"The system should not perform the design process without recourse to the designer, optimisation and other automated design methods are to be avoided." – *Dicks, 1998*

This was a continuation of one of the fundamental concepts of all previous work on the approach; that the tool should not automatically attempt to iterate the design as a whole to a balanced solution. Rather, areas where the design is out of balance should be clearly indicated to the designer, who then decides on the measures taken to achieve a balanced design. A SURFCON tool would improve the modelling, representation and communication of the design, but a capable expert user would still be required, as was made clear in the description of the SUBCON tool [*Andrews et al, 1996b*].

The functional specification outlines the application of the tool and indicated that it would ultimately become a replacement for the CONDES system used in early stage design [*Hyde & Andrews, 1992*]. Thus, Dicks' SURFCON tool was primarily intended to be used in the earliest stages of the design, when the major features and main characteristics of the design are amenable to change.

## 3.3 THE SURFCON SYSTEMS REQUIREMENT DOCUMENT (SRD)

### 3.3.1 Background

As outlined in Appendix 3 the ship design software developer Graphics Research Corporation (GRC) was contracted by UCL, for the new Design Research Centre, to take the functional specification drawn up by Dicks [*Dicks, 1998*] and to develop SURFCON as a module in their existing ship design PARAMARINE software [*Munoz & Forrest, 2002*]. GRC produced a Systems Requirement Document for SURFCON [*GRC, 2002*] for the Design Research Centre (DRC), as part of the Marine Research Group in the Department of Mechanical Engineering at UCL. Developed on behalf of the Future Surface Combatant (FSC) IPT, the purpose of this document was to define the software requirements to perform preliminary design studies for the FSC. The first version was sent to UCL in January 2002 and the candidate's first task was to assess the SRD against Dicks' functional specification and for DRC agreement. Subsequently, the first version of the PARAMARINE software, incorporating the SURFCON functionality, was evaluated by the candidate and a test exercise undertaken involving the modelling of an in-service vessel, the RN Type 23 frigate. This is described in Section 4.3.

### 3.3.2 Overview of the SURFCON SRD

The GRC produced SURFCON SRD compared the projected SURFCON components and functionality, outlined in the Functional Specification, with the then-current PARAMARINE functionality and other preliminary ship design tools being used by the FSC IPT. A development of PARAMARINE was proposed as a "Commercial Off The Shelf" (COTS) solution to the SURFCON functional specification, making use of the existing software through the addition of new modules. The functionality to be provided by the new modules was then outlined from three main perspectives:-

- How the functionality was intended to be used in a preliminary ship design procedure;
- How the functionality would be provided to the designer (how the software would appear to function, rather than detailed code);
- How the modules would function (a text and flow-chart description, list of outputs, inputs and links to other modules and a summary of the most significant algorithms).

Figure 3.11 shows the proposed system dataflow presented in the SURFCON SRD. This diagram also shows the intention to transfer data (hulforms and equipment definitions) from the legacy preliminary ship design tool (PC GODDESS) into the new SURFCON tool.

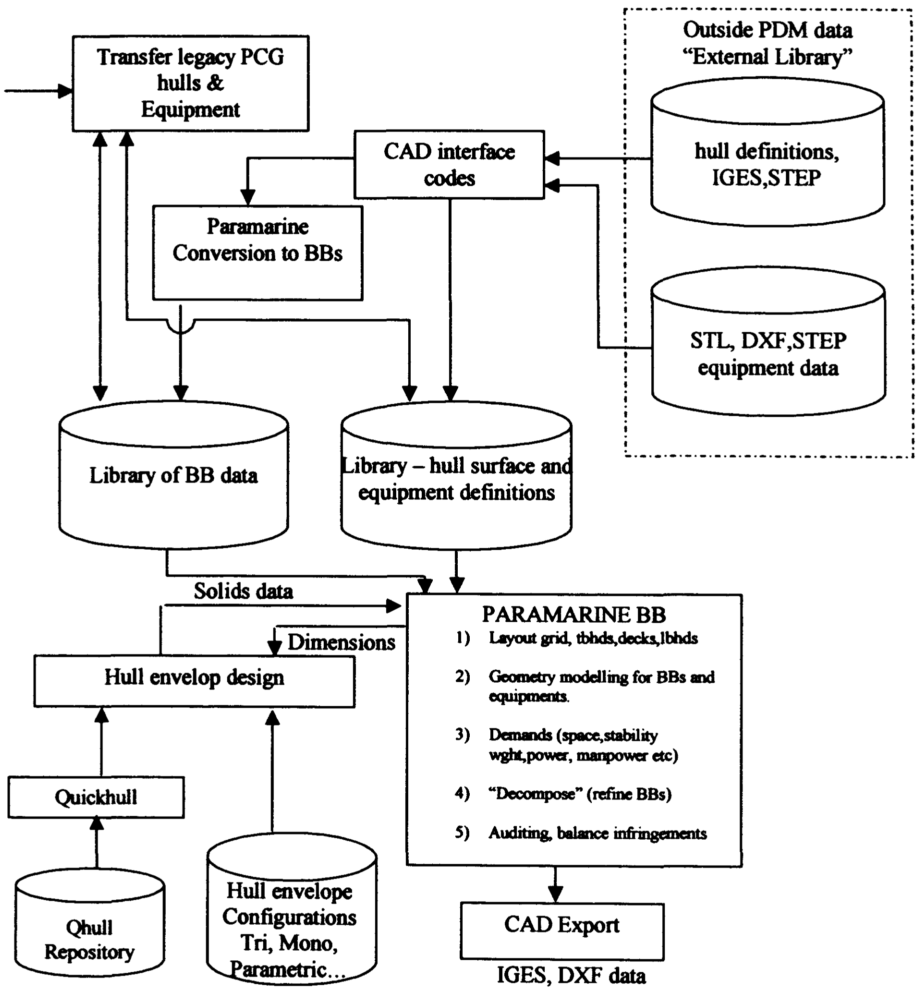



***Figure 3.11: System data flow proposed for the SURFCON module within PARAMARINE [GRC, 2002]***

The main points to note in this diagram are:-

- The new Design Building Block objects would read in information from libraries of previous hull shapes, Building Blocks and equipment definitions (machinery, weapons etc);
- The generation of the new hullform was to be carried out using the existing PARAMARINE "Quickhull" tool, (outlined in Appendix 5) and would be separate from the Design Building Blocks with only dimensional data and the resultant hullform exchanged;
- All Design Building Block definition and auditing was to take place in the new Design Building Block objects.

A more detailed flow chart, showing the data flow between the new SURFCON components was also included in the SRD and is reproduced as Figure 3.12. This figure also shows the sub-division of the SRD by GRC, into SRD 1 to SRD 6.

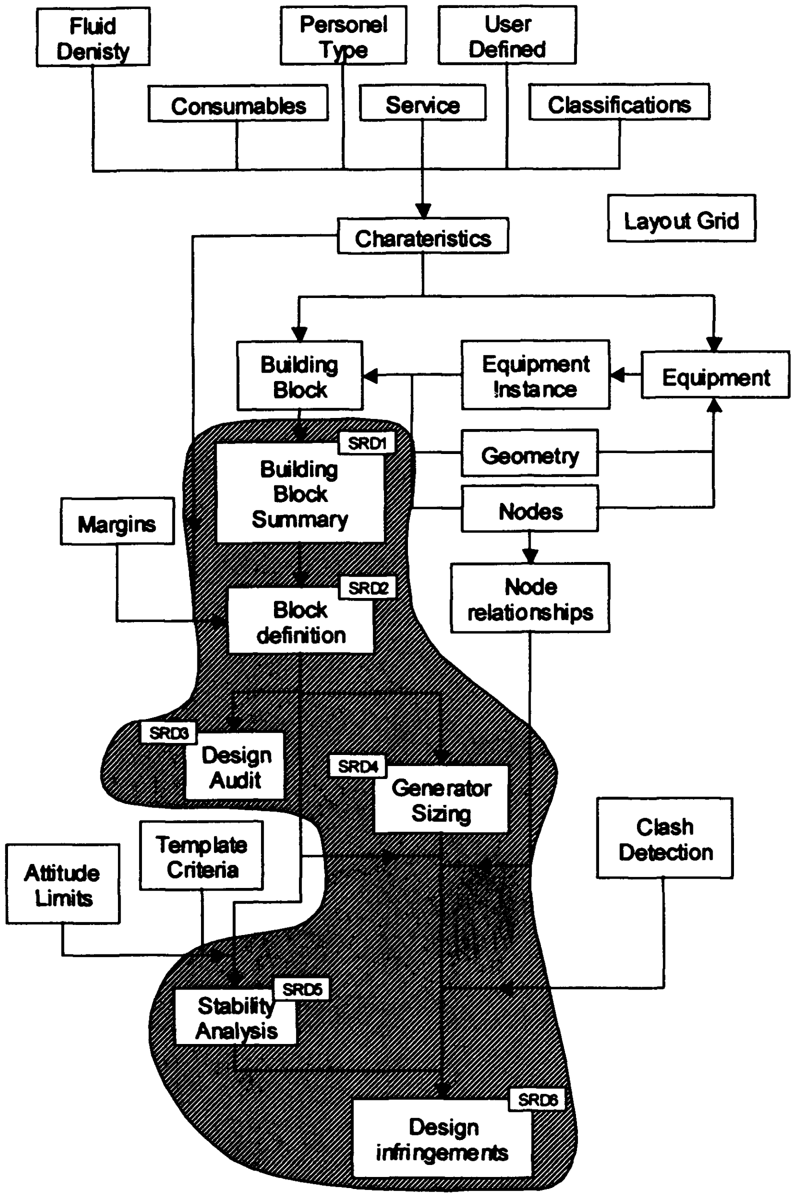



***Figure 3.12: Components of SURFCON specified in the SRD [GRC, 2002]***

The shaded area in Figure 3.12 encloses those objects used for numerical auditing and analysis of the overall ship characteristics. The structure is similar to Figure 3.11, with the information being read from libraries of equipment (via the "equipment instance" object), definitions of consumables (fuel oil, fresh water etc) and weight and space classification systems into the appropriate Design Building Block. Data flows into the "Design Audit" object, which can be used to produce numerical outputs, such as weight summaries and the "Design Infringements" object. The latter evaluates the numerical characteristics of the design for a balance of supply and demand.

### 3.3.3 Evaluation of the SRD

In addition to comparing the text of the Systems Requirements Document with the Functional Specification, the first release of the SURFCON functionality within the PARAMARINE software was evaluated by the candidate in two stages. In the first stage, two preliminary ship designs, previously developed in UCL MSc and BEng Ship Design Exercises using conventional software tools (Excel, AutoCad and GODDESS), were modelled using the new SURFCON functionality. These were not complete models of the ships with all internal spaces and weight groups represented and were only detailed to a level sufficient to verify that the functionality had been provided. Figure 3.13 shows these two designs, a general purpose frigate [*Pawling, 2000*] and a conventionally powered aircraft carrier [*Scheele & Menon, 1997*].

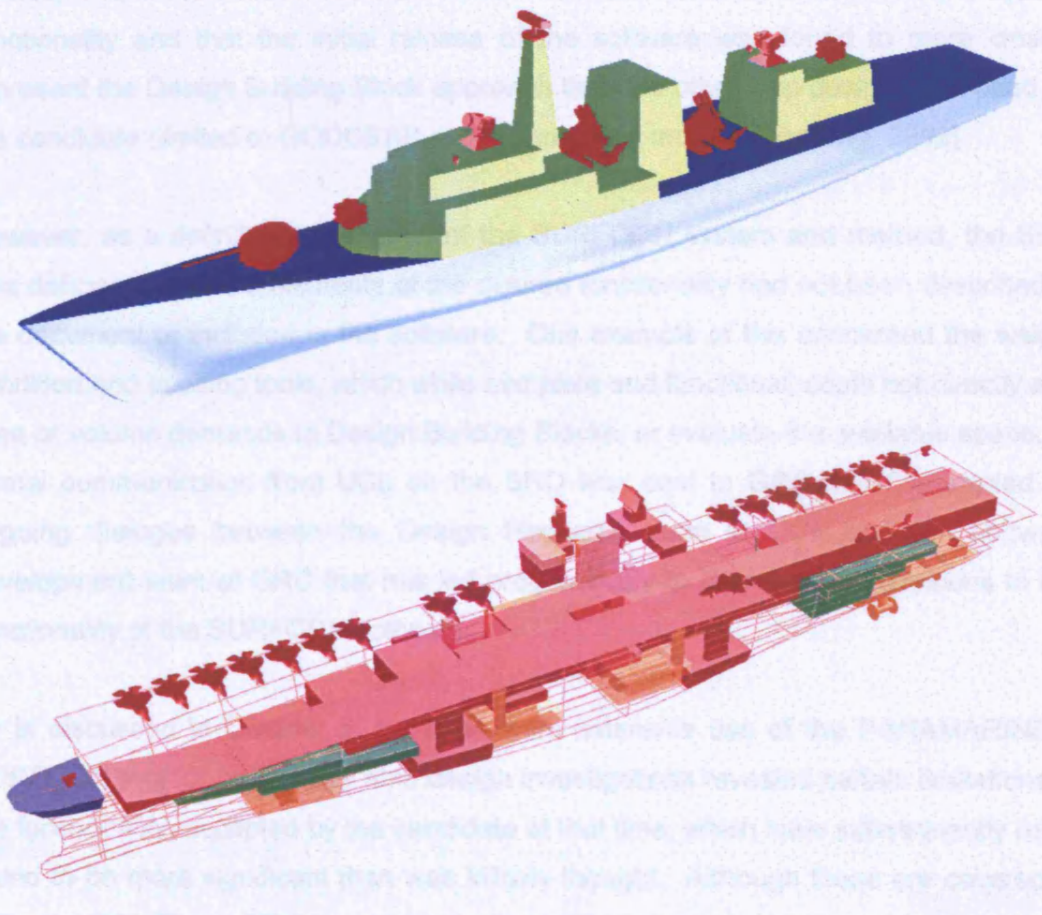


***Figure 3.13: Overall design models of a general purpose frigate and an aircraft carrier studies modelled to evaluate the functionality of the new SURFCON model within PARAMARINE***

These models were used to verify specific capabilities of SURFCON within PARAMARINE, such as the ability to model a range of hullforms (modern frigate or aircraft carrier hulls), the functionality of the numerical auditing tools and capabilities of the geometric modelling tools. The carrier model contained 90 Design Building Blocks, representing spaces such as accommodation blocks and distributed weights such as the structural weight and 19 equipment items representing machinery, sensors and defensive weapons. The frigate model was produced to investigate the solid modelling tools used in the generation of a model of the Type 23 frigate, described in Section 4.3, and only the upperdeck equipment was modelled using the new SURFCON functionality.

### 3.3.4 Conclusions from the Evaluation

As a description of the then-current state of the SURFCON software, the SRD was found to be broadly satisfactory. It outlined the general concepts of what SURFCON was expected to do and explained how these were achieved in PARAMARINE. Overall, it was concluded that the SRD document correctly reflected the required functionality and that the initial release of the software was found to more closely represent the Design Building Block approach than the other ship design tools used by the candidate (limited to GODDESS and spreadsheet models) [*Pawling, 2002*].

However, as a definitive description of the SURFCON system and method, the SRD was deficient, as some elements of the desired functionality had not been described in the document or included in the software. One example of this concerned the weight definition and auditing tools, which while complete and functional, could not directly add area or volume demands to Design Building Blocks, or evaluate the available space. A formal communication from UCL on the SRD was sent to GRC and this started an ongoing dialogue between the Design Research team at UCL and the software development team at GRC that has led progressively to changes and additions to the functionality of the SURFCON software.

As is discussed in Chapter 6, the later more extensive use of the PARAMARINE – SURFCON tool for preliminary ship design investigations revealed certain limitations in the functionality, accepted by the candidate at that time, which have subsequently been found to be more significant than was initially thought. Although these are covered in more detail in Chapter 6, they are worth summarising here:-

- No use of the layout grid. In Figure 3.12 this object, the layout grid, which is described in Appendix 5, has no connections to any other objects, because it is only a visual aid for the designer. Subsequent design work has revealed that this object is only useful to the designer for a very brief time in the initial layout. As described in Chapter 6, a more functional Layout Grid could have been much more useful.

- Importance of the user interface was not fully appreciated. Although the provision of an interactive integrated graphical display in PARAMARINE was found to be a significant improvement over the previous ship design tools, the SURFCON SRD was focussed on the technical aspects of providing geometrical modelling and numerical auditing tools, with little consideration to the overall "user experience" of the designer using the tool.

## 3.4 THE IMPLEMENTATION OF THE DESIGN BUILDING BLOCK APPROACH IN PARAMARINE

### 3.4.1 The PARAMARINE Tool

The wider development history of PARAMARINE is summarised in Appendix 3. Those features that made the software suitable for the implementation of the Design Building Block approach are specifically addressed in this section which expands on the outline given in Andrews and Pawling [*2003*]. PARAMARINE provides the means for interfacing the Design Building Block approach to a capable naval architectural design environment with integrated analysis of hydrostatics, resistance and propulsion, seakeeping and strength.

The PARAMARINE software package uses the commercial PARASOLID solid modeller kernel to describe the design [*GRC, 2003*]. The Graphical User Interface can then be used to analyse this model of the vessel by a variety of naval architectural tools. The main features of relevance in the PARAMARINE software are; the fact that it uses an integrated graphical and numerical representation of the model; the use of a single design configuration (explained below); the object based architecture of the software; and the open and largely unconstrained nature of the design environment.

#### Integrated Graphical Representation

Figure 3.14 below shows the interface in use, in this case viewing a design developed using the SURFCON functionality. The software normally runs in a single window, although dialogue boxes will appear to allow the entry of variables, showing the contents of tables and displaying graphs. The use of a single, multi-pane window allows the user to remain in a single unified software environment, removing the need to switch between different interfaces as analyses of the different performance aspects of the design are conducted in accordance with the designer's instructions.

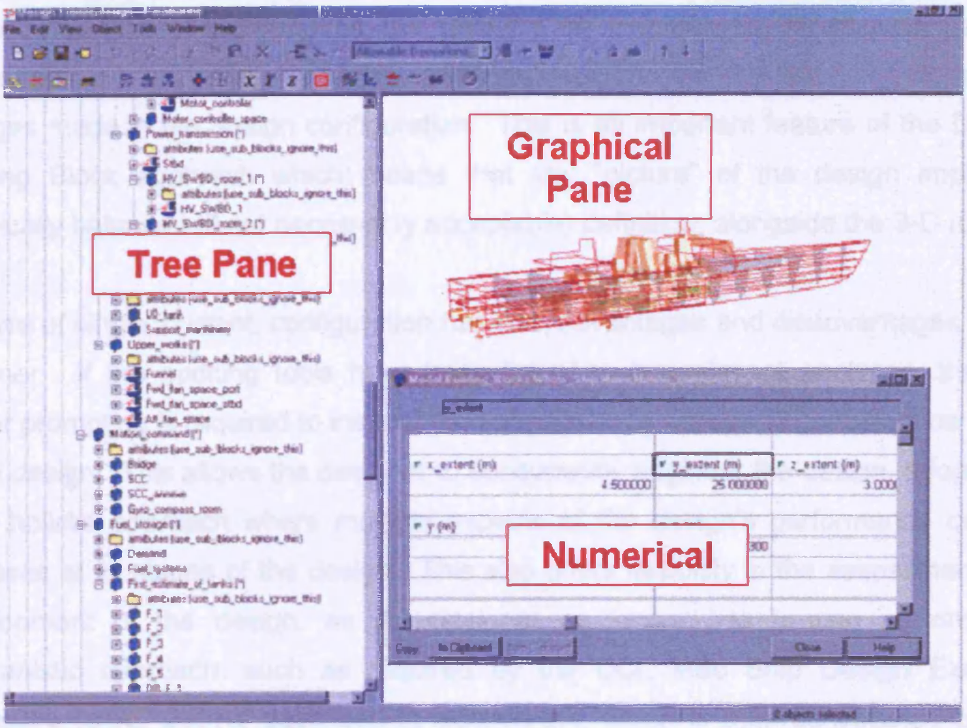



***Figure 3.14: PARAMARINE software interface showing SURFCON objects in use***

There are three main ways to view the design, or an element of it. The main 'Graphical Pane' on the right of the window shows the spatial aspects of the design. Some elements, such as centres of weight and sectional area curves, also have a graphical representation, which indicates their relationship with the rest of the design configuration. The graphical view can be panned left and right, rotated and zoomed and fixed views are available for the three main orthogonal views.

The "Tree Pane" to the left of the program window shows a hierarchical view of the objects used in the design. It is in this hierarchical structure that the designer adds new objects and connects them to the existing design structure. Double clicking on any item in the graphical or tree panes will open a dialogue box showing the numerical representation of the item in tabular form. The characteristics of the item can be edited from the numerical view or the 'Tree Pane'.

### The Single Design Configuration

A key feature of the PARAMARINE software is that it utilizes a single integrated model of the design. If any object can be seen in any dialogue box or pane of the screen, then it must have been re-calculated to reach the latest results based on the current configuration of the design. Placeholder objects, which act like folders, can be used to 'hide' time-consuming analyses, such as stability calculations, and thus prevent them from recalculating after every small change made to the design. When the overall design is audited for performance, the software will automatically recalculate stability, resistance and any other available analyses selected by the designer, to reflect changes made in the design configuration. This is an important feature of the Design Building Block approach which means that any "picture" of the design implies a technically balanced (if not necessarily acceptable) definition, alongside the 3-D model.

The use of single, current, configuration has both advantages and disadvantages to the designer. If the auditing tools have been linked to the relevant analyses, then no further prompting is required to instruct the software to re-assess all performance areas of the design. This allows the designer to concurrently engineer the design, adopting a more holistic approach where multiple aspects of the design's performance can be assesses at all stages of the design. This also offers flexibility in the assessment and development of the design, as the designer no longer has to use an ordered, mechanistic approach, such as required by the UCL MSc Ship Design Exercise Procedure [*UCL, 2001a*] described in Section 2.4, which is then constrained by the requirements of the current modelling and analysis tools.

There are, however, disadvantages in the use of a single design configuration. The first of these concerns the ability to conduct surveys of possible alternative configurations for the design. As the previous alternative design model will be lost when the next is produced, care must be taken to record the alternative possibilities, or to save them in completely separate design files. The second disadvantage to the current approach is that only a single designer can access and alter the design at any given time. This is in contrast to large scale detailed ship design systems, such as Tribon M3 and VANTAGE Marine [*RINA, 2005a*] [*RINA, 2005b*]. As explained in Chapter 2, these utilise an Integrated Product Data Environment (IPDE) which contains the extensive description of the design. Sophisticated software allows multiple designers to simultaneously work on different areas of the configuration [*Ross, 2006*]. As mentioned in Appendix 3 a multi-user version of PARAMARINE, known as ULTRAMARINE is under development.

This last point means that the single user – single design approach used in the PARAMARINE implementation of SURFCON is most appropriate to preliminary design, before a sizeable design team has been established and while there is still a large degree of uncertainty in the final configuration. However, there could be situation when multiple designers are working on parallel designs, such as a range of innovative hullform topologies designed to meet the same requirements (SWATH, Trimaran etc). In this case it would be important for the designers to share data and to be able to compare outputted results. It is currently only possible to achieve this by careful planning to ensure the use of the same overall hierarchy for each design study.

## Open and Object Based Structure

PARAMARINE is an object-based system [*Forrest, 2001*]. The designer can insert objects for the creation and analysis of the design in the hierarchical 'Tree Pane'. Figure 3.15 below shows this hierarchy for a generic warship, showing the four main Functional Groups.

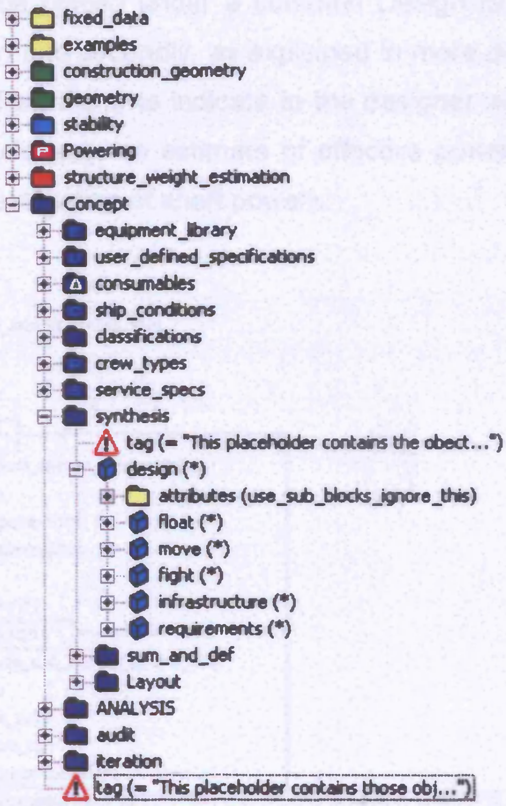



***Figure 3.15: Typical objects in a design file as used by the SURFCON module in PARAMARINE***

The use of objects is an effective way of managing the different types of analysis, such as stability and resistance, as the objects used for each type of specialised analysis can only be placed within specialised 'placeholders'. Figure 3.15 shows the typical arrangement of top-level placeholders (folders) in a design. The different colours of the placeholders indicate the role they play in modelling and analysing the design. For example, green placeholders contain modelling tools used to produce complex geometries, red placeholders are for objects that are used to develop an initial estimate of the structural scantlings, light blue placeholders are used for stability calculations and dark blue for the objects associated specifically with the early stage concept design of the vessel, such as the 'Design Building Block' object (discussed below in Section 3.3.2). The practical implementation of SURFCON in PARAMARINE consists of a new 'placeholder', which acts as a folder, containing new objects for the generation and analysis of early stage design configurations.

A key point to note regarding the "Tree Pane" is that it is not a direct representation of the relational structure of the design, or of the connections between the objects in the model of the design, although elements of its functionality can be used to represent this information. Firstly, as shown in Figure 3.16 those Design Building Blocks describing a single function can be placed under a common Design Building Block (known as a Super Building Block) and secondly, as explained in more detail below, graphical cues are provided in the Tree Pane to indicate to the designer what information is required by the analysis objects (e.g. an estimate of effective power and a propeller must be defined to allow the estimation of shaft power).

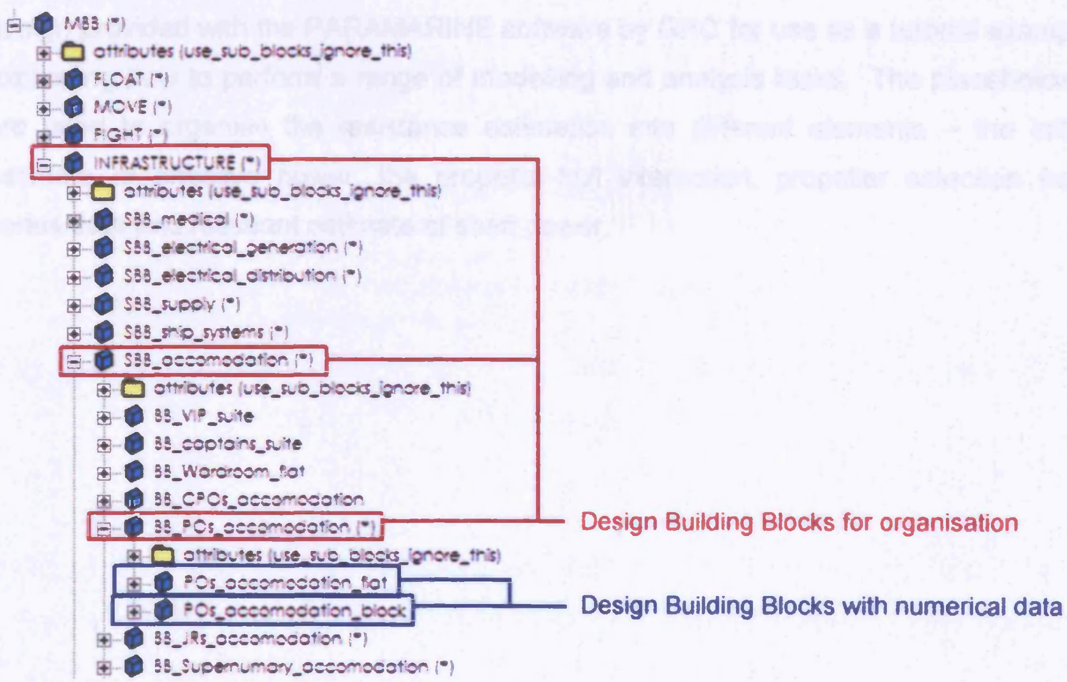



***Figure 3.16: Detail of the tree pane showing the use of Design Building Block objects to "file" Design Building Blocks containing numerical and spatial data***

The "Tree Pane" is more analogous to a filing cabinet in an office – it stores all information relating to a specified project. A well organised filing cabinet can reflect the structure of the project, but it does not directly display it. A poorly organised filing cabinet or poorly structured PARAMARINE-SURFCON hierarchy will have no link to the structure of the design and may even be counter-productive. It can be argued that the specialisation of placeholders (e.g. light blue placeholders can only contain stability analysis objects) described above encourages a coherent structure to some extent. Early in the subsequent work, described in Chapter 4, however, a standard style of hierarchical structure was developed that approximated the connections between modelling and analysis objects in the design. The importance of the "organisational" hierarchy, as opposed to a "relational" hierarchy, is discussed further in Chapter 6.

The object based structure of the software and the interface, make PARAMARINE ideal for the incorporation of the Design Building Block approach, through a series of new objects and tools. PARAMARINE features a consistent graphical style in all the objects and interfaces. This makes the operation of the tool easier to learn and also gives a graphical representation of data required by each analysis object. For example, Figure 3.17 shows the powering estimation objects. In this case, the Holtrop and Mennen method [*Holtrop & Mennen, 1982*], [*Holtrop, 1984*] has been used to estimate the resistance of the 550 tonne Mine CounterMeasures Vessel (MCMV) design provided with the PARAMARINE software by GRC for use as a tutorial example explaining how to perform a range of modelling and analysis tasks. The placeholders are used to organise the resistance estimation into different elements – the initial estimate of effective power, the propeller-hull interaction, propeller selection from series data and resultant estimate of shaft power.

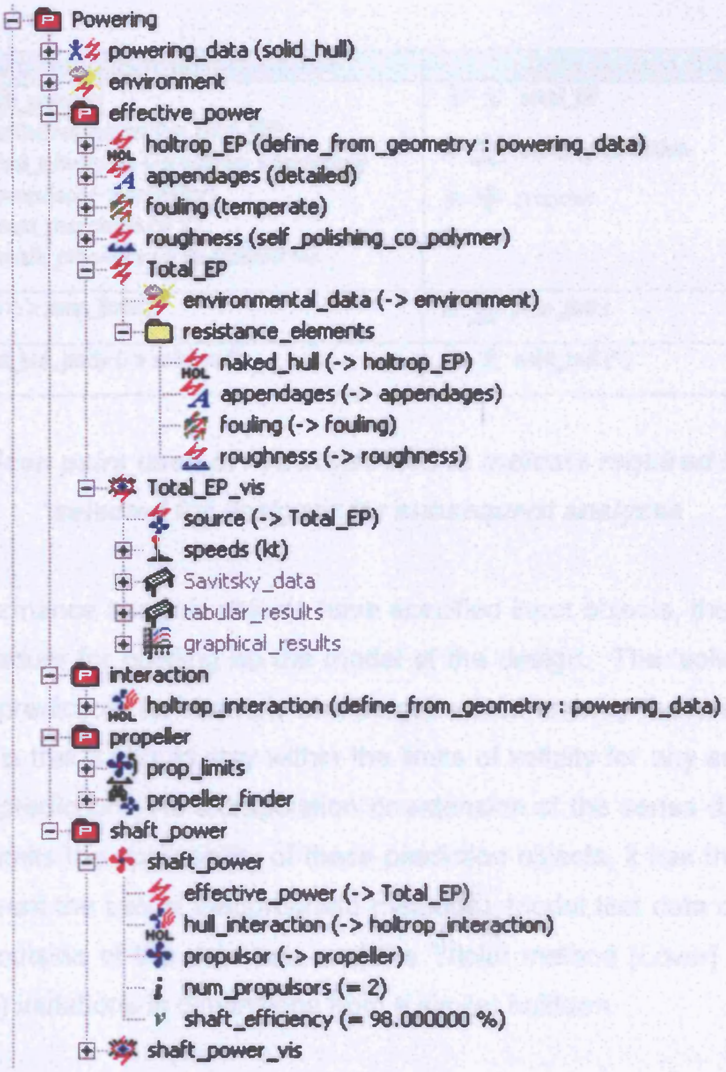



***Figure 3.17: Resistance and Powering prediction objects from PARAMARINE for MCMV study***

The required inputs for the objects are shown through the use of the icons – the 'shaft_power' object, which calculates the shaft power of the design, needs to be connected manually to an effective power estimate, a hull interaction calculator and a definition of the propulsor. Table 3.6 below shows the pairs of icons used to indicate this. On the left is the 'request' for an input and on the right is the object used to provide the input.

| Data Input Into Analysis Object | Data Source Object |
|---|---|
| shaft_power<br>effective_power (-> Total_EP)<br>hull_interaction (-> holtrop_interaction)<br>propulsor (-> propeller)<br>num_propulsors (= 2)<br>shaft_efficiency (= 98.000000 %) | Total_EP<br>holtrop_interaction<br>propeller |
| limits (-> prop_limits) | prop_limits |
| naked_hull_body (-> solid_hull) | solid_hull (*) |

***Table 3.6: Icon pairs used in PARAMARINE to indicate required inputs to be selected for designer for subsequent analyses***

Although performance analysis objects have specified input objects, there is no overall specified procedure for building up the model of the design. The 'solid_hull' required for resistance prediction, for example can be generated anyway the user wishes. The only limitation is that it should stay within the limits of validity for any series data used for resistance prediction. No extrapolation or extension of the series data is provided. Although this limits the applicability of these prediction objects, it has the advantage of helping to prevent the use of inappropriate methods. Model test data can be used for hulls that fall outside of the data sets and the Triplet method [*Lover*] is available for small (+/- 10%) variations in dimensions from a similar hullform.

With the high level of flexibility inherent in the PARAMARINE software, it is important that the designer and the recipient of the design, be it the designer's line manager or a customer, can readily assess the interconnections in the design and the methods, assumptions and data that have been used. For all objects a 'property' dialogue box is available, with four main options, shown in Figure 3.18.

The 'General' tab displays the full name of the object, indicating its position in the hierarchy. The 'Ancestors' tab shows which objects the currently selected object uses as inputs and the 'Descendents' tab indicates those objects that use data from the current one. The 'Sequence' tab shows the sequence of operations that were carried out on the current object to bring it to its current state. In this case, the list in Figure 3.18 shows the instructions needed to connect the 'shaft_power' object to its ancestors. This properties box can be used to interrogate any object in the design.

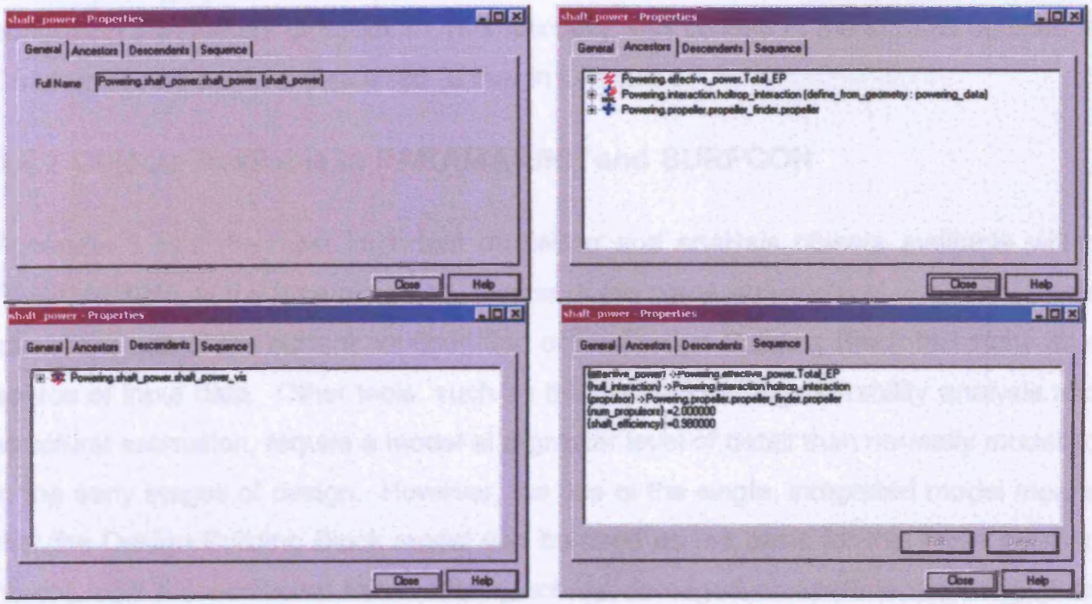



***Figure 3.18: The PARAMARINE Properties dialogue box, showing General, Ancestors, Descendants and the Sequence of the currently selected object.***

The PARAMARINE software also records all actions taken by the user during a session and records them as a 'log' file. This is in the form of 'Kernel Command Language' (KCL), which is the language used to instruct the software kernel in creating the design. The saved log of actions can be viewed in text format, or even re-played to recreate part or all of the design. An example of this language is included, with a description, in Appendix 4. The main importance of this feature is that it can be used to transfer parts of a ship model between PARAMARINE design files. As it is text-based, spreadsheets and other tools can be used to generate KCL macros, increasing scope for communication between PARAMARINE-SURFCON and other software tools.

### Unconstrained Nature of the Design Environment

The PARAMARINE – SURFCON tool as a whole is not limited to any specific type of vessel, although specialist analysis objects, such as those for resistance estimation, are limited in applicability by the mathematical methods that they employ, particularly in a highly unconventional design. The flexibility of the tool is manifested in several ways. Numerical characteristics, such as weight and space demand, can be estimated using any algorithm the designer wishes and the software does not contain any assumed values. The geometry of the hullform, superstructure and Design Building Blocks can be generated using a wide range of modelling tools, allowing multihulls to be designed, in addition to conventional monohulls. Additionally, the flexibility of the tool permits different methods to be used to generate the same geometry, dependent on the controlling parameters of interest. This flexibility was utilised in the studies outlined in Chapters 4 and 5 and is discussed further in Chapter 6.

### 3.4.2 Objects Available in PARAMARINE and SURFCON

Appendix 5 lists the most important modelling and analysis objects available within PARAMARINE at the time of writing. Some of the naval architectural analysis objects can make use of the current configuration of the Design Building Block hierarchy as a source of input data. Other tools, such as the detailed damaged stability analysis and structural estimation, require a model at a greater level of detail than normally modelled in the early stages of design. However, the use of the single, integrated model means that the Design Building Block model can be used as the basis for this more detailed model, with the additional information (such as damaged compartments) defined as required.

#### Data Flow within a SURFCON Design File

Figure 3.19 is a diagram showing the main elements of the data flow in a typical SURFCON design file. It is not representative of a process, but is a very high-level map of connections between objects in the file, hence there are no iterative loops shown. However, this data flow between objects within PARAMARINE – SURFCON was an influence on the procedure for using the tool, as it determined in part what was required for each stage of modelling and analysis. More detailed versions of this diagram are included with the specific designs presented in Chapter 4. This diagram was drawn by the candidate during the initial work in assessing the SRD, to better understand the most effective way of using the software.

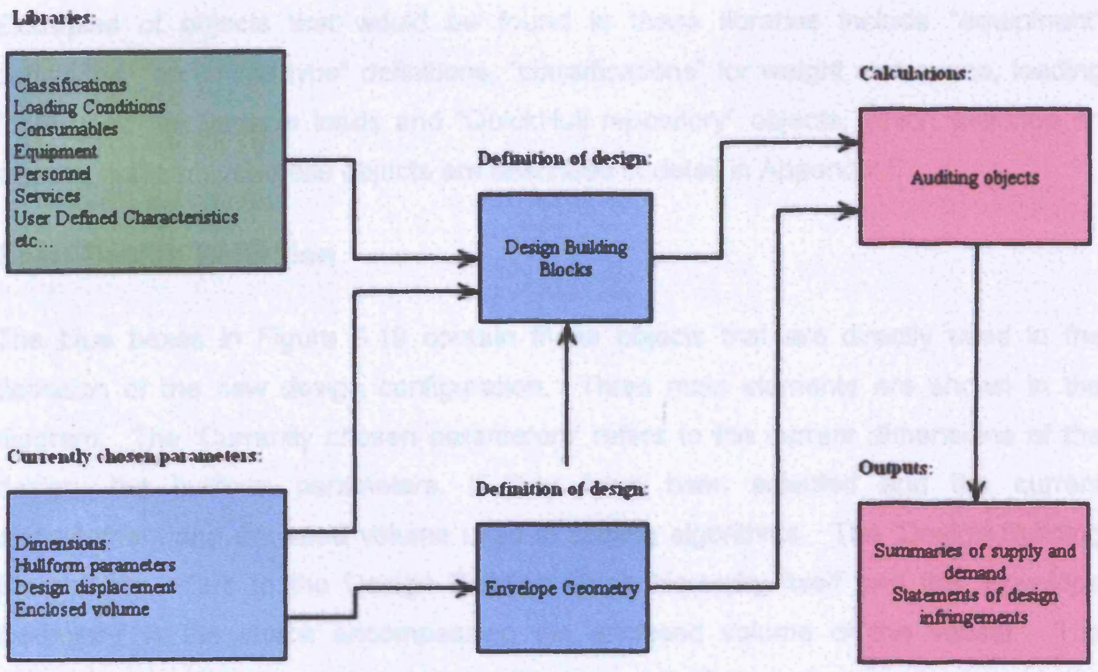



***Figure 3.19: Data flow diagram for a generic SURFCON design file***

The individual objects described in Appendix 5 each fall within one of the boxes in Figure 3.19. The three colours, green, blue and red show the division of these main elements into three main roles within the design file (libraries, definition of design and auditing / analysis). These also correspond to their roles in the design process. Again, these are not the functions of the vessel being designed – this diagram only represents the overall way in which objects are connected together to allow a design to be generated. The green blocks are libraries of information to be used in the new design; the blue blocks are the objects used in synthesising the new design configuration and the red blocks are used to assess the design for performance and produce outputs from the current stage of the iterative process.

## Green: Libraries and References

A SURFCON design description uses a variety of reference objects. These include explicit declarations of certain variable types to be used in the design, such as the different ranks of personnel, or the weight group classification system ("classifications") to be used. These definitions are then referred to by the design definition objects; the Design Building Blocks, equipment items and the hullform generation tools. Standard items of equipment, such as missile launchers or gas turbines, can be defined in a single object which is then referred to wherever this equipment is used in the design. Similarly, different parent hullforms might be included, so that alternative hullform styles could be considered in the design.

Examples of objects that would be found in these libraries include "equipment" definitions, "personnel type" definitions, "classifications" for weight and space, loading "conditions" for variable loads and "QuickHull repository" objects, which describe an existing hullform. All these objects are described in detail in Appendix 5.

### Blue: Design Definition

The blue boxes in Figure 3.19 contain those objects that are directly used in the definition of the new design configuration. Three main elements are shown in the diagram. The 'Currently chosen parameters' refers to the current dimensions of the design, the hullform parameters, if they have been selected and the current displacement and enclosed volume used in scaling algorithms. The 'Design Building Blocks' box refers to the Design Building Block hierarchy itself and the 'Envelope Geometry' is the shape encompassing the enclosed volume of the vessel. The dimensions are used to size and shape the current hullform and superstructure blocks that make up the envelope and may also be used to size certain Building Blocks. For instance, the current ship's length may be used as a parameter in estimating the structural weight. Similarly, the Envelope feeds information into the Design Building Block hierarchy, as the shape of tanks, machinery spaces etc, is dependent upon the hullform.

The most important object in this category is the "building block" object. An example is shown in Figure 3.20.

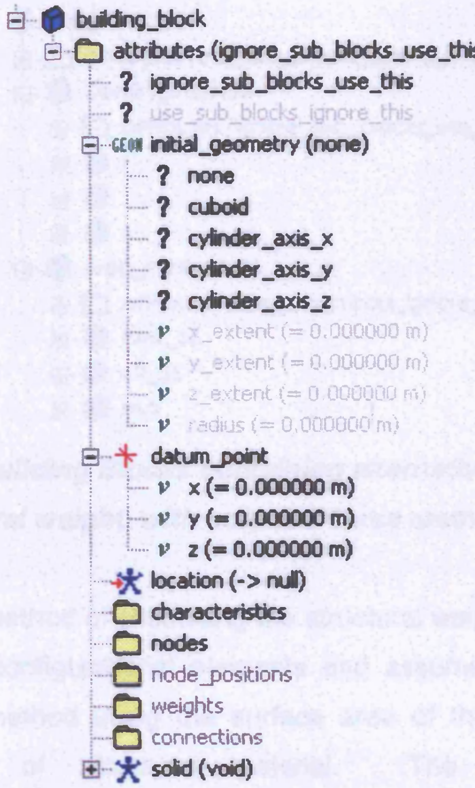



***Figure 3.20: Building block object as first inserted in the design hierarchy in the SURFCON module***

The Design Building Block object is used to represent an entity in the Design Building Block hierarchy of the design. This can be an individual functional space, such as the Operations Room or a magazine, a Super Building Block, such as a hangar and the associated workshops and stores, or one of the four Functional Groups normally used – FLOAT, MOVE, FIGHT and INFRASTRUCTURE. In the latter case, the object acts as a placeholder, containing all the lower-level Building Blocks.

Due to the fundamental importance of this object to the implementation of SURFCON in PARAMARINE, its composition is covered in detail here, rather than in Appendix 5.

The **"ignore_sub_blocks_use_this/use_sub_blocks_ignore_this"** options allow the designer to control whether the data within this block, or any daughter blocks, is used in the auditing of the design. Figure 3.21 shows an example of this switch in use.

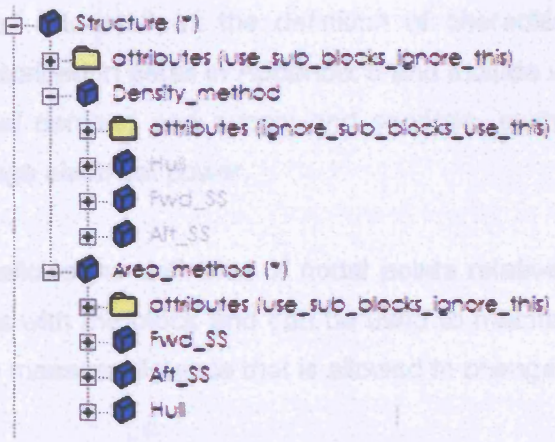



***Figure 3.21: Design Building Blocks containing alternative methods of estimating structural weight, with only the "Area method" in use***

In this case, an initial method of estimating the structural weight of the vessel, from the volume of the major configurational elements and assumed structural density, has been replaced by a method using the surface area of the main elements and an equivalent thickness of structural material. The Building Block object "Density_method", used to contain daughter blocks for each of the main structural weights, has been set to "ignore_sub_blocks_use_this" so that the weights will not be used in any audit or stability analysis. The names of the daughter blocks are highlighted in a lighter colour to indicate that they are not currently used.

The **"initial_geometry"** attribute allows the definition of simple cuboid or cylindrical geometries for the block. In a surface ship design, most blocks would be assigned the initial geometry of a cuboid.

The **"datum_point"** specifies the position of the centroid of the block relative to the world origin. The location of the origin is not controlled explicitly by the designer – rather, the design can be constructed anywhere relative to it in the design space. Typical locations have included at the keel amidships and at the baseline at the after perpendicular.

The **"location"** pointer allows another solid body to be specified as the required location for this block. If it is not within that space, the designer is alerted. For example a folded helicopter could be assigned a "location" referred to the hangar geometry. Thus if design changes make the hangar too small then the designer will be alerted to the infringement.

The **"characteristics"** folder allows the definition of characteristics of the Building Block. These are described in detail in Appendix 5 and include weight, space demand and supply, personnel demand and supply and services, such as chilled water (for cooling) and low voltage electrical power.

The **"nodes"** folder allows the definition of nodal points relative to the "datum point". These move in space with the block and can be used to maintain a fixed relationship between blocks, or to measure distance that is allowed to change.

The **"connections"** folder shown in Figure 3.20 is part of the recent developments in Design for Production made to PARAMARINE / SURFCON. When these developments are complete, this will allow defining connections between equipment items and building blocks and modelling of the resulting service routes, such as electrical cabling or chilled water piping.

The final object in the building block is the **"solid"** that describes the block's spatial extent, resulting from the selection of an initial geometry or more detailed modelling operations, such as the "subtract" and "intersect" operations. These operations allow a Design Building Block to be "trimmed" to fit within the hullform, or to have sections removed to represent intersecting spaces, such as vertical engine intakes etc.

As PARAMARINE uses a solid-modelling kernel for its spatial calculations, terms such as "solid-body" are frequently used to describe its operations. This is because the PARASOLID software is usually used in product design applications, where the objective is to model the location of the physical material in the product. However, in the early-stage ship design application, we are more concerned with modelling where the available space is (essentially) where the designer has yet to specify any physical material. Thus PARAMARINE and SURFCON are using volume-based modelling. This change in modelling terminology can cause confusion when teaching designers how to use the tool for the first time. When referring to specific technicalities of PARAMARINE – SURFCON models, the GRC terminology of "solid body", meaning the geometry of that item, will be used.

### Red: Design Auditing and Analysis

The red boxes in Figure 3.19 contain those objects used to audit the design and assess its performance. The basic auditing objects are the "block summary", "block definition" and "design audit" objects outlined in Appendix 5. These generate tabular listings of any variable used in the design, showing the distribution by block (a direct representation of the Design Building Block hierarchy) or by any weight group classification system used, e.g. NES 163 [*MoD, 1989*].

As described in Appendix 5, the "design infringements" object is used to summarise all problems currently detected in the design. This object is shown in Figure 3.22.

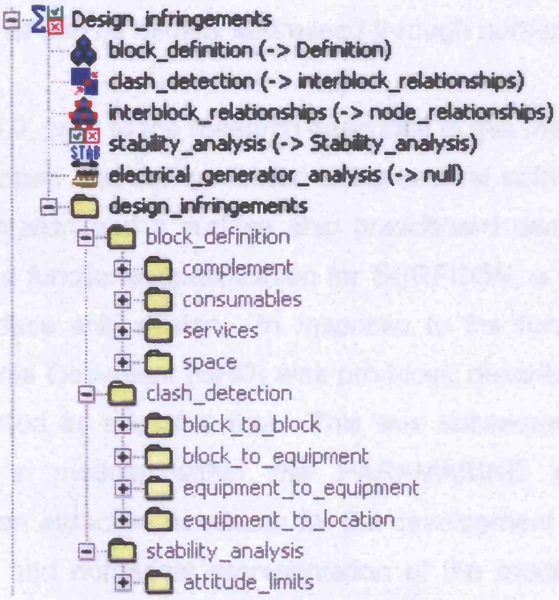



***Figure 3.22: Design Infringements object in the SURFCON module***

There are direct inputs to allow the assessment of supply and demand for variables, spatial clashes, nodal relationships, intact stability and generator power versus total electrical load. In addition to these specialist SURFCON analysis objects, outputs from the "design audit" objects, such as weight, centre of gravity and buoyancy provided by the hullform, can be used in more detailed assessments of damaged stability and resistance. These assessments use the analysis objects included within PARAMARINE, which are not part of the SURFCON module.

## 3.5 Conclusions From Chapter 3

This chapter has summarised the development and application of the Design Building Block approach to submarines and surface ships. The key underlying principles are:

- The Design Building Block approach is a holistic approach to design synthesis, using architecture as the integrating factor;
- The approach integrates architectural description with the numerical synthesis and analysis;

- The approach requires tools that provide an integrated interactive display of the architectural configuration of the design;
- The Design Building Block approach is not an automated process of decision making. Rather, it encompasses aspects requiring designer judgement and the softer, more customer-focused aspects of design, that may not be amenable to numerical analysis at the earliest stages, with the more traditional performance related aspects that can be usually addressed through numerical analysis.

As shown in Figure 3.2, prior to the research described in this thesis, the new approach to design was developed and demonstrated using several software tools, including a submarine implementation and a surface ship breadboard demonstrator. The latter demonstrator led to a functional specification for SURFCON, a software tool applying the approach to surface ship design. In response to the functional specification a Systems Requirements Document (SRD) was produced describing how the approach was to be implemented as a usable tool. This was subsequently done by GRC at UCL's behest as a module within the PARAMARINE ship design system. PARAMARINE was an attractive candidate for the development as it: made use of an integrated graphical and numerical representation of the model; employed a single design configuration; and featured an object based architecture and a flexible geometric modelling environment.

The candidate assessed the SRD and software implementation against the functional specification, in a process which is outlined in more detail in the next chapter. Overall, it was found that the functional specification was largely satisfied. However, subsequent preliminary ship design studies have shown that additional software functionality would enable the PARAMARINE-SURFCON tool to satisfy the specification more closely and also to more closely reflect the philosophy of the Design Building Block approach. These issues are discussed in Chapter 6.

# Chapter 4: The Procedural Implementation of the Design Building Block Approach

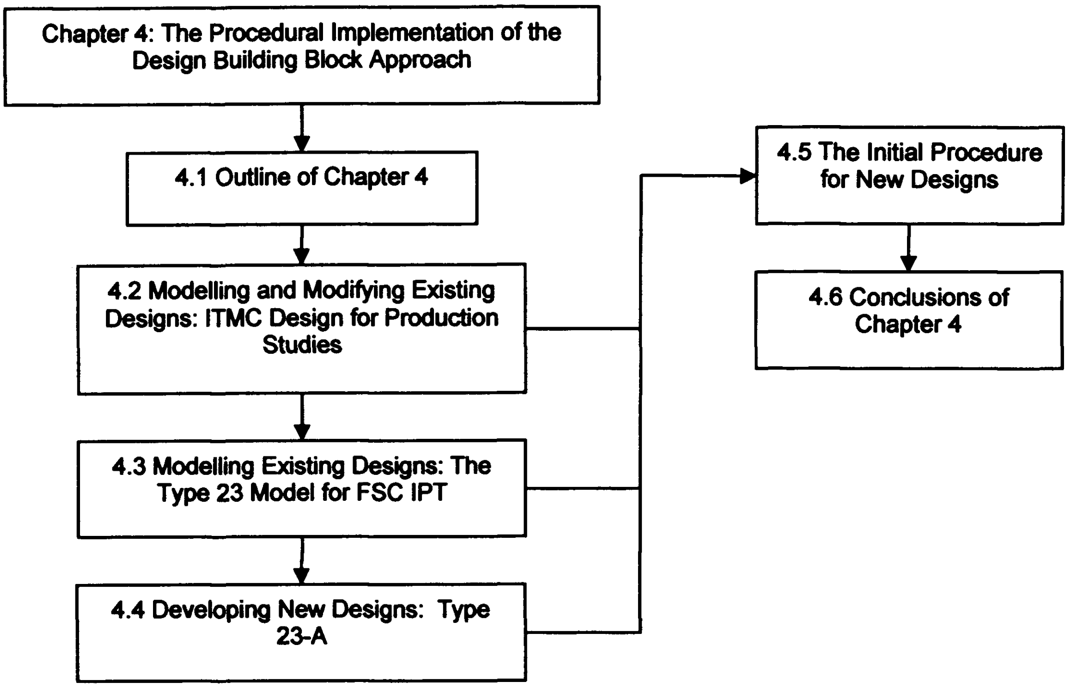



***Figure 4.1 Schematic of Chapter 4***

## 4.1 OUTLINE OF CHAPTER 4

The previous chapters have provided a general background on the development of the Design Building Block approach and how the software requirements, derived from this overall philosophy of design, were implemented in software tools, culminating in the PARAMARINE-SURFCON software produced by Graphics Research Corporation. Any approach to design consists of not just philosophy and tools but also a procedure for their use and this chapter describes the development and demonstration of a practical procedure for the effective utilisation of the capabilities of the tool over three early stage ship design studies. The chapter concludes with an outline of the initial procedure that was developed for synthesising new designs in the PARAMARINE-SURFCON implementation of the Design Building Block approach. This procedure then provided the complete design toolset required to generate the early-stage designs outlined in Chapter 5.

## 4.2 Modelling and Modifying Existing Designs: ITMC Design for Production Studies

### 4.2.1 Aims of the Project

Between October and December 2001 and November and December 2002, the candidate was involved in a project investigating the use of the Design Building Block approach to improve the producability of vessels, entitled "Integrated Technology for Marine Construction (ITMC): The Use of Design Building Block Methodology Based Preliminary Ship Design Tool to Facilitate a Generic Concurrent Engineering Approach in Advanced Shipbuilding". [*Andrews & Zhang, 2002*] This project, funded by the Shipbuilders and Shiprepairers Association using DTI LINK funds involved the use of the SURFCON tool to model baseline designs provided by industrial partners, with subsequent improvements to reduce production costs.

The majority of the research work on this project was carried out by Burger, working as a research student at UCL [*Andrews, Zhang & Burger, 2005*]. The candidate was involved in the development of the overall procedure for the modelling of the baseline and variant designs, the construction of two of the baseline models and some of the variant studies, as described below.

### 4.2.2 Designs Studied

Three designs were examined in this project; an indicative design for the Royal Navy's Landing Platform, Dock (Replacement) (LPD(R)) provided by BAE Systems; an Offshore Missile Vessel (OMV) provided by Vosper Thornycroft and a Platform Supply Vessel (PSV) provided by Fergusson Shipbuilders. The candidate primarily worked on the LPD(R) model, the baseline SURFCON model for which is shown in Figure 4.2. In this and all subsequent designs, a common colour scheme was used. FLOAT Building Blocks were blue (light blue for access spaces), MOVE Building Blocks were yellow / orange, FIGHT red and INFRASTRUCTURE green.

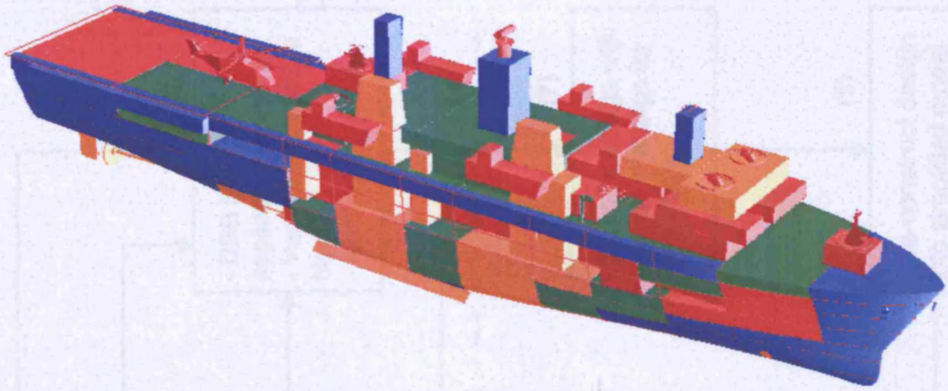


***Figure 4.2 LPD(R) baseline model produced for the ITMC project [Andrews et al, 2002]***

The first milestone in the ITMC project was the creation of accurate SURFCON representations of the three baseline vessels from the data provided by the industrial partners. Each design would be represented by an integrated model, with weight and space data included to allow re-sizing of the vessel to incorporate the effects of later producibility driven changes. This also provided a validation of the capabilities of the new PARAMARINE / SURFCON tool to the three shipbuilders. Subsequent to the generation of these models, a series of variants investigating various design features, intended to reduce the production costs of the vessels, were created.

### 4.2.3 Development of the Procedure

Figure 4.3 shows the flowchart drawn up by the candidate in October 2001 to describe the overall process of modelling the existing designs in SURFCON and then undertaking design studies of variants. The flowchart is divided into two main sections and numbers have been added to assist in the overview which follows. This flowchart represented the planned process and so, in some cases, the actual work carried out differed from this initial process.

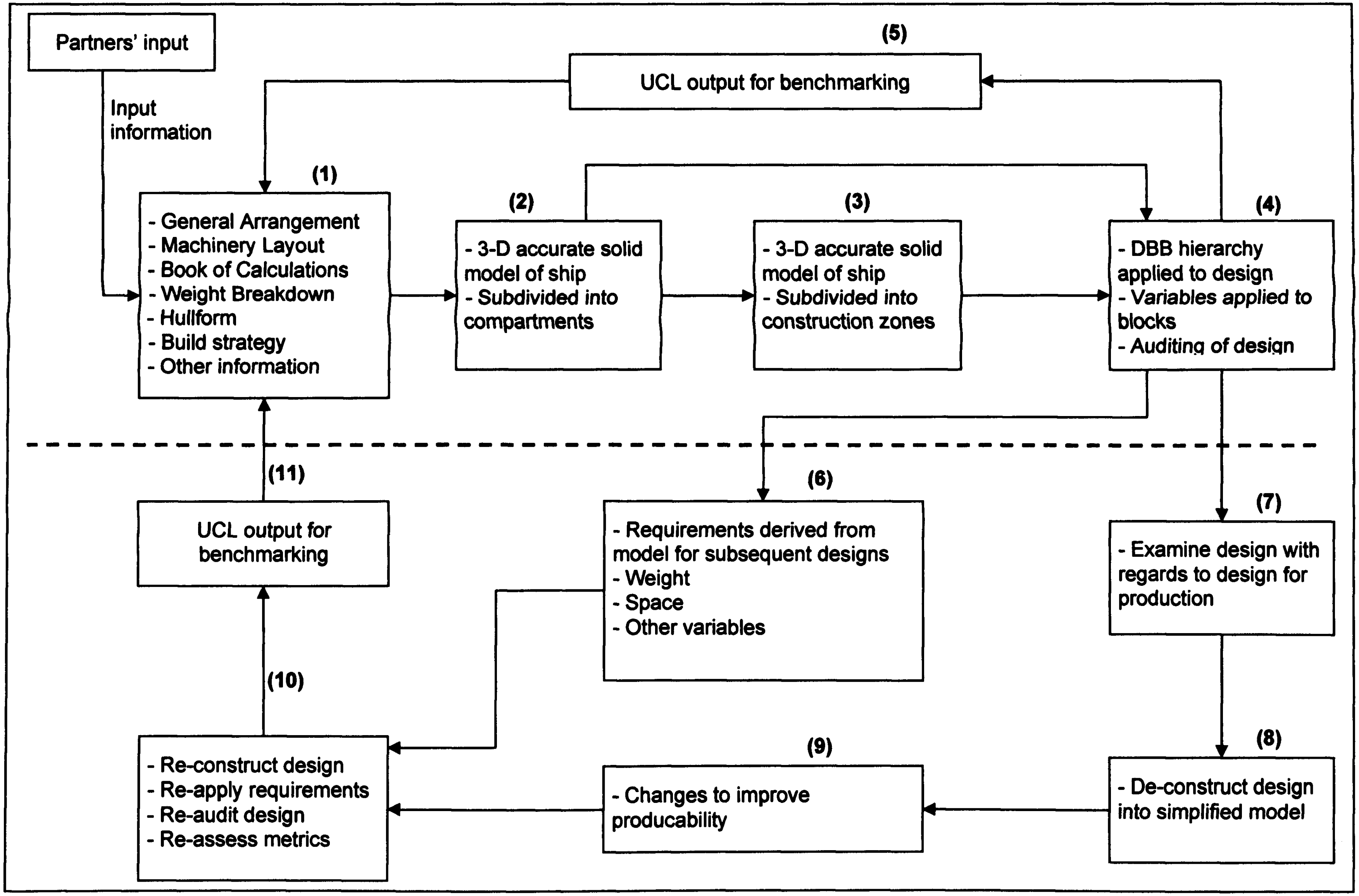



***Figure 4.3: Flow chart showing overall procedure for ITMC project design modelling and variant studies (October 2001)***

The upper part of Figure 4.3 represents those tasks required to achieve the first milestone, namely the creation of a baseline model of each of the designs. This model contained sizing algorithms and fixed data, which not only correctly represented the information provided by the shipyards but also allowed easy modification and assessment of the impact of changes to the configuration of the design. Considering each step in Figure 4.3 in turn:-

1. The industrial partners in the ITMC project were able to supply various descriptions of the ship designs, including weight breakdowns in costing – based weight systems such as NES 163 [*MoD, 1989*], general arrangement drawings, hullform line plans and illustrations of the build strategy.

2. The first model developed for each of the designs utilised a spatial or locational hierarchy, where the ship is broken down by watertight section and deck. This is spelt out in more detail in Section 4.3, where the modelling of the Royal Navy Type 23 frigate is described. This was undertaken for the UK Ministry of Defence project team for the future combatant – Future Surface Combatant Integrated Project Team (FSC IPT). This type of model would reflect accurately the layout as shown on the General Arrangement drawings, but would not contain any numerical design data, such as weight.

3. Where production strategies were available, the constructional zones were also modelled as part of the initial model construction. In practice this was delayed until after the production of a Design Building Block hierarchy populated with all the required data.

4. & 5. These items represent the most challenging part of the generation of the baseline models –the population of the Design Building Block hierarchy with the design data supplied by the shipbuilders. This necessitated the translation of weight breakdowns, given in the NES 163 system, into a functional hierarchy (with four main functional groups, FLOAT, MOVE, FIGHT and INFRASTRUCTURE) and the choice of suitable scaling algorithms. The methods used to break down the weight data into a functional hierarchy are described in detail for the Type 23 in Section 4.3.

The lower part of Fig 4.2-2 describes the process of modifying a design in the producability studies:-

6. In order to ensure the "producability driven variant designs" had the same operational capability (i.e. ship performance) as the baseline configuration, the internal spaces had to be assessed for sufficient area or volume. The demand for these spaces in the variant was derived from that in the baseline.

7. The baseline design was examined to identify producability areas for study. Some variants were suggested by the shipbuilders and others were identified by UCL researchers.

8. For studies involving large changes to the overall layout of the vessel, the model was simplified to allow rapid re-design. For instance, accommodation spaces were represented as large blocks and fuel tanks by large groups of tanks. In practice, this was implemented via the establishment of fixed spatial relationships between specified Design Building Blocks, permitting them to be treated as a single Super Building Block. A generic example of such a fixed spatial relationship is shown in Figure 4.4, where a group of Design Building Blocks are defined as discrete items, but can be moved as a group.

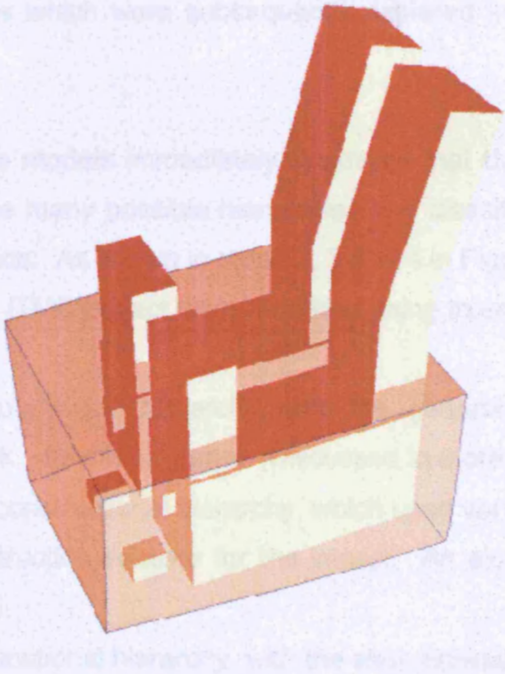


***Figure 4.4: Generic example of grouped objects. The Gas Turbines, uptakes and ancillary equipment move with the machinery space in which they are placed***

9. The designs were modified to incorporate the features identified in step 6 that were perceived to lead to improved producability.

10. The modifications made to improve producability could result in an unbalanced design, e.g. by reducing required functional spaces or requiring the propulsive power, to achieve the designated speed, to be increased beyond that provided in the baseline design. This step in the process refers to the need to re-balance the design and thus accounts for the whole-ship effects on the modification to the baseline configuration of the changes made.

11. The final stage in this proposed procedure was to output the design description in an appropriate format to allow direct comparison with the baseline design. This benchmarking was undertaken by the UCL team, with costing data supplied by the shipbuilders, based on the modified design's weight and configuration characteristics.

### 4.2.5 Discussion and Conclusions on the ITMC Design for Production Studies

The initial work carried out by the candidate for the SSA ITMC project overlapped with the development of a detailed model of the RN Type 23 frigate and so the issues identified below were derived from lessons on both projects. The ITMC studies identified certain issues which were subsequently explored in the Type 23 and later studies.

The construction of the models immediately illustrated that there could be significant differences between the many possible hierarchies and classification systems used to describe and model ships. As shown in steps 2, 3 and 4 in Figure 4.3 each of the three baseline designs in the ITMC project were modelled using three hierarchies:-

- The first was a subdivision hierarchy, with the general form hull – watertight compartment – deck – functional space (Discussed in more detail in Section 4.3).
- The second was a constructional hierarchy, which used very large cuboid shapes to represent the construction scheme for the vessel. An example for the LPD(R) is shown in Figure 4.5.
- The third was the functional hierarchy, with the ship represented by Design Building Blocks. This is shown in Figure 4.2

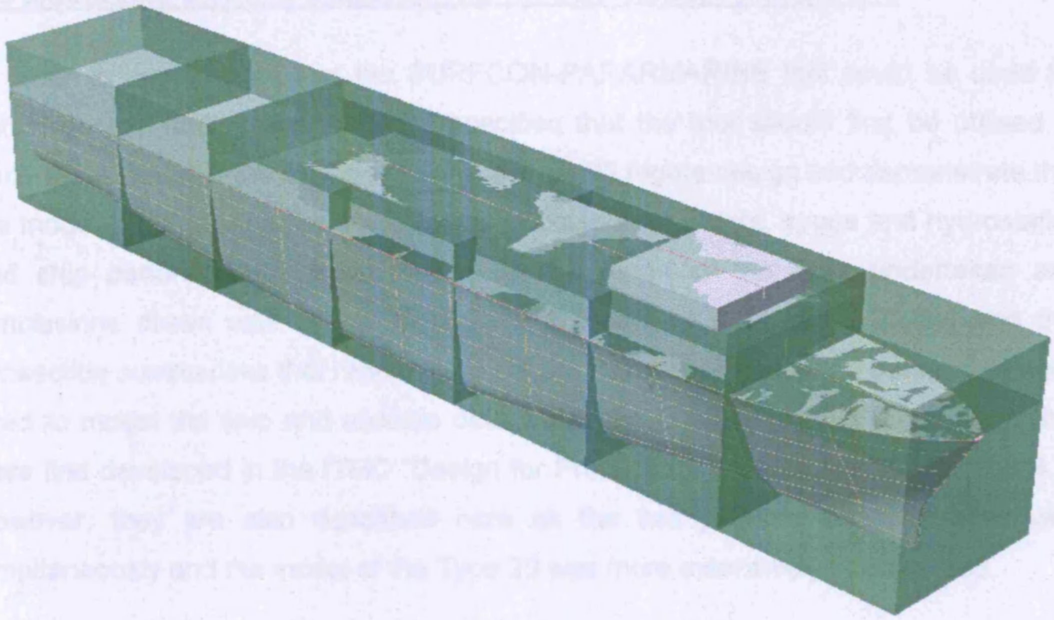


***Figure 4.5: Constructional hierarchy for the ITMC LPD(R) baseline model***

The relative advantages and disadvantages of the subdivision and functional hierarchies developed for the ITMC studies were explored in more detail in the Type 23 study presented in Section 4.3.

As the ITMC project involved the development of balanced variant designs, the models contained scaling algorithms, together with fixed ("point") weights derived from the UCL MSc SDE data and from information provided by the industrial partners and finally geometry-derived data, such as fragmentation protection (armour) weight, which was scaled using the dimensions of the relevant spaces. The Baseline models provided the first demonstration that the new SURFCON functionality in PARAMARINE allowed the effective storage, representation and then manipulation of these types of data, in addition to the spatial modelling tools. The initial work in generating the baseline models was the first use of the PARAMARINE-SURFCON implementation of the Design Building Block approach, and provided the first indication that the interactive graphical representation of the spatial model provided a new environment, for ship design and ship design research, with significant development potential and consequences for the initial ship design process.

## 4.3 MODELLING EXISTING DESIGNS: THE TYPE 23 MODEL FOR FSC IPT

In order to demonstrate that the SURFCON-PARARMARINE tool could be used for actual design studies, the FSC IPT specified that the tool should first be utilised to generate a model of the existing in service Type 23 frigate design and demonstrate that the model could provide the correct level of balance of weight, space and hydrostatics and ship performance characteristics. A full report of the work undertaken and conclusions drawn was written for FSC IPT [*Andrews & Pawling, 2002a*] and this subsection summarises that report. Many of the techniques described below, that were used to model the ship and allocate data within the Design Building Block hierarchy, were first developed in the ITMC "Design for Production" work outlined in Section 4.2. However, they are also described here as the two projects occurred effectively simultaneously and the model of the Type 23 was more extensively documented.

### 4.3.1 The Model

When producing designs ab initio, using the UCL Ship Design Exercise database, [*UCL, 2001b*] Design Building Blocks are assigned scaling algorithms usually from that source. However, for this demonstration the objective was to model an existing design, so the structure of the model was dependent on available data. The main sources of data were a General Arrangement drawing [*Yarrow Shipbuilders Limited, 1990*] a lines plan of the hull [*Yarrow Shipbuilders Limited, 1984*], a Book of Calculations [*MoD, 1983*], [*MoD, 1985*] (which did not completely represent the as-built design), a table of internal areas and a table of the 'weighed weights' – i.e. the actual weights as were recorded during the construction of the first of class vessel [*Yarrow Shipbuilders Limited, 1991*].

### The Solid Model

Between December 2001 and April 2002, two models of the ship were produced. The first was a 'solid model', which consisted of a subdivided model of the actual arrangement of the ship as built and represented a single 'point' design, not a Design Building Block model capable of easy alteration and improvement. It was constructed to assess the usefulness of the geometric modelling tools within PARAMARINE and to provide a source of data for positions, deck areas and volumes of compartments, to populate a separate Design Building Block hierarchy.

This solid model is shown in Figures 4.6 and 4.7. The complete 'solid model' of the ship contained 343 spaces, grouped into decks, twelve watertight sections and superstructure blocks.

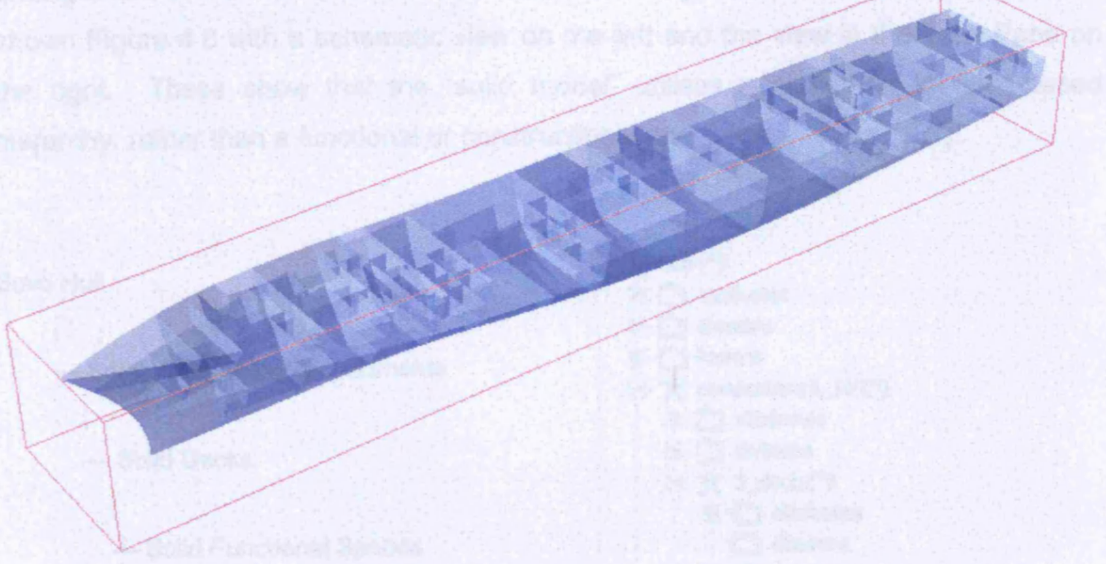


***Figure 4.6: Solid SURFCON model of the Type 23 hullform showing internal subdivision produced for validation of SURFCON in August 2001***

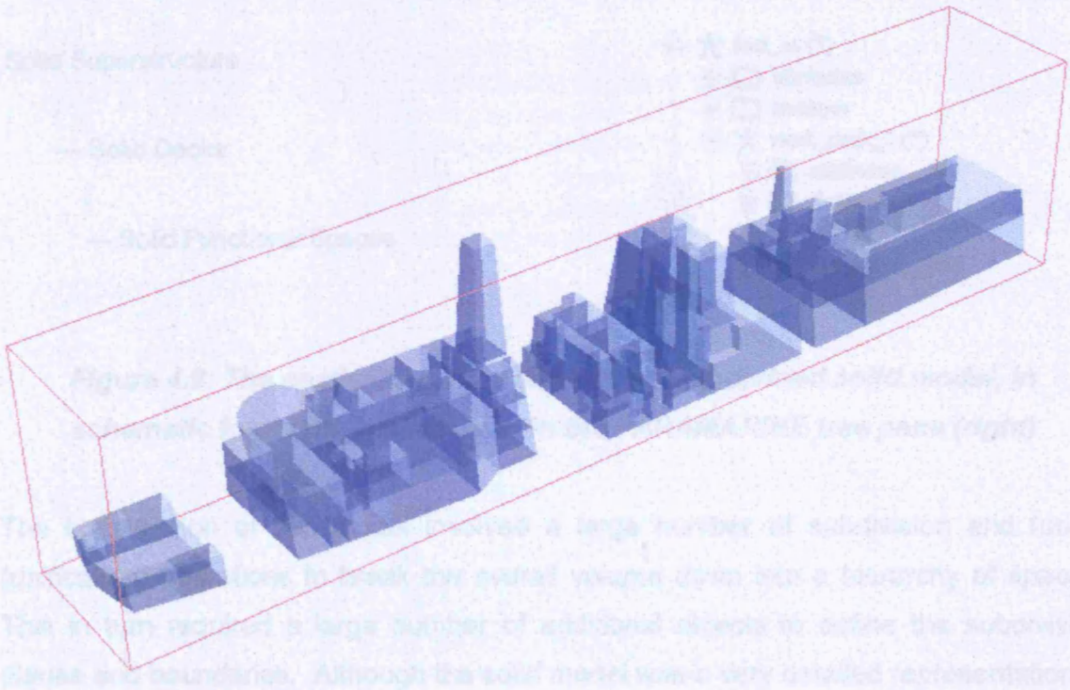


***Figure 4.7: Solid SURFCON model of the Type 23 superstructure blocks showing internal subdivision produced for validation of SURFCON in August 2001***

The hullform was produced using the 'Quickhull' hullform generation procedure (described in Appendix 6), with curves for shape and cross sectional area derived from the actual lines plan and Book of Calculations. This would allow the same hullform model to be used in a Design Building Block model intended for easy modification.

Figures 4.6 and 4.7 show how the overall envelopes of the hull and superstructure were subdivided transversely, horizontally and longitudinally to represent the general arrangement of the vessel. The solid model is arranged in a hierarchical manner, as shown Figure 4.8 with a schematic view on the left and the view in the Tree Pane on the right. These show that the "solid model" utilises a spatial or location-based hierarchy, rather than a functional or constructional one.

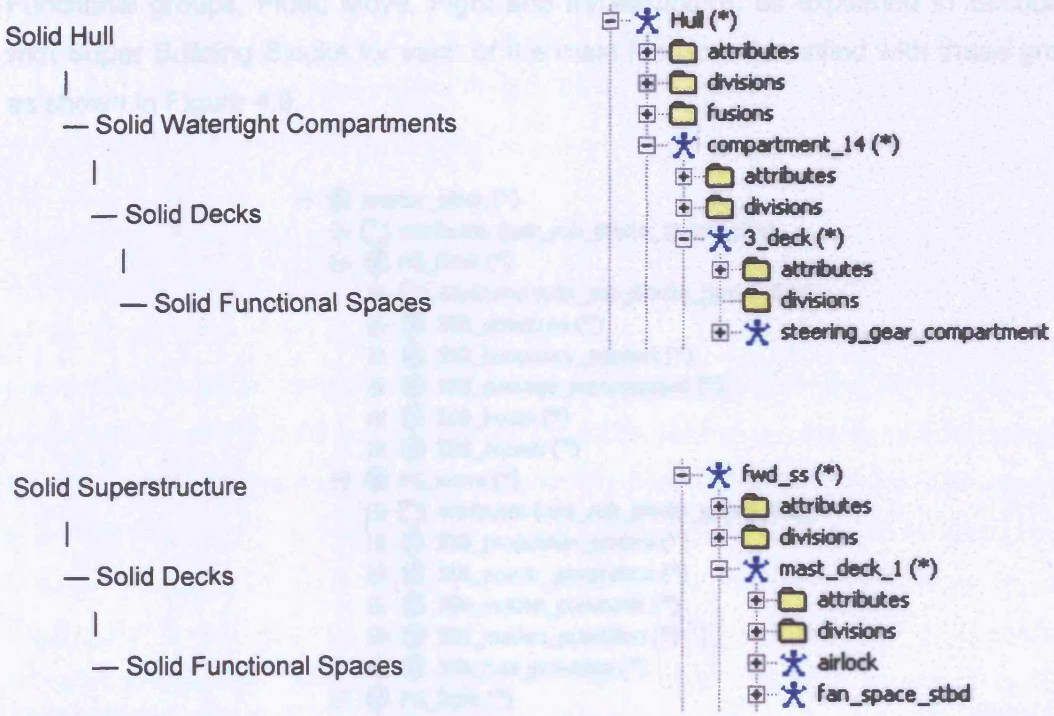



***Figure 4.8: The spatial hierarchy used in the subdivided solid model, in schematic form (left) and as seen in the PARAMARINE tree pane (right)***

The construction of this model involved a large number of subdivision and fusion (unification) operations to break the overall volume down into a hierarchy of spaces. This in turn required a large number of additional objects to define the subdivision planes and boundaries. Although the solid model was a very detailed representation of the ship, providing useful data on areas and volumes, this method was unsuitable for rapidly generating a readily alterable model, required during the early stages of an *ab initio* design. This was due to the large number of operations needed to break the design down and the resulting model complexity (as opposed to design complexity) and the lack of effective representation of functionality or numerical properties, such as weights or service requirements, necessary to synthesise a new design.

## The Design Building Block Model

The second model to be constructed was a Design Building Block model. This was a functional hierarchy of Building Blocks representing all the spaces that had been described in the solid model of the design. The hierarchy was arranged with four main Functional groups, Float, Move, Fight and Infrastructure, as explained in Section 3.2 with Super Building Blocks for each of the main functions identified with these groups, as shown in Figure 4.9.

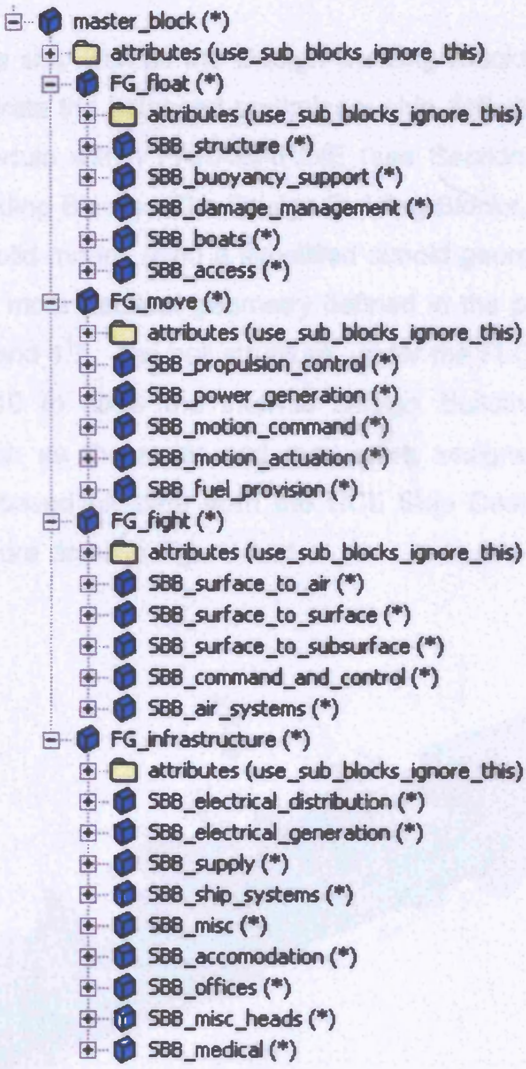



***Figure 4.9: Functional Groups and all Super Building Blocks within the Master Building Block of the Type 23 model in October 2001***

The functional breakdown was based on that used in Dicks' studies, [*Andrews & Dicks, 1997*] and the ship description used in the UCL Ship Design Exercise [*UCL, 2001a*]. In a conventional vessel such as the Type 23 the most appropriate allocation of most of the Design Building Blocks in the functional hierarchy was clear. One possible area of uncertainty in this design was the correct location of the diesel generators in the hierarchy. These supply power for the main propulsion motors, used at low speed (part of the MOVE group) and the hotel load (Electrical Distribution, under the INFRASTRUCTURE group). This type of dual–use equipment is more common in modern ships with Integrated Full Electric Propulsion. Closer consideration of the electrical system of the Type 23, however, showed that motor generators were used to convert from high (propulsion) to low (hotel) voltages. These equipment items were used as the electrical generators in the INFRASTRUCTURE group, with all prime movers being placed in the MOVE group.

Figure 4.10 shows the ship with all the Design Building Blocks and Equipment Items necessary to demonstrate the balanced preliminary ship definition for the initial testing of the SURFCON module within PARAMARINE (see Section 3.4) and consisted of some 470 Design Building Blocks. The Design Building Blocks, created to model each of the spaces in the solid model, used a simplified cuboid geometry, defined within the block, rather than the more detailed geometry defined in the purely spatial model, as shown in Figures 4.6 and 4.7. The hull structure, under the FLOAT functional group, is omitted in Figure 4.10 to allow the internal Design Building Blocks to be seen. Equipment items, such as the radar and gun, were assigned working circles and required clearances, based on data from the UCL Ship Design Exercise database. These are shown in more detail in Figure 4.11.

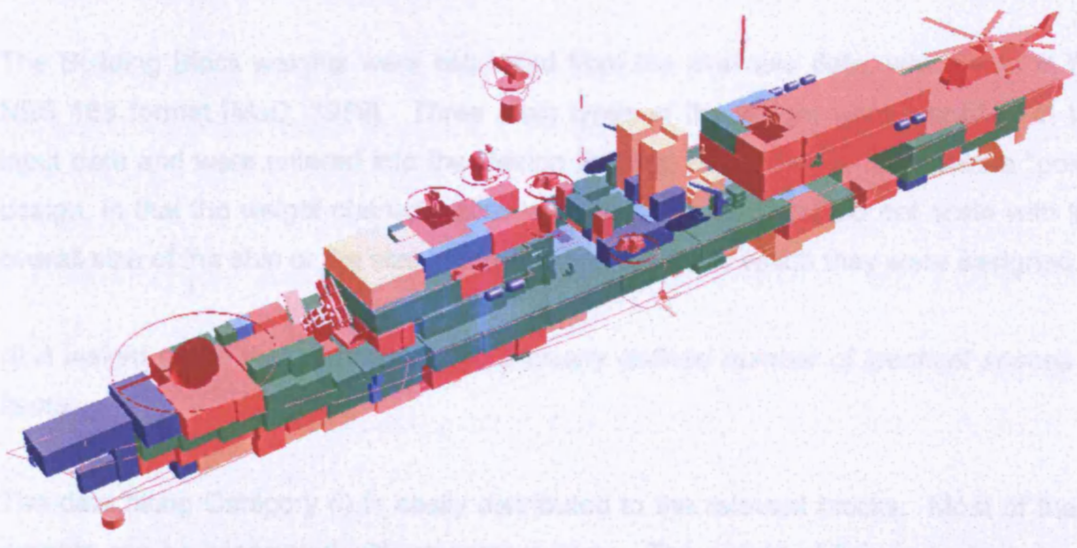


***Figure 4.10: SURFCON Graphical representation of the Design Building Block hierarchy for the Type 23 validation exercise (October 2001)***

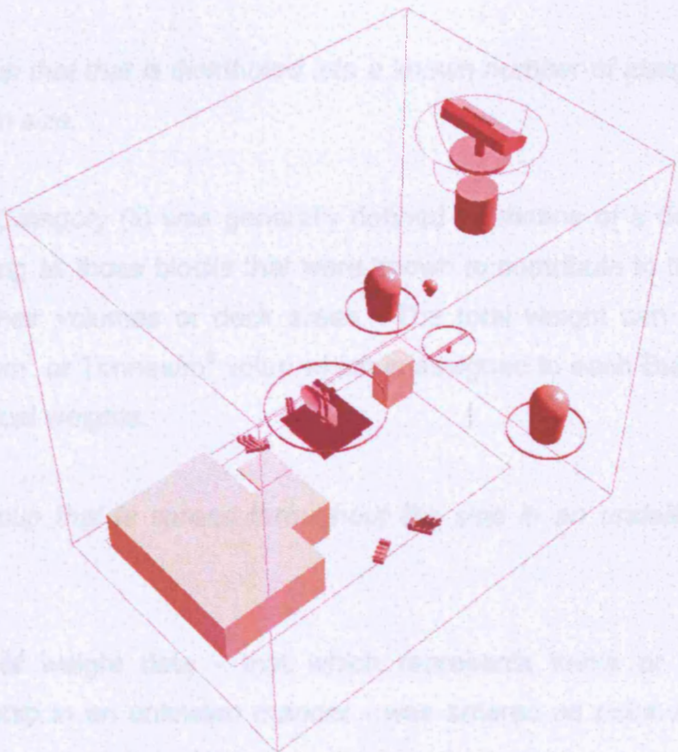


***Figure 4.11: Electronics equipment on forward superstructure of the Type 23 SURFCON model showing clearance envelopes used in 2001 SURFCON validation exercise***

The following numerical characteristics were included in the Design Building Blocks.

## Weight

The Building Block weights were estimated from the available data, which was in the NES 163 format [*MoD, 1989*]. Three main types of the weight were identified in the input data and were entered into the Design Building Block model. This was a "point" design, in that the weight characteristics were single values and did not scale with the overall size of the ship or the size of the Building Blocks to which they were assigned.

*(i) A weight group that corresponds to a clearly defined number of identical spaces or items.*

The data fitting Category (i) is easily distributed to the relevant blocks. Most of these weights can be associated with equipment items. The weight of fluid in tanks belongs to this category and was calculated using a fluid density and percentage fullness for the tank blocks. More recent versions of the software contain the 'Tankage' characteristic which allows a Design Building Block to be specified as a tank, but in this model each tank was modelled as a point weight.

*(ii) A weight group that that is distributed into a known number of identifiable spaces or items that differ in size.*

The data fitting Category (ii) was generally defined by means of a density. This was derived by locating all those blocks that were known to contribute to this weight group, then summing their volumes or deck areas. The total weight can thus be used to derive a Tonnes/$m^2$ or Tonnes/$m^3$ value which is assigned to each Building Block, thus giving the individual weights.

*(iii) A weight group that is spread throughout the ship in an undefined or unknown manner.*

The final type of weight data - that which represents items or systems spread throughout the ship in an unknown manner - was entered as point weights in blocks with no spatial extent, only a location.

The structural weight was split between all three. Some items, such as the mass of structural castings and forgings, was entered as a point weight, while others, such as the bulkhead mass, were distributed based on the area of the main watertight bulkheads.

### Volume required and achieved

The version of the software in use at the time of this work did not contain a Design Building Block characteristic to allow the automatic auditing of area and volume. In the Type 23 studies, a dimensionless 'User Defined Characteristic' called 'Volume' was defined. In each block with a spatial extent, this new characteristic was assigned a numerical demand based on the block's area, measured from the initial spatial model. The corresponding supply for that block, representing its current volume, was entered by the designer. This repetitive task of manual updating has since been rendered unnecessary by the addition of objects in SURFCON for the automatic calculation of the current area or volume of the Building Block.

### Accommodation supply / demand

A supply of accommodation for the appropriate crew type (Commanding Officer, Officer, Chief Petty Officer, Petty Officer and Junior Rate) was included in the cabin and mess blocks. Total demands for each type or rank were included in the "Block Definition" object (See Appendix 5).

## Services

Chilled water supply data was added to each of the Air Treatment Units (ATUs) corresponding to data from a tabular breakdown of the chilled water demand in the Book of Calculations. Total demand was included in the "Block Definition" object.

## Analysis and Auditing Tools in the Model

The basic analysis and auditing tools as described in Section 3.3.2 were used in the model of the Type 23 design. The "Design Infringements" object, assessing the Type 23 model, was connected to the Block Definition, Clash Detection and Node Relationships objects (See Appendix 5). Subsequently, this object was capable of auditing the design for a series of different features (e.g. supply and demand of space, services, accommodation, user-defined characteristics and consumables; spatial clashes between Building Blocks; nodal relationships, such as those describing the firing arc of the 114mm gun forward, the length of the mooring space available on the upperdeck forward and the longitudinal separation of the masts).

As this model represented a sufficiently detailed and balanced design for preliminary design, the Design Infringements object was only needed as a check for any major inaccuracies in the design configuration. The Design Audit object was used to produce tables of weight and space breakdown by block and by either of the classification systems used in the model (functional hierarchy or NES 163), to assess the accuracy of the model in detail.

In addition to the audit of the numerical balance of the Design Building Block model, a set of stability analysis objects were included. The functionality of these specialist objects is outlined in Appendix 5. The stability objects performed an intact and damaged stability assessment of the vessel against the UK MoD NES 109 criteria [*Mod, 2000*]. Two loading conditions were incorporated, light load (typically 5% of variables) and deep load (typically 95% of variables). Ten different damage cases were assessed, to compare with those included in the Book of Calculations [*MoD, 1983*] [*MoD, 1985*]. These damage cases covered flooding in three or four compartments at different positions along the entire length of the vessel and the model showed that SURFCON could replicate the existing design audit results.

### 4.3.2 Outputs Generated

Data was outputted from the model in the form of tables, drawings, images and a fly-around animation. Numerical values for dimensions and hullform coefficients could also be evaluated directly from the model.

**Tabular Data**

Tabular outputs were produced of the weight breakdown in the model, following the NES 163 hierarchy [*Mod, 1989*]. These were produced to two levels of detail – a "1 digit" summary of the main weight groups (see Table 4.1) and a "3 digit", more detailed breakdown. Tables were also produced of the total accommodation and variables supply and demands in the design. These were arranged by Design Building Block. A table of hullform offsets was also produced from the hullform generated by the QuickHull tool.

Table 4.1 summarises the main weight groups in the SURFCON model of the Type 23 frigate and the excess weight in the SURFCON model as a percentage of the source data. The source data is drawn from the Book of Calculations (BoC) [*MoD, 1983*] [*MoD, 1985*] and the as-built values measured by Yarrows Shipbuilders Limited. [*Yarrow Shipbuilders Limited, 1991*] The error in the position of the centroid of the weight group in X, Y and Z directions is also shown. The very large errors (greater than 100%) for some values occur because the target value is very small (the weight centroid is close to amidships), so a small absolute error leads to a large percentage error.

| Group | | | | | | |
|---|---|---|---|---|---|---|
| **Number** | **Name** | **Source** | **% Error in Weight** | **CofG % X Error** | **CofG % Y Error** | **CofG % Z Error** |
| 1 | Hull | As Built | -0.1 | 43.8 | 146.4 | 0.4 |
| 2 | Propulsion | As Built | 0.0 | -4.1 | 40.8 | 2.6 |
| 3 | Electrical | As Built | -0.7 | -196.1 | -10.7 | 0.6 |
| 4 | C and C | As Built | 0.4 | 53.6 | -44.4 | 2.3 |
| 5 | Auxiliaries | As Built | -2.7 | -29.2 | -90.9 | -5.1 |
| 6 | Outfit | As Built | -1.4 | -72.3 | 68.4 | -0.5 |
| 7 | Armament | As Built | 0.0 | -5.9 | 9.8 | -4.7 |
| 8 | Variable | BoC | 0.7 | -198.4 | | 15.4 |
| % Error in Total Weight | | BoC | 3.8 | | | |
| % Error in Total Weight | | As Built | -0.3 | | | |
| Total SURFCON model weight | | | 4180 te | | | |

***Table 4.1: Summary of percentage errors in SURFCON Type 23 model compared to supplied design information produced in validation exercise (October 2001)***

The primary source of data for modelled weights was the as-built listings. While the Book of Calculations data was used to verify the tank capacities, when compared with the input data, the weights modelled in the SURFCON design closely matched the actual Type 23 design. This was due to the fact that many of the items were added to the SURFCON design as point weights, in a single Design Building Block, with no estimation based on the geometry of the design. Examples of this type of data included the minor bulkheads and floor coverings.

The larger errors in Groups 5 and 6 were due to the fact that more of the weights under these groups were calculated using densities from the actual configuration of the Design Building Block model. An example of this is the weight group "641: Furnishings for crew accommodation". The total area of the crew accommodation was calculated from the solid model and used to estimate a density in tonnes/$m^3$ for this weight group, which was then applied to the accommodation Design Building Blocks to estimate their weight. This particular group had a total error of -5.6% in comparison with the "As Built" value. It was suggested that this arose due to the simplified Building Blocks not having exactly the same volume as the spaces within the ship that they were representing. Figure 4.10 shows that a cuboid representation was used for most of the blocks. The main source of errors in Group 5 was the distributed weight of the ventilation systems, which was difficult to attribute to a specific space in the ship and was not directly accounted for.

The centroids of the weight groups in the model and the "As Built" data were found to differ more significantly. The vertical position was generally modelled accurately; however the longitudinal and, particularly, the transverse locations were subject to greater errors. The small absolute values of the transverse centroids for many of the weight groups contributes to this, as a small "real-world" error can equate to large percentage errors.

The main source of error in the positioning was felt to be the uncertainty as to the exact distribution of the system weights throughout the function based Building Block hierarchy. For example, the weights classified under "Group 53: Air and Gas Systems" describe the systems associated with the ship's helicopter. In the Design Building Block model, these weights were assigned to aviation workshop blocks. In the actual ship, however, this would include piping runs between these spaces and the distribution within the workshops might not be uniform. It was concluded that more time and information on the design would be needed to improve the definition of the distributed systems weights within the building blocks, although it was agreed with MoD FSC IPT that the verisimilitude was well within what was required to validate the SURFCON tool's ability to represent naval ship preliminary design [*Jarvis, 2003*].

## Drawings

The drawing objects included in PARAMARINE were used to produce two main drawings of the design model, a General Arrangement drawing (based on the solid model of the vessel labelled with the names of compartments and spaces); and a lines plan of the hullform. This illustrated that the SURFCON generated hullform was properly faired and represented all the distinctive features of the Type 23 hullform, such as the flare amidships and "S" –shaped sheer line [*Thomas & Easton, 1991*]. Together with the data tables, these represent the traditional methods of describing a preliminary ship design.

Samples of these drawings are shown as Figures 4.12 and 4.13. As with all other objects in the PARAMARINE software, the drawing objects used to construct the drawings then automatically re-calculated to represent the latest configuration of the model when they were viewed. This integration of design numerical and configurational data represents a significant advantage over the use of a separate CAD tool to produce drawings and a traditional numerical synthesis tool, such as CONDES [*Hyde & Andrews, 1992*].

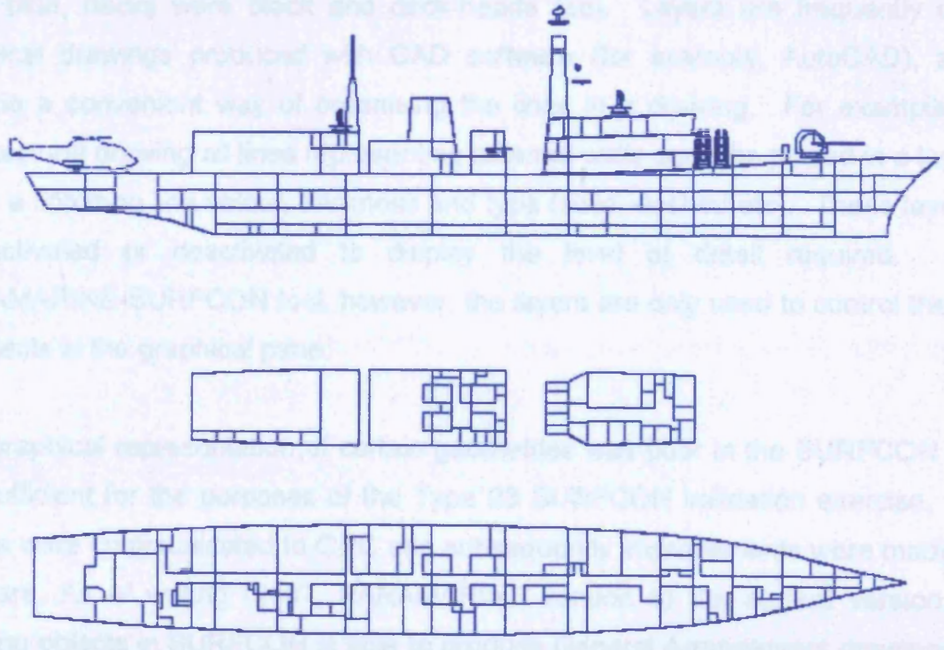


***Figure 4.12: Sample General Arrangement drawing of Type 23 model produced from SURFCON model for validation (August 2001) (with text labels removed)***

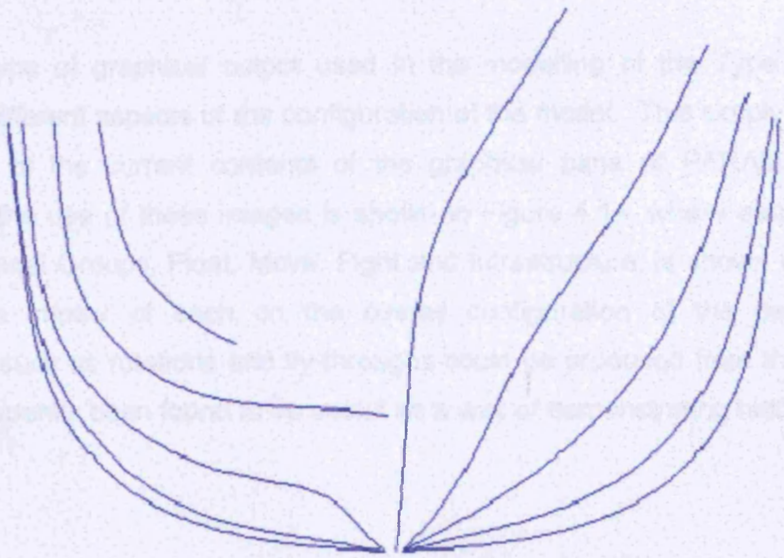


***Figure 4.13: Simplified body plan for Type 23 generated by PARAMARINE for SURFCON validation (August 2001)***

However the study identified that certain additional capabilities would be desirable. Drawings could only be produced for the sub-divided solid model, (see Figures 4.6 and 4.7 compared with Figure 4.10) and not the more flexible Design Building Block based model used with the SURFCON tool. The colour layers assigned to the objects in the design were not automatically used in the drawings, with line colours in the output drawing assigned instead by the nature of the geometry they represented (sections were blue, decks were black and deck-heads red). Layers are frequently used in technical drawings produced with CAD software (for example, AutoCAD), as they provide a convenient way of organising the lines in a drawing. For example, in an architectural drawing all lines representing external walls could be placed in a layer and given a common line colour, thickness and type (solid, dashed etc). These layers can be activated or deactivated to display the level of detail required. In the PARAMARINE-SURFCON tool, however, the layers are only used to control the colour of objects in the graphical pane.

The graphical representation of certain geometries was poor in the SURFCON output, but sufficient for the purposes of the Type 23 SURFCON validation exercise. These issues were communicated to GRC and subsequently improvements were made to the software. As of writing (2007, PARAMARINE version 5) the current version of the drawing objects in SURFCON is able to produce General Arrangement drawings of the entire Design Building Block hierarchy of a SURFCON model. (See Figure 5.9 for an example)

## Images

The other type of graphical output used in the modelling of the Type 23 was the imaging of different aspects of the configuration of the model. This simply consisted of the capture of the current contents of the graphical pane of PARAMARINE. An example of the use of these images is shown in Figure 4.14, where each of the four main Functional Groups, Float, Move, Fight and Infrastructure, is shown on its own to illustrate the impact of each on the overall configuration of the design. Also, animations, such as rotations and fly-throughs could be produced from the model and have subsequently been found to be useful as a way of demonstrating hidden details.

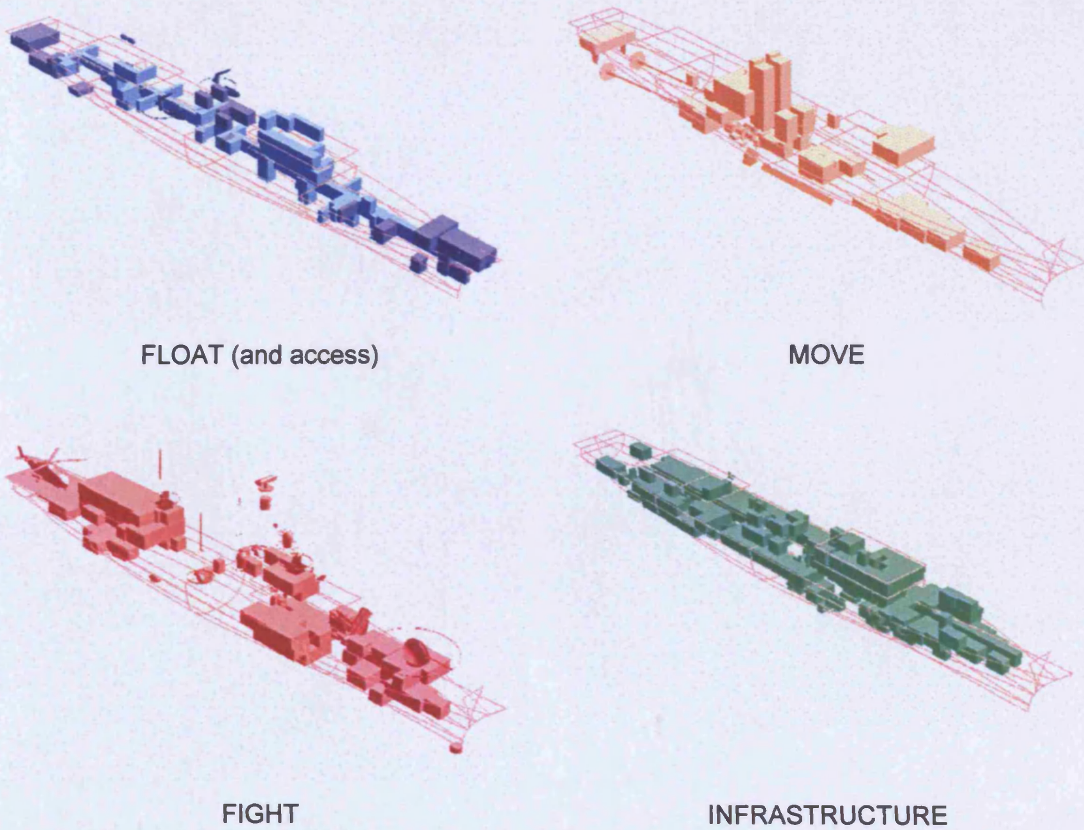



***Figure 4.14: The four Functional Groups: Float, Move, Fight and Infrastructure for the Type 23 validation of SURFCON (October 2001)***

## Stability

Although the PARMARINE software is capable of carrying out a wide range of performance assessments on the design, in this study, only the stability was examined in any detail because the power and hullform were specified. This analysis demonstrated that the use of the single numerically and spatially integrated model of the design allowed data, contained in the Design Building Block hierarchy, to be used directly in assessments of the performance (stability) of the design, without the necessity of transferring the definition of the design to another software package.

The ship was analysed for intact and damaged stability in the deep and light loaded conditions. Ten different damage conditions were modelled, based on those examined in the Type 23 Book of Calculations. As this referred to an earlier version of the design than that built, a detailed numerical comparison of the two sets of stability estimations was not worthwhile. Even so, the two were found to give similar stability values, with differences in values of maximum GZ, angle of vanishing stability etc. of between 5 and 10 percent. The GZ curves produced from the software model had a similar general shape to the Book of Calculations examples. A sample of the PARAMARINE-SURFCON output is shown in Figure 4.15.

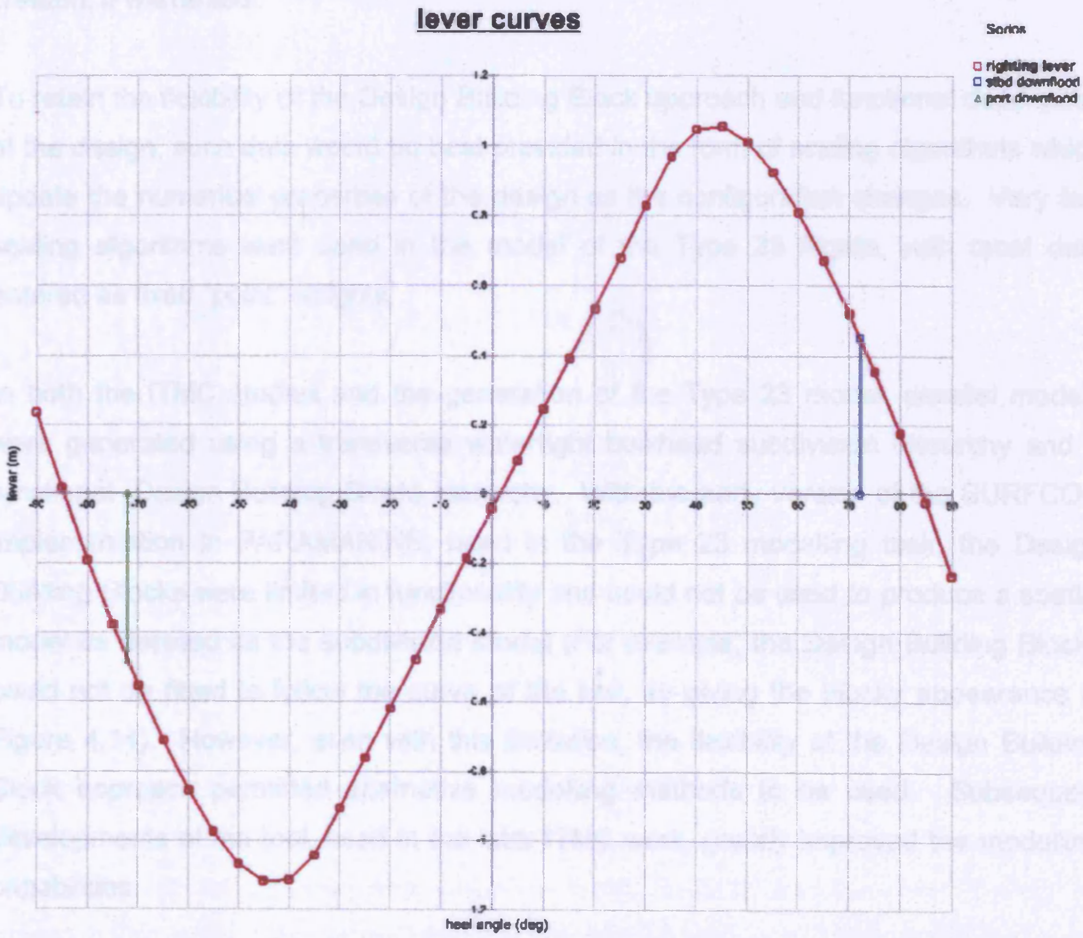



***Figure 4.15: A representative GZ curve for the deep, intact condition of the Type 23 SURFCON study (2001)***

### 4.3.3 Discussion and Conclusions on the Type 23 Building Block Model Study

This early work demonstrated that the PARAMARINE implementation of SURFCON could be used to represent a ship design to a level of detail appropriate to the early or concept stages of the design process. The model generated was slightly different from that described by the input data, as shown in Table 4.1, although this difference was found to be largely due to the uncertainties in incorporating "as-built" ship data into the simpler Design Building Block model. More information on the distribution of different weight groups throughout the functional spaces of the ship would have been required for a SURFCON model of the design of a greater level of accuracy to have been created, if warranted.

To retain the flexibility of the Design Building Block approach and functional description of the design, such data would be best provided in the form of scaling algorithms which update the numerical properties of the design as the configuration changes. Very few scaling algorithms were used in the model of the Type 23 frigate, with most data entered as fixed "point" weights.

In both the ITMC studies and the generation of the Type 23 model, parallel models were generated using a transverse watertight bulkhead subdivision hierarchy and a functional (Design Building Block) hierarchy. With the early version of the SURFCON implementation in PARAMARINE, used in the Type 23 modelling task, the Design Building Blocks were limited in functionality and could not be used to produce a spatial model as detailed as the subdivision model (For example, the Design Building Blocks could not be fitted to follow the curve of the hull, so giving the blocky appearance in Figure 4.14). However, even with this limitation, the flexibility of the Design Building Block approach permitted alternative modelling methods to be used. Subsequent developments of the tool, used in the later ITMC work, greatly improved the modelling capabilities.

The use of a single model of the design in software with integrated modelling and analysis capabilities allowed these analyses to be treated as part of the numerical balancing process, rather than checks to be performed on a design drawn up by other means. This was illustrated by the stability analysis, which used weight distribution data read in automatically from the Design Building Block hierarchy, while the initial stability analysis was greatly facilitated by the spatial model's derivation of the centroid. The full extent of these analysis capabilities were not exploited in this study but were used in the subsequent projects described in Chapter 5. This indicated the potential that an integrated, concurrent spatial model of the design provides for increased confidence in the realism of the design definition in early stage design work.

Table 4.2 gives some basic statistics for the Design Building Block hierarchy used in this study to describe the Type 23 frigate. In total 602 Building Blocks and Equipment Items were utilised in the hierarchy.

| | |
|---|---|
| **Total Number of Entities in Hierarchy** | 602 |
| **Total Number of Equipment Items in Hierarchy** | 130 |
| **Total Number of Entities With Data** | 476 |
| **Percentage of Entities With Data** | 79.1 |
| **Percentage of Entities For Organisation Only** | 20.9 |

| | |
|---|---|
| **Master Building Blocks** | 1 |
| **Functional Groups** | 4 |
| **Super Building Blocks** | 24 |
| **Building Blocks Level 1** | 101 |
| **Building Blocks Level 2** | 274 |
| **Building Blocks Level 3** | 144 |
| **Building Blocks Level 4** | 51 |
| **Building Blocks Level 5** | 3 |

***Table 4.2 Design Building Block hierarchy statistics for the Type 23 model validation of SURFCON (October 2001)***

The second part of Table 4.2 shows the number of Entities at each level of the hierarchy. Unsurprisingly, the intermediate levels contain most of the objects. Some parts of the design were described using more complex hierarchical structures, hence the smaller number of objects in levels 4 and 5.

The total number of entities in the hierarchy is the total number of Building Blocks and equipment items contained in the SURFCON representation of the ship. However, only some of these blocks, those with numerical or spatial data, are used in modelling the design. The other 126 entities that do not contain data are used to construct the descriptive model of the design - they give structure and organisation to the Design Building Block hierarchy. Examples of both uses of the Design Building Block are shown as Figure 4.16 (previously shown in Figure 3.16). Note that the asterisk denotes that further Design Building Blocks exist at sub-levels and that the characteristics of these daughter blocks will be used in auditing.

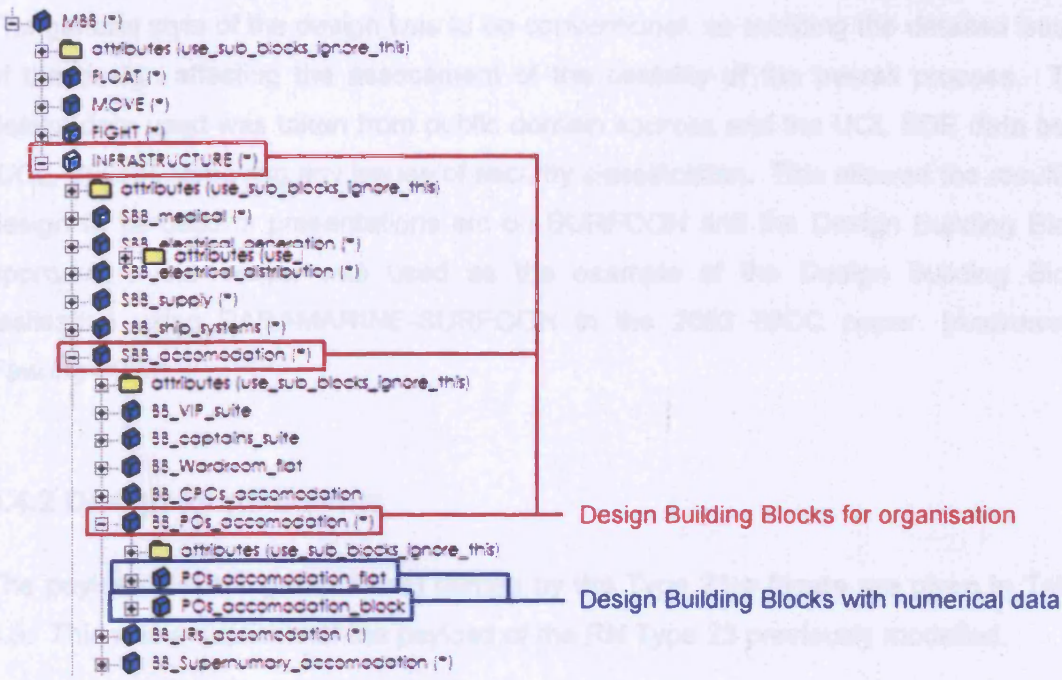



***Figure 4.16: Examples of Building Blocks with no data used for design organisation and those with data used for design synthesis.***

The 79.1% of blocks with numerical data contain information on weights and the other audited characteristics. Table 4.2 shows the importance of organisation in the development of a useful design model. The 20.9% of entities "for organisation only" were produced for designer convenience – they allowed the construction of a functional hierarchy as shown in Figure 4.9 and structured the model in such a way the human designer or reviewer could understand it. For an automated system where the design description would only be accessed and manipulated by a computer, the entire design could have been constructed in a "flat" structure – with all Design Building Blocks on one level and the necessary hierarchy descriptions (Functional Group and SBB associations) recorded as properties internal to the Design Building Block.

## 4.4 Developing New designs: Type 23-a

### 4.4.1 Aims of the Study

To generate a more detailed procedure for the practical application of the Design Building Block approach, it was necessary to use PARMARINE - SURFCON for the design of a new vessel. The ship that was designed was known as the "Type 23-a", or "Type 23–alternate". This was to be a general purpose frigate, designed to performance requirements meeting the as-built capabilities of the Type 23 frigate.

The general style of the design was to be conventional, so avoiding the detailed issues of the design affecting the assessment of the usability of the overall process. The design data used was taken from public domain sources and the UCL SDE data book [*UCL, 2001b*], removing any issues of security classification. This allowed the resulting design to be used in presentations etc on SURFCON and the Design Building Block approach. This vessel was used as the example of the Design Building Block realisation using PARAMARINE-SURFCON in the 2003 IMDC paper. [*Andrews & Pawling 2003*]

### 4.4.2 Design Requirements

The payload (FIGHT group items) carried by the Type 23-a frigate are given in Table 4.3. This was a duplicate of the payload of the RN Type 23 previously modelled.

| Role | Payload |
|---|---|
| ASW | 1 x EH-101 Merlin ASW helicopter with hangar<br>Sonobuoy stowage for helicopter<br>4 x 324mm fixed torpedo tubes with MTLS and 32 torpedoes<br>Type 2050 bow sonar<br>Type 2031z towed sonar |
| AAW | 32 x Vertically Launched Sea Wolf missiles<br>2 x 911 guidance radars<br>1 x 996 surveillance radar |
| AShW | 2 x 4 Harpoon missiles in Mk 141 launchers<br>2 x 2 BMARC 30mm guns, 3000 rounds each |
| NGS | 1 x 114mm Mk 8 gun with 250 rounds<br>1 x General Purpose Electro Optical Device |
| Sensors | 2 x Type 1007 navigational radar |
| Command | CACS 4 command system |
| Communications | Standard frigate communications fit<br>2 x SATCOM systems<br>Link 11 and 14 systems |
| Countermeasures | Type 182 towed torpedo decoy<br>4 x Seagnat launchers<br>UAF (1) ESM |

***Table 4.3 Payload fit for Type 23-a frigate***

In addition to the usual initial requirements of speed and endurance, the exact machinery fit was also specified for this design. Normally, this would be derived from the resistance characteristics of the hull, the required performance and the chosen propulsion architecture (Mechanical, electric, gas turbine, diesel etc), after considering a range of combinations. However, as this design was intended to be similar to the

Type 23, this restriction on the design process was deemed acceptable. The specified machinery fit and performance requirements are shown in Table 4.4.

| | |
|---|---|
| **Propulsion System Architecture** | CODLAG (Combined Diesel eLectric And Gas turbine) |
| **Gas Turbines** | 2 x 13MW SM1a Spey |
| **Diesel Generators** | 4 x 1.3MW 600V DG |
| **Electric Motors** | 2 x 1.5MW DC motors |
| **Hotel Load** | 2 x 1MW Motor-generator sets |
| **Maximum Speed (deep displacement, 6 months out of dock)** | 28 knots |
| **Cruise Speed** | 15 knots on diesel-electric propulsion |
| **Range at 15 knots** | 7800 miles |

***Table 4.4 Propulsion requirements for Type 23-a frigate***

The third area of the design that was specified from the start was the complement. The official total accommodation for the Type 23 was broken down into ranks using the equations adopted in the UCL ship design exercise, which are based on recent Royal Navy ships. The resulting figures are shown in Table 4.5

| | |
|---|---|
| **Total Accommodation** | 186 |
| **Commanding Officer (CO)** | 1 |
| **Officers** | 14 |
| **Chief Petty Officers (CPO)** | 20 |
| **Petty Officers (PO)** | 26 |
| **Junior Rates (JR)** | 125 |

***Table 4.5 Accommodation for Type 23-a frigate***

### 4.4.2 The Development of the Design

The procedure for generating new designs using SURFCON was under development during this study and evolved as the design progressed. Included is an overview of the main points.

- The first stage was to prepare the design space, by compiling data (from the UCL Ship Design Exercise data book) and the selection of pre-constructed PARAMARINE-SURFCON files, such as an empty Design Building Block hierarchy that was to be populated with data.

- The overall dimensions of the design were estimated using the UCL Ship Design Exercise method. [*UCL, 2001a*] This starts with the required payload volume (FIGHT Functional Group) and uses an assumed Payload Volume Fraction (PVF) and an assumed overall density, to generate a first estimate for the overall enclosed volume and displacement:-
    - Payload volume required = 3202.76 $m^3$;
    - Payload Volume Fraction assumed = 0.2;
    - Overall density assumed = 0.3 te/$m^3$;
    - Overall enclosed volume estimated = 16014 $m^3$;
    - Deep displacement estimated = 4804 te.
- Using a set of typical monohull frigate hullform shape coefficients, the overall displacement was used to make an initial estimate of the hullform dimensions, using the UCL method, which is derived from the work of van Griethuysen [*1993*] The initial dimensions were:
    - Waterline Length = 125.5 m;
    - Waterline Beam = 15.58 m;
    - Hull Depth = 9.79 m;
    - Hull Draught = 4.79 m.
- The Quickhull tool was then used to generate a hullform with these dimensions, with the style of a modern RN frigate, as outlined in Appendix 5. Figure 4.17 shows the initial hullform developed.

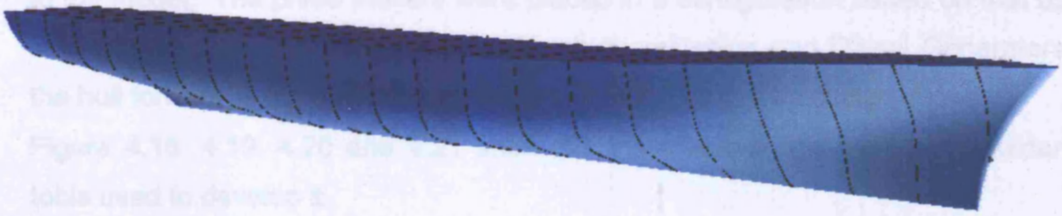


***Figure 4.17: Initial hullform developed for the Type 23-a design***

- The overall layout style of the design was now developed by placing the main combat system elements in the design space, which had been partially bounded by the development of an initial speculative hullform. The FIGHT Functional Group elements placed were:
    - Flight deck on upperdeck right aft (length based on helicopter requirements);
    - Hangar forward of flight deck;
    - *Aft limit of superstructure defined by hangar;*

- o Torpedo magazine and tubes (MTLS) and aviation support spaces grouped forward of hangar and main aviation fuel (AVCAT) storage grouped in the hull beneath it;
- o 114mm gun and magazine placed forward, 15% of waterline length aft of the bow, to avoid excessive green sea loading;
- o Sea Wolf launch canisters placed in a single group aft of the gun;
- o Harpoon launch canisters placed aft of the Sea Wolf canisters;
- o *Forward limit of superstructure defined by location of Harpoon canisters;*
- o Type 2050 sonar placed at bow with supporting equipment in hull further aft;
- o Type 2031Z towed sonar and equipment placed as a group in the hull under the flight deck, with a winch well spanning Nos. 2 and 3 Decks;
- o Bridge placed to meet visibility requirements over bow and motion limits (30% of waterline length aft of the bow);
- o Operations Room complex placed in hull under bridge;
- o Type 996 surveillance radar placed over forward superstructure at minimum height required (from UCL Databook);
- o Notional communications mast placed 30m aft of the main mast;
- o *Possible locations for breaks in superstructure defined by mast location;*
- o Placed 30mm guns on upperdeck amidships;
- o *Maximum midships superstructure width defined by 30mm gun firing arcs.*

- The main machinery, specified in the requirements for this design, was then added to the model. The prime movers were placed in a configuration based on that used in the Type 23, with Gas Turbines in the hull amidships and Diesel Generators in the hull forward and superstructure aft of the Gas Turbine Machinery Room.
- Figure 4.18, 4.19, 4.20 and 4.21 show the initial layout and the visual guidance tools used to develop it.

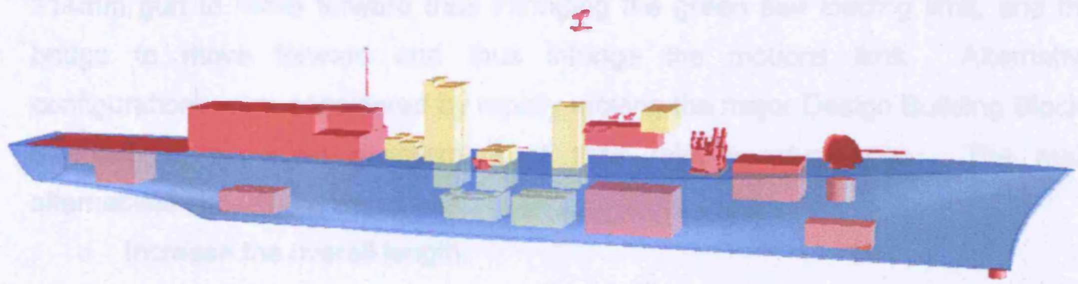


***Figure 4.18: Design Building Blocks representing major features and initial hullform***

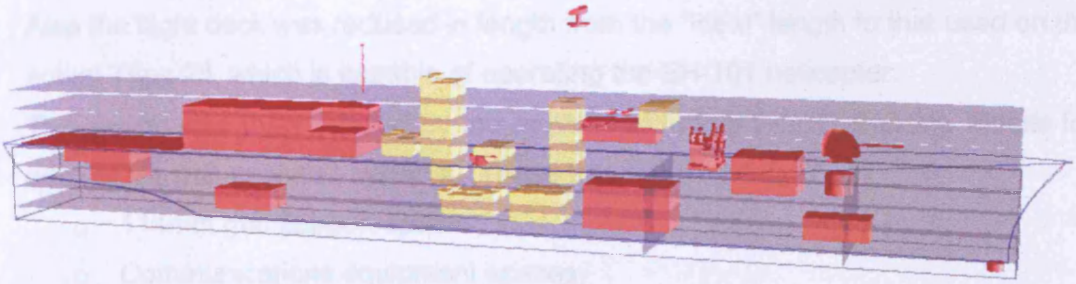


*Figure 4.19:* ***Addition of initial assumed deck positions and indicators for forward limits on upperdeck equipment and bridge position***

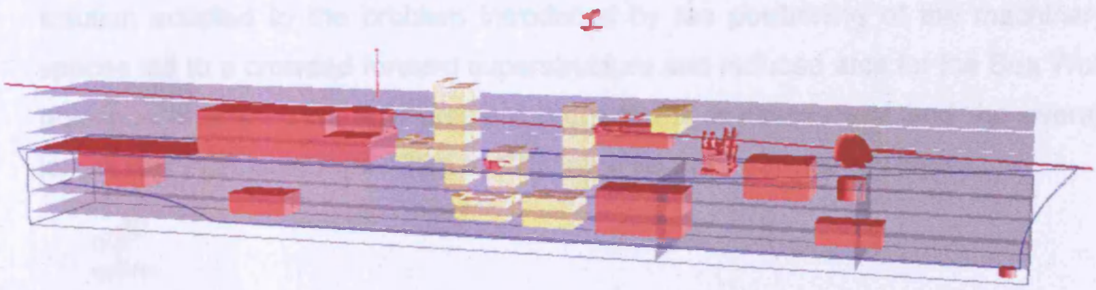


***Figure 4.20: Addition of bridge sightline visualisation (angled line)***

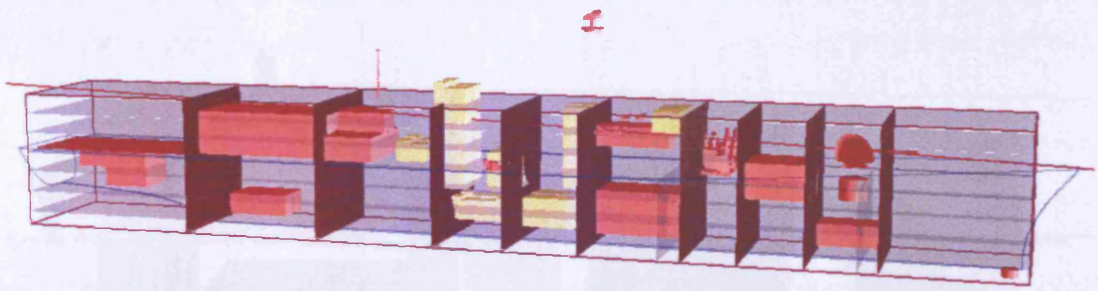


***Figure 4.21: Initial bulkhead placement defined by current layout***

- At this point, it was found that the combination of the length of the machinery spaces and the requirement to maintain structural continuity would cause the 114mm gun to move forward thus infringing the green sea loading limit, and the bridge to move forward and thus infringe the motions limit. Alternative configurations were considered by rapidly moving the major Design Building Blocks freehand to allow an assessment of their relative advantages. The main alternatives considered were:
    - Increase the overall length;
    - Use a "minimum change" alternative configuration;
    - Use a radical alternative configuration;
    - Ignore the position limits.
- The solution adopted was to use a "minimum change" approach, where the forward superstructure was made very short, so allowing the position limits to be met.

- Also the flight deck was reduced in length from the "ideal" length to that used on the actual Type 23, which is capable of operating the EH-101 helicopter.
- The design was then detailed by the addition of further FIGHT Building Blocks for each of the main combat systems. These included:
  - 114mm gun support spaces;
  - Communications equipment spaces;
  - Sea Wolf Type 911 guidance radars.
- The addition of the latter items into the forward superstructure showed that the solution adopted to the problem introduced by the positioning of the machinery spaces led to a crowded forward superstructure and reduced arcs for the Sea Wolf guidance radars. This new problem prompted a re-assessment and the overall length was increased from 125m to 129.5m to permit a satisfactory layout.

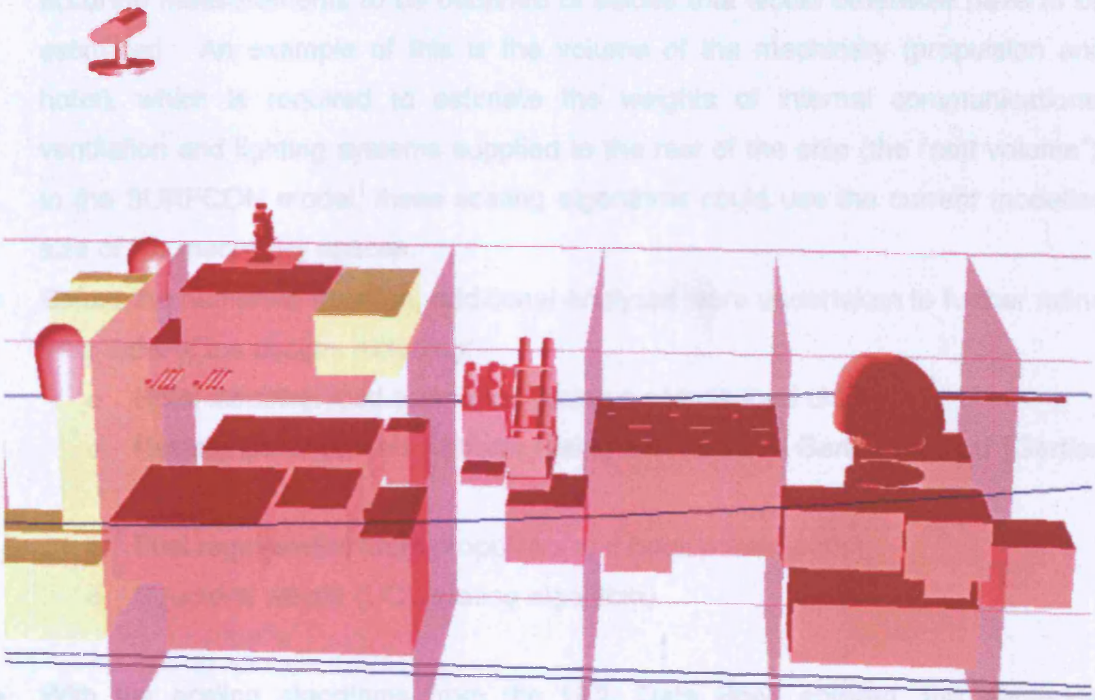


***Figure 4.22: Detail of the forward superstructure and weapons showing potential for crowding and interference***

- The next features to be added to the model were the main accommodation and personnel support (dining) areas, in the form of Super Building Blocks representing groups of cabins for officers and senior rates and large mess spaces for junior rates.
- These were positioned in a conventional arrangement, with the officers in the forward superstructure, the senior rates in the hull forward and the junior rates on

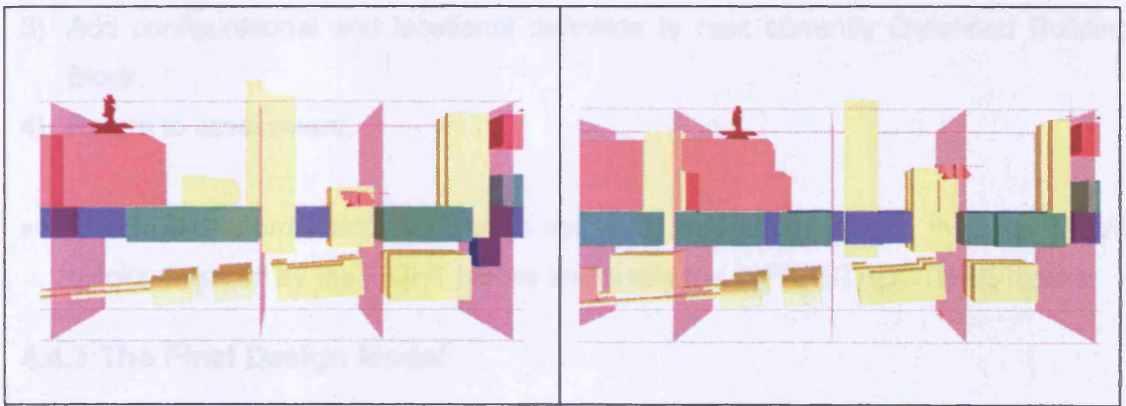
No. 3 Deck in the hull forward and aft. This allowed an assessment of the feasibility of the configuration, as the accommodation spaces are very large.

- At this point in the development of the design, the displacement used for hull sizing was still that estimated from the FIGHT group volume, PVF and overall density. The sizing algorithms used relied on a numerical iterative process that balanced volume required against volume available and weight against displacement. Most of the algorithms scale on the overall enclosed volume (volume available) or displacement of the design. These algorithms were initially included as Design Building Blocks with weight and area demands, but no spatial extents or location. This allowed them to be used in the numerical iteration without requiring a full general arrangement to be developed.
- The availability of an integrated spatial model of the design allowed some more accurate measurements to be obtained of values that would otherwise have to be estimated. An example of this is the volume of the machinery (propulsion and hotel), which is required to estimate the weights of internal communications, ventilation and lighting systems supplied to the rest of the ship (the "nett volume"). In the SURFCON model, these scaling algorithms could use the current modelled size of the machinery spaces.
- Before the numerical iteration, additional analyses were undertaken to further refine the model of the design, including:
    - Hotel electrical load estimation (using a sample load chart);
    - Resistance of current hullform (using the Taylor – Gertler method [*Gertler, 1954*]);
    - Fuel requirement (from propulsive and hotel power loads);
    - Structural weight (UCL scaling algorithm).

- With the scaling algorithms from the UCL Data Book entered, the numerical iteration was carried out until the weight and displacement were within 10 tonnes of each other and total enclosed volume required was less than the total volume available:
    - Displacement = 4158.85 te;
    - Weight = 4154.43 te;
    - Volume required = 15076.12 $m^3$;
    - Volume available = 15085.12 $m^3$.
- With the power of modern desktop computers, such numerical iteration is "cheap", with each cycle requiring between 1 and 10 seconds of calculation, so the design could be iterated to a close numerical balance at an early stage. However, with

many of the Design Building Blocks undefined in configuration or location, this iteration did not represent a balanced design.

- The next items to be placed in the configuration were the auxiliary machinery spaces, sized from the dimensions of the diesel generators. It was found that the subsequent changes to the layout made the after, (upper) auxiliary machinery space unacceptably close to the torpedo magazine given Royal Navy magazine regulations [*Mod, 2005*]. The decision was taken to move the after diesel generators into the hull. This would require additional acoustic silencing (double mounting) of the diesel generators to achieve a signature level comparable with mounting them on No. 1 Deck, but was found to permit an improvement in the aft accommodation arrangements. Figure 4.23 shows the initial and final configuration in this area, including the larger and heavier diesel generators reflecting the use of double mounting.



| Original Configuration | Revised Configuration |
| --- | --- |

***Figure 4.23: Original and revised configuration of aft DG space, showing new uptake configuration***

- This change in machinery configurational style was significant and so the design was taken through the numerical balancing process and resulted in:-
  - Displacement = 4066.67 te;
  - Weight = 4060.53 te;
  - Volume required = 14059.54 $m^3$;
  - Volume available = 14071.98 $m^3$.
- With the overall configuration of the design verified as feasible, the model was developed to a similar level of detail as the Type 23 study described in Section 4.3. Additional detail was added in the form of main watertight doors and vertical ladders, to investigate the practicality of modelling these in SURFCON. In the

candidate's MEng Ship Design Exercise studies [*Pawling, 2000*], [*Mailer & Pawling, 2001*], these features had been added into the final General Arrangement drawings, sometimes by altering the designed configuration. Using the integrated SURFCON model these could easily be incorporated at an earlier stage, before the production of 2-dimensional drawings.

- A set of steps was specified to be followed in this phase of the design:

1) Assess the design for the following, if the current design definition allows;
   a) Spatial clashes
   b) Volume and area requirement and supply
   c) Suitability of layout for required functionality (access, weapon arcs etc)
   d) Stability
   e) Trim
   f) Resistance, powering and endurance
   g) Hullform design (check that lines are fair).
2) Alter the design to resolve any infringements or inadequacies in these areas.
3) Add configurational and locational definition to next currently undefined Building Block.
4) Return to assessment.

- In item 3, the order adopted was to start with the FLOAT blocks, then the MOVE blocks, followed by the FIGHT blocks and finally the INFRASTRUCTURE blocks.

### 4.4.3 The Final Design Model

The final model of the design is shown in Figure 4.24. Figure 4.25 shows the overall envelope and external equipment items, while Figure 4.26 shows the level of detail modelled, with accommodation cabins on No 2 deck and equipment items in the machinery spaces.

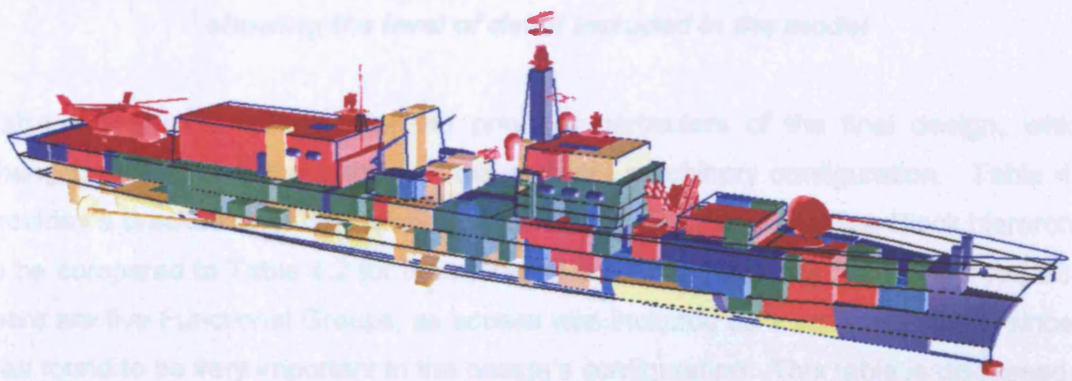


***Figure 4.24: Final model of the Type 23-a design with all Design Building Blocks visible***

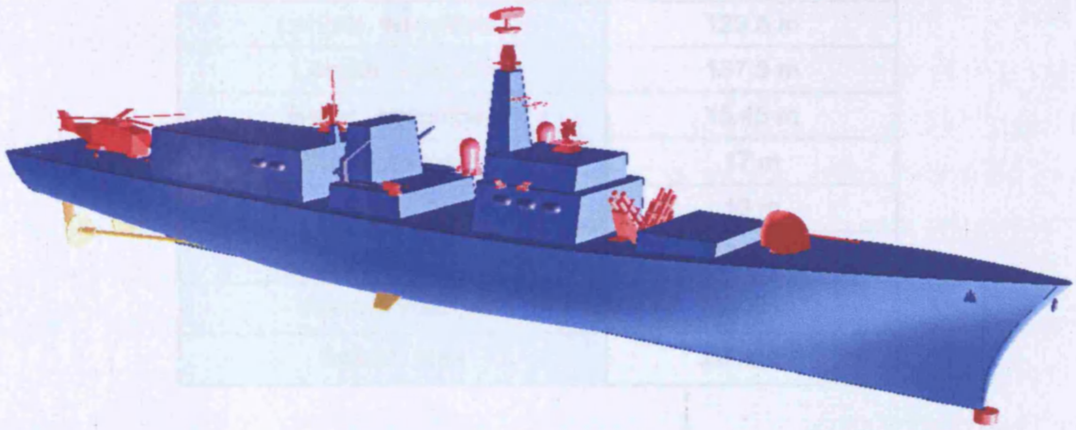


*Figure 4.25: Overall envelope (hull and superstructure) and upperdeck equipment items*

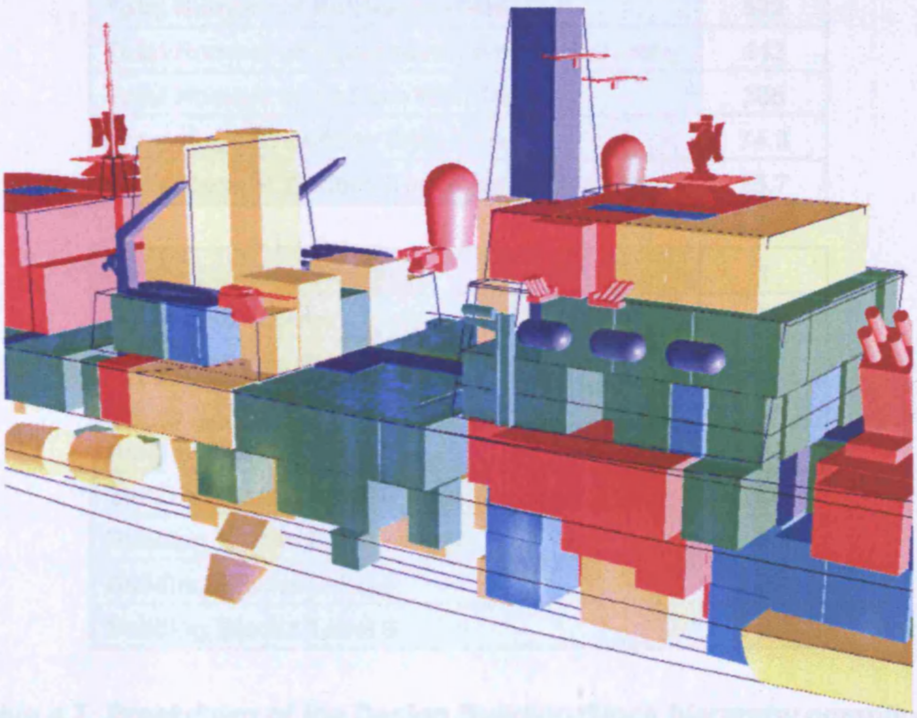


*Figure 4.26: Detail view of the forward superstructure and machinery spaces showing the level of detail included in the model*

Table 4.6 gives a summary of the principal particulars of the final design, which changed little after the alteration of the auxiliary machinery configuration. Table 4.7 provides a breakdown of the numbers of entities in the Design Building Block hierarchy, to be compared to Table 4.2 for the model of the Type 23 frigate. For the Type 23-a there are five Functional Groups, as access was included as a separate group, since it was found to be very important in the design's configuration. This table is discussed in more detail in Chapter 5, Section 5.6.

| | |
|---|---|
| **Length, waterline:** | 129.5 m |
| **Length, overall:** | 137.5 m |
| **Beam, waterline:** | 15.45 m |
| **Beam, overall:** | 17 m |
| **Draught, hull** | 10 m |
| **Displacement, deep** | 4082 te |
| **Internal volume** | 18550 $m^3$ |
| **Speed, max** | 28 knots |

***Table 4.6: Principal particulars of the final Type 23-a design***

| | |
|---|---|
| **Total Number of Entities in Hierarchy** | 522 |
| **Total Number of Equipment Items in Hierarchy** | 142 |
| **Total Number of Entities With Data** | 388 |
| **Percentage of Entities With Data** | 74.3 |
| **Percentage of Entities For Organisation Only** | 25.7 |

| | |
|---|---|
| **Master Building Blocks** | 1 |
| **Functional Groups** | 5 |
| **Super Building Blocks** | 27 |
| **Building Blocks Level 1** | 70 |
| **Building Blocks Level 2** | 148 |
| **Building Blocks Level 3** | 266 |
| **Building Blocks Level 4** | 3 |
| **Building Blocks Level 5** | 2 |
| **Building Blocks Level 6** | 0 |

***Table 4.7: Breakdown of the Design Building Block hierarchy complexity***

### 4.4.4 Discussion and Conclusions on the Type 23-a Design Study

This study demonstrated that it was possible to develop designs *ab initio* using PARAMARINE-SURFCON, showing that the functionality of the tool was sufficient and that a practical procedure now existed. The complexity of the design problem had been reduced, however, by specifying certain aspects of the design, such as the machinery configuration, that would normally be investigated more widely in a preliminary design and by adopting a conventional configurational style for the vessel. The Type 23-a study raised issues regarding designer decision making, data sources and the nature of a "balanced design".

## Designer Decision Making

As shown in Figure 4.18, the availability of the spatial model, with an integrated interactive graphical display at the earliest stages of the design process, was instrumental to the generation of the overall design style. The study also demonstrated that this allowed identification of emergent spatial relationships and assessment of possible alternatives, as shown in Figure 4.23. This also demonstrated a further important advantage of the tool and procedure, namely, the ease with which the design configuration could be altered to reflect major changes. Although initially a "minimum change" approach was adopted, the significant changes subsequently made to the configuration demonstrated that this was no longer a necessary approach, as the effects of the change on the design could be rapidly assessed. The time taken for such modifications was increased, however, by the fact that many of the Design Building Blocks were positioned in the 3-D model space by hand, with limited opportunities found to make use of the type of groupings illustrated in Figure 4.4.

Another issue that emerged in the Type 23-a study was that of recording design decisions and actions. As outlined in Section 4.4.2, at certain points in the design process (such as the choice over how to resolve the issue of the upperdeck equipment being too far forward) multiple choices were considered. In some cases these were quickly modelled by moving some of the Design Building Blocks, but overall the alternatives were considered in the mind of the designer rather than producing separate models. In the case of the Type 23-a a log was kept, using word processing software (due to its more developed functionality for storing text, tables and images in a single file), with such decisions noted (in very rough form).

Where such alternatives were investigated, only a short summary was retained in the log to describe them. This would include a short text description of the modification, an image of the PARAMARINE graphical display and the pertinent numerical design characteristics. This type of summary was also used to record the overall progress of the design. However, this method relied on the conscientiousness of the candidate and the use of a separate tool meant that such notes could not be associated directly (via a software link) with the objects they concerned, thus losing some of the context of the decision. This type of design decision, incorporating an assessment of many different numerical and spatial aspects of the design, can be contrasted with the purely numerical parametric surveys of hullform coefficients etc. described in Section 2.3, where the total range of possibilities considered can be displayed in a simple set of graphs. Finding and implementing a method of storing these multi-facetted decisions, that not only retains the relevant information but is also sufficiently convenient to use that the designer will do so, could further increase the understanding of the relationships in the design. These relationships often emerged during the process and such a method would assist the designer in reviewing past progress and deciding on actions when considering new choices.

Another issue regarding designer decision making, that was first identified in the Type 23-a, study was that of "what to do next", particularly in the later stages of the process. In this study a simple procedure was adopted where unplaced or undefined blocks were considered in the order FLOAT, MOVE, FIGHT and then INFRASTRUCTURE. This decision making issue was considered in the subsequent wider ranging design studies described in Chapter 5, before the range of methods described in Section 5.4.2 were adopted.

### Data Sources

The Type 23-a model was developed using the UCL design algorithms, which are intended for use in numerical spreadsheet models, based on frigate type ships and scale most weight and space requirements from the overall enclosed volume of the vessel. In the case of the Type 23-a, the conventional monohull frigate configuration meant that these were appropriate, but the availability of an integrated spatial model, from the earliest stages, would allow the use of more configuration and feature based sizing algorithms to be used. Examples of these for merchant ships are given by Watson & Gilfillan [*1976*], where, for example, the structural weight includes the number of watertight bulkheads. This would ensure that there is consistency in the modelled spatial configuration and the associated weight. This type of scaling could also be applied to manning. In the Type 23-a the complement was specified as part of the design requirements, but in the more general case of preliminary design, the required complement could be a numerical requirement associated with specific items of FIGHT and MOVE group equipment, with further support personnel demanded by Design Building Blocks within the INFRASTRUCTURE functional group. The main problem in implementing these types of scaling algorithms to take full advantage of the spatial model and functional breakdown has, however been identified by Dicks [*1997*], namely a lack of data on past designs that could be used to develop them.

### The Nature of a "Balanced Design"

In a conventional numerical sizing method, such as the UCL MSc SDE method [*UCL, 2001a*], a process of numerical iteration is carried out to reach a numerical balance of weight and displacement together with volume required met by volume available. Only after this numerical iteration has been carried out is the configuration of the design considered. In this process, numerical balance is achieved immediately, but a wider naval architectural balance, considering all the $S^5$ aspects, defined by Brown and Andrews [*1981*], is only achieved later. The disadvantage of this approach is that it requires a complete set of sizing algorithms to describe the ship and these may be inappropriate for the configuration adopted. This would only be found after the generation of the configurational model, so resulting in further work to re-balance the design.

With the availability of the spatial model at the earliest stages, the first stages of developing a design, using the Design Building Block approach, concentrate on the configuration, using very crude estimates of overall size to allow an early hullform to be developed. In the Type 23-a, this estimate was based on an assumed payload volume fraction and overall density. The numerical balance, rapidly achievable with the purely numerical model, is only introduced into the Design Building Block model after the overall configuration has been initially modelled, including FIGHT, MOVE and some INFRASTRUCTURE Super Building Blocks. This has the advantage of allowing more appropriate sizing algorithms to be selected for the process of numerical balance, but it also means that important designer decisions are taken using a model that is not balanced in the traditional numerical sense. This is discussed in more detail in Chapter 6.

## 4.5 The Initial Procedure for New Designs

The three areas of work outlined in this chapter; the SSA ITMC Design for Production studies, FSC IPT Type 23 demonstration and Type 23–a *ab initio* design, allowed the development of an overall procedure for the use of PARAMARINE – SURFCON in the production of new designs. Figure 4.27 describes this procedure and is based on that produced during the Type 23–a design study. This procedure draws on three main sources; the UCL Ship Design Exercise, with which the candidate was familiar; the original proposal for a ship design process incorporating architectural aspects by Andrews [*1984*] and the more recent procedure associated with the SURFCON breadboard demonstrator developed by Dicks [*1999*].

The action boxes in Figure 4.27 have been coloured and numbered to reflect the main activities carried out in the process. These are explained below, with reference to the four stages in the Design Building Block approach outlined by Andrews and Dicks [*1997*] and shown in Table 4.8.

| Design Preparation |
|---|
| Selection of Design Style |
| **Topside and Major Feature Design Phase** |
| Design Space Creation |
| Weapons and Sensor Placement |
| Engine and Machinery Compartment Placement |
| Aircraft Systems Sizing and Placement |
| Superstructure Sizing and Placement |
| **Super Building Block Based Design Phase** |
| 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. |
| **Building Block Based Design Phase** |
| 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. |
| **General Arrangement Phase** |
| Drawing Preparation |

***Table 4.8: Building Block design phases [Andrews & Dicks, 1997]***

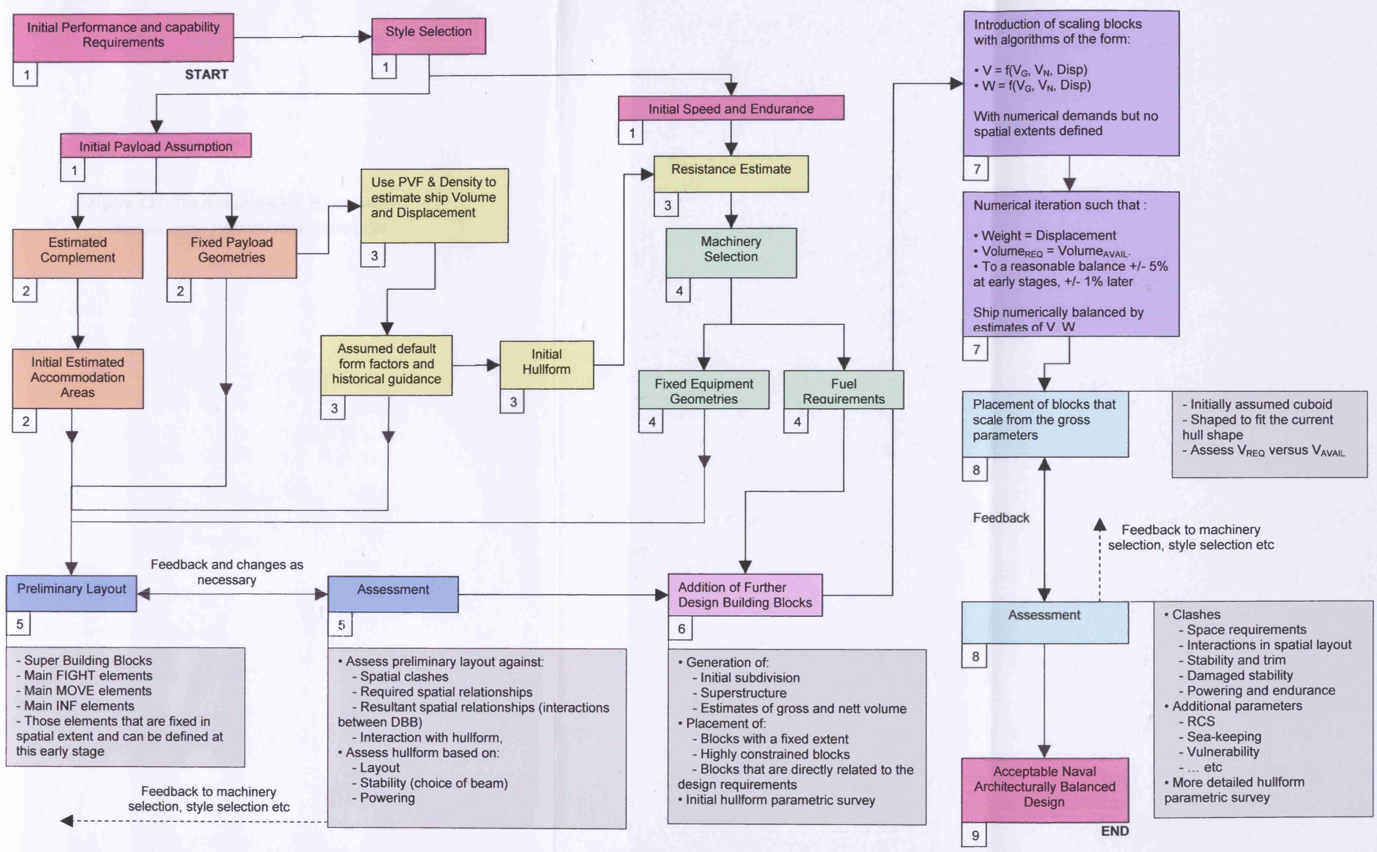



***Figure 4.27: The first procedure for developing designs using PARAMARINE-SURFCON***

### 1. Preparation stage

- Identification of design generators;
- Identify capabilities (functions) required;
- Define weapons systems, required ship features and performance
- Define or select overall style to be adopted (design standards, hullform topologies, margin philosophy etc);
- Design space creation:-
    - Implementation of numerical requirements for speed, endurance, magazine capacity etc;
    - Selection of data sources (libraries of algorithms);
    - Implementation of output objects (auditing tools etc).

### 2. Major Feature Design Stage

- First definition of new design;
- Define or select Design Building Blocks for FIGHT group, with design margins in Building Blocks, where uncertainty exists;
- Estimate complement from defined FIGHT group requirements and estimated support personnel (using UCL SDE method [*UCL, 2001a*]).

### 3. Major Feature Design Stage - Initial sizing

- Initial estimate of overall vessel size and displacement;
- Generation of initial hullform;
- Initial resistance estimate.

### 4. Major Feature Design Stage – Machinery Selection

- Gross machinery sizing, based on adopted style and estimated resistance and endurance.

### 5. Major Feature Design Stage – Layout

- Initial layout of FIGHT, MOVE, some INFRASTRUCTURE (accommodation) and hullform;
- Alternative layout styles generated and compared, rejected or retained for parallel development;
- Identification of the main design drivers and interactions in design.

## 6. Super Building Block Design Stage

- Placement of additional Super Building Blocks such as:
    - Fuel tanks;
    - Auxiliary Machinery Spaces;
    - Super Building Blocks that can be derived from the current configuration, rather than those that need numerical iteration (scaled from overall volume and weight).
- More detailed application of style:
    - Structural topology;
    - Subdivision;
    - Functional zoning (high level definition only at this stage).
- Initial structural weight estimate, based on:
    - Historical data for similar vessels;
    - Structural weight fraction;
    - Structural weight density for enclosed volume.
- Limited stability assessment (possibly even simple damaged cases).
- Initial hullform parametric survey, possible at this stage with limits informed by Design Building Block definition.

## 7. Design Building Block Design Stage – Numerical Balance

- Implementation of scaling algorithms:
    - Initial implementation as weight only (VCG for stability possible through items on appropriate decks).
- Margins application (through life growth and Board margins [*Andrews, 2001*], also design margins for those Building Blocks not yet assessed).
- Iteration to numerical balance between:
    - Total Design Building Block weight and displacement;
    - Total volume demand and enclosed (available) envelope volume.
- Still not a naval architecturally balanced design, as those Design Building Blocks that scale on the overall size of the ship will not have been placed yet and nor have many support related blocks (e.g. ships stores, weapons maintenance workshops etc.).

## 8. Design Building Block Design Stage – Development of design

- Further definition of weight-only Design Building Blocks with geometry and location.
- Detailed parametric surveys on hullform shape:

  - Level of detail dependent on hullform design tools used. With the Quickhull hullform generation tool, the parameters varied are $C_P$, $C_M$, LCB position, length, beam and draught;
- Iterative process of design development;
- Extension to additional performance assessments carried out as soon as sufficient detail is provided by model (e.g. external shape and upperdeck equipment for preliminary Radar Cross Section (RCS)).

## 9. Achievement of naval architecturally balanced design

- Preparation of outputs / design report / summary using output tools implemented in step 1.

This procedure can be compared with the diagrammatic description of a new ship design process provided by Andrews [*1984*], which is shown as Figure 4.28. Certain key differences between the two procedures are worthy of note:

- In Figure 4.27 all numerical criteria to be used in selecting the design are defined in the preparation stage, whereas in Figure 4.28 they are developed as the design proceeds.
- Figure 4.28 refers to a synthesis model, meaning an algorithm based numerical sizing routine, similar to the UCL SDE (when implemented in a spreadsheet), but importantly featuring a configurational model. As discussed in Section 4.4.4, the process of synthesis used in the candidate's initial studies utilised a Design Building Block model with few sizing algorithms, particularly at the early stages. Alternative configurations were assessed by manipulating objects in the early sparsely populated model, rather than by re-iterating a numerical model with different hullform coefficients etc.
- The items numbered 8 in Figure 4.27 encompass several items in Figure 4.28. The latter gives a clearer representation of the process of iteration that takes place in the later stages of the design right through to final as fitted drawings (i.e. whole design process not just preliminary design).

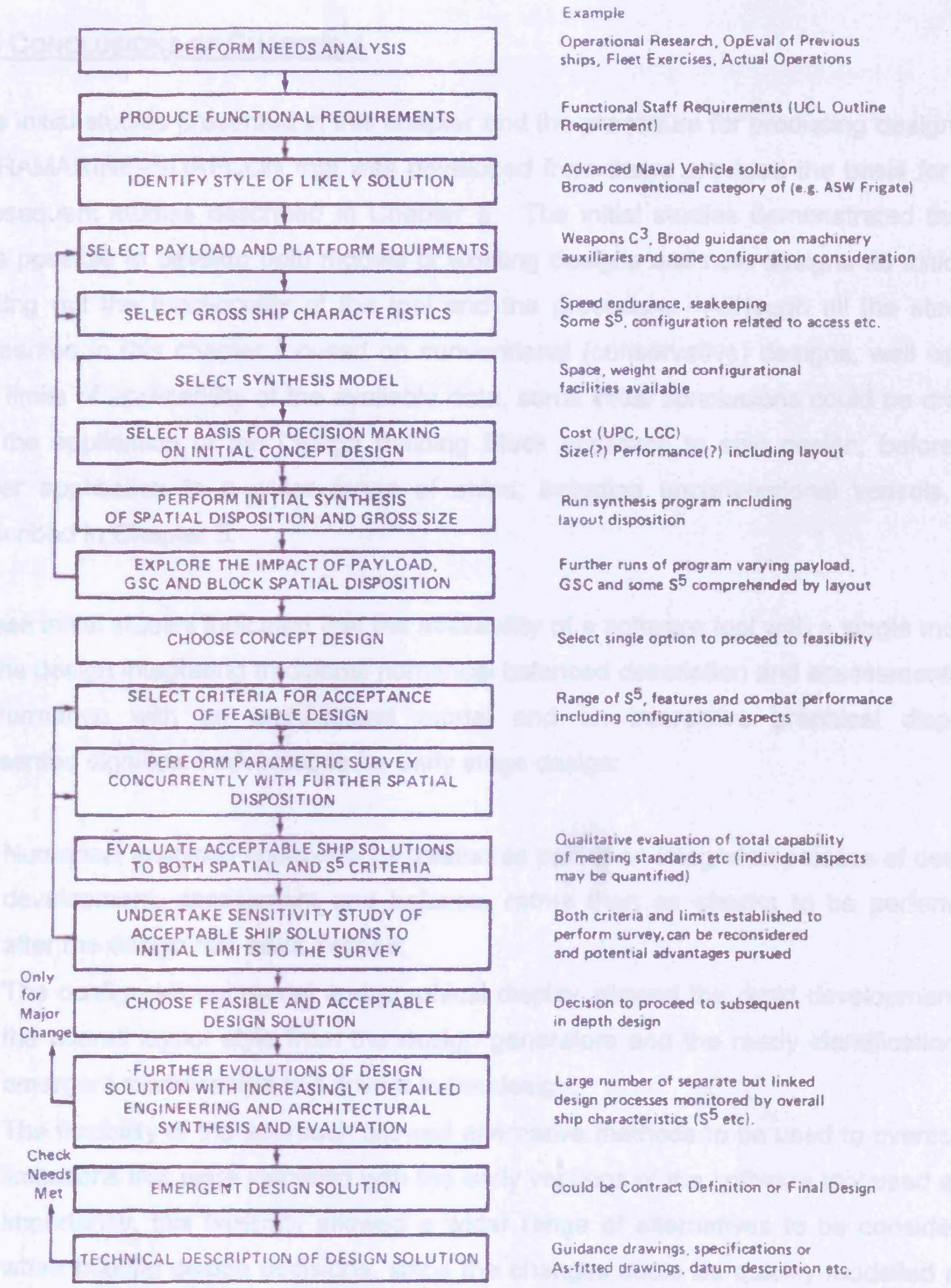



***Figure 4.28: A representation of the ship design process incorporating architectural aspects in a fuller synthesis, as proposed by Andrews [1984]***

## 4.6 Conclusions of Chapter 4

The initial studies presented in this chapter and the procedure for producing designs in PARAMARINE–SURFCON that was developed from them, provided the basis for the subsequent studies described in Chapter 5. The initial studies demonstrated that it was possible to develop both models of existing designs and new designs *ab initio*, in testing out the functionality of the tool and the procedure. Although all the studies presented in this chapter focused on conventional (conservative) designs, well within the limits of applicability of the available data, some initial conclusions could be drawn on the application of the Design Building Block approach to ship design, before its wider application to a wider range of ships, including unconventional vessels, as described in Chapter 5.

These initial studies indicated that the availability of a software tool with a single model of the design integrating traditional numerical balanced description and assessments of performance with an architectural model and an interactive graphical display, presented significant advantages for early stage design:

- Numerical analyses could now be treated as part of an integrated process of design development, assessment and balance, rather than as checks to be performed after the design had been defined;
- The configurational model and graphical display allowed the rapid development of the overall layout style from the design generators and the ready identification of emergent relationships and drivers in the design;
- The flexibility of the approach allowed alternative methods to be used to overcome limitations that were identified with the early versions of the software tool used and, importantly, this flexibility allowed a wider range of alternatives to be considered when making design decisions, since the changes could be quickly modelled and assessed. However, this flexibility was not used to its full extent in these conservative initial studies;
- The possibility arises of making more use of configurationally and functionally based sizing algorithms, although the lack of a historical database of ship designs represented in this way would make the generation of such algorithms difficult.

Some limitations were found with the functionality of the software used in these early studies. A dialogue was started with GRC, which subsequently led to changes in later software versions, to add the required functionality. A wider question was raised, however, as to how modern computer-aided ship design tools could be used effectively to record the processes of decision making in the development of designs. This was particularly seen with regards to the more holistic, multi-faceted decisions that are a consequence of the more descriptive nature of solutions provided by the Design Building Block approach to design.

The software implementation of the approach and the initial procedure developed from it, both utilise a different philosophy regarding the concept of the "balanced design" than that found in traditional numerical early stage design models. Although at the most detailed levels, when the concept design was frozen, the PARAMARINE–SURFCON studies maintained the same type of numerical balance of supply and demand as the traditional methods, at the early stages of the design development this was not the case. Instead a sparsely-populated design model was utilised, consisting of several major features or Super Building Blocks with only very loose connections between them. This decoupled model provided flexibility early in concept design, while containing the fundamental design elements, such as a hullform and rough configuration, needed to perform numerical analyses, such as intact stability.

# Chapter 5: Application of SURFCON to Ship Design

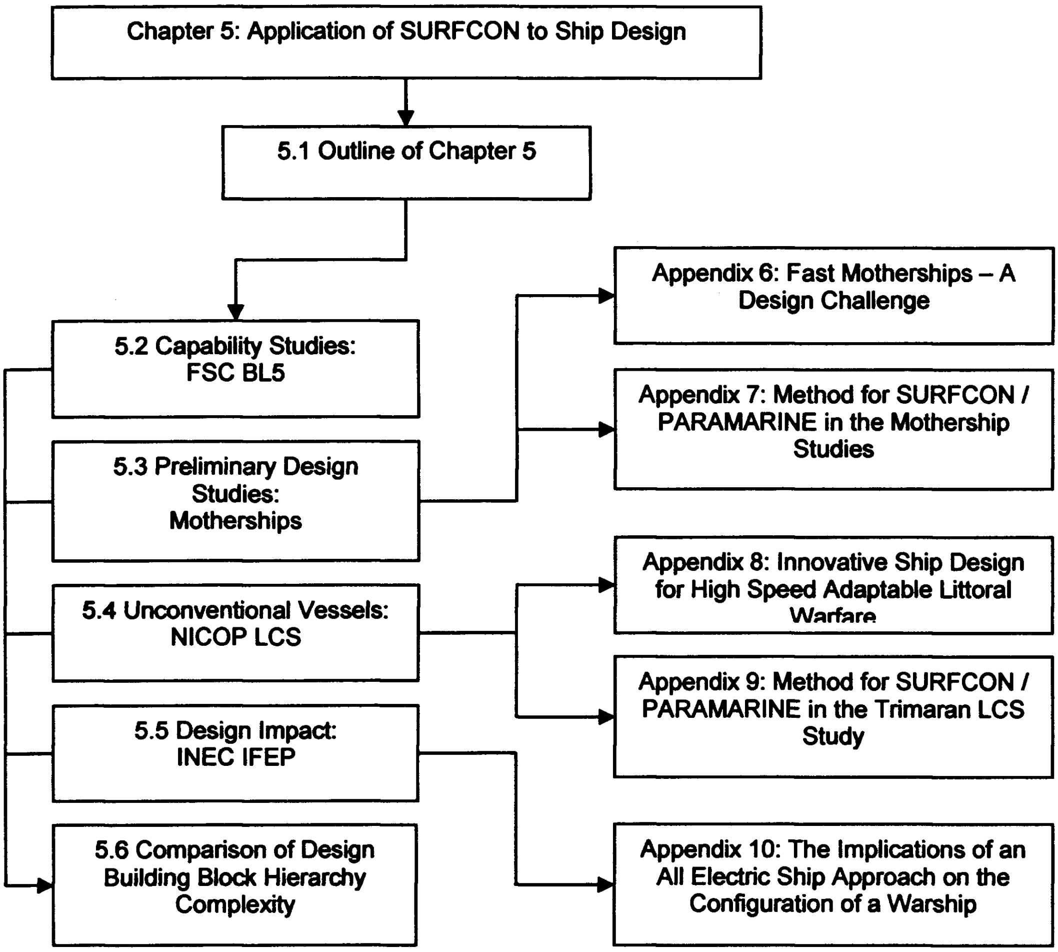



***Figure 5.1: Schematic of Chapter 5***

## 5.1 OUTLINE OF CHAPTER 5

The previous chapter described GRC's implementation of the Design Building Block approach as a module within their PARAMARINE software and the candidate's initial work in assessing the functionality of this new tool and developing an initial method. This chapter outlines the application of the tool and method to a range of real-world ship design problems, beyond the research demonstrations described in Chapter 4 and undertaken in Dicks' previous work on the application of the approach [*Dicks, 1999*]. The main four sections of this chapter each contain a summary of the work carried out and the main issues revealed in one of the design studies. The more detailed descriptions of the designs are given in appendixes, where appropriate. The final section of this chapter compares the complexity of the models used in the studies, illustrating the range of design studies carried out.

## 5.2 CAPABILITY STUDIES: FSC BASELINE 5

### 5.2.1 Aims of the Study

This study was performed under contract from the UK MoD / DPA Future Surface Combatant Integrated Project Team (FSC IPT) [*Andrews, 2002*]. The aim of the study was to develop a capability-based cost model of the FSC concept design and to evaluate the demands of the various elements of capability on the overall design. The full report on the study and designs that was submitted to the FSC IPT [*Andrews & Pawling, 2002b*], [*Andrews & Pawling, 2002c*] cannot be reproduced in an Appendix as it contains classified information and so the key points on the approach undertaken and procedure adopted are summarised here.

The baseline FSC design used for the study represented a large multi-role vessel, intended to enter service in the early 21st century. Both monohull and Trimaran versions of the design were considered, as shown in Figures 5.2-1 and 5.2-2.

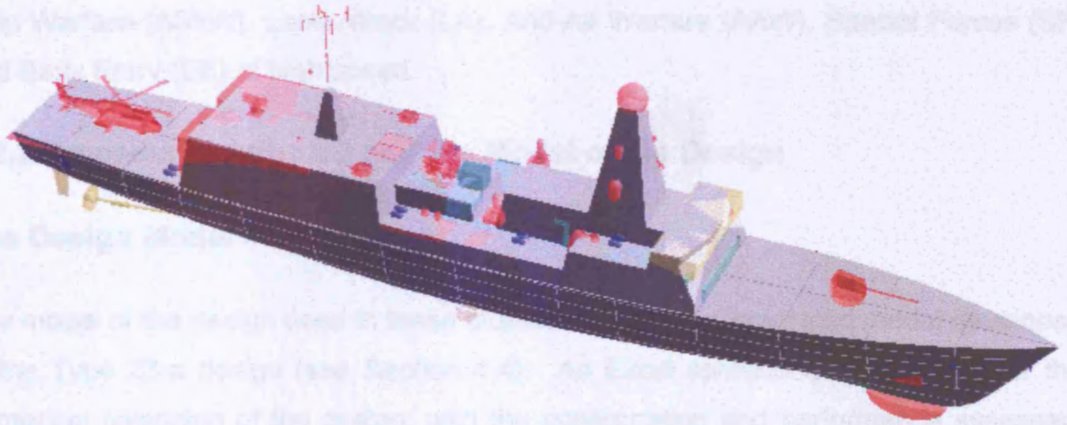


***Figure 5.2: Monohull baseline design for capability study [Andrews & Pawling, 2002b]***

***Figure 5.3: Trimaran baseline design for capability study [Andrews & Pawling, 2002c]***

For both the monohull and trimaran design, a numerical spreadsheet model of the design and a basic PARAMARINE model, used for stability assessment, were provided by the FSC IPT, representing the "Baseline 5" configuration of the vessel. These two separate representations of the design were combined, via the Design Building Block approach, to form a capability-based cost model of the design. In order to demonstrate this model, a study of the impact of each of the capability areas was undertaken. The four main stages of this study were:

1. Identification of specific areas of capability to be examined
2. Removal of a specific capability from the baseline design
3. Rebalance of the design
4. Assessment of the new balanced design against the baseline design performance requirements (aside from those specific to the removed capability)

The six main capability areas investigated were; Anti-Submarine Warfare (ASW), Anti-Ship Warfare (AShW), Land Attack (LA), Anti-Air Warfare (AAW), Special Forces (SF) and Early Entry (EE) at high speed.

### 5.2.2 Procedures Adopted and the Model of the Design

#### The Design Model

The model of the design used in these studies was not the integrated model developed in the Type 23-a design (see Section 4.4). An Excel spreadsheet was used for the numerical balancing of the design, with the configuration and performance assessed, using the SURFCON objects within PARMARINE. The data reflecting the current configuration of the design was transferred by hand between the two representations of the vessel. The reason for this was that the spreadsheet was a wide-ranging, pre-established numerical model with many interconnections and contained a large pool of source data in the form of tables and algorithms that had been produced by the FSC IPT over considerable time. There was insufficient time, within the scope of these studies, to integrate the two components of the model (Excel numerical spreadsheet and PARAMARINE-SURFCON architectural model) into a single PARAMARINE based SURFCON model.

Data on space demands estimated by the spreadsheet was used to size the blocks in the UCL PARMARINE / SURFCON model. Weights and centres of gravity estimated by the spreadsheet were inputted into the spatial model as point weights. Some major equipment items, such as the vertical launchers and Gas-Turbines, were fully defined with their own weight data, as they had a significant effect on the overall vertical and longitudinal centres of weight for the ship and were items that were part of the specific capability study. Variable loads were also entered separately into the PARMARINE / SURFCON model, as this allowed the direct estimation and sizing of tank capacities.

Table 5.1 shows the breakdown of Design Building Blocks in the baseline monohull model in the same manner as the breakdown shown in Table 4.32. This table is compared to its equivalent for each of the other designs described in this chapter at Section 5.6.

| | |
|---|---|
| **Total Number of Entities in Hierarchy** | 395 |
| **Total Number of Equipment Items in Hierarchy** | 84 |
| **Total Number of Entities With Data** | 186 |
| **Percentage of Entities With Data** | 63.3 |
| **Percentage of Entities With Numerical Data** | 47.1 |
| **Percentage of Entities For Organisation Only** | 36.7 |

| | |
|---|---|
| **Master Building Blocks** | 1 |
| **Functional Groups** | 4 |
| **Super Building Blocks** | 29 |
| **Building Blocks Level 1** | 67 |
| **Building Blocks Level 2** | 113 |
| **Building Blocks Level 3** | 123 |
| **Building Blocks Level 4** | 58 |
| **Building Blocks Level 5** | 0 |

***Table 5.1 Design Building Block hierarchy statistics for the capability study monohull baseline model (July 2002)***

## The Procedure

The procedure used in the FSC Baseline 5 studies was first outlined in a diagram included with the proposal submitted in May 2005 [*Andrews, 2002*]. This procedure was based on experience with the SSA ITMC Design for Production models and the design of the Type 23-a vessel (both described in Chapter 4). This general method encompassed the generation of the balanced baseline model and subsequent variants while assuming that the studies would make use of a single model of the design. In such a model, the spatial model and numerical sizing algorithms are integrated in a single PARAMARINE – SURFCON file, as in the Type 23-a design, rather than in separate software tools.

Figure 5.4 shows the procedure divided into four sections:-

**Section 1** of the procedure covers the assembly of the integrated model of the design, by the addition of the scaling algorithms, contained in a spreadsheet to the Design Building Blocks in the SURFCON model. This would inherently include the identification of those blocks and algorithms that were associated with each capability in the design, as it would involve the transfer of data from a costing hierarchy (NES 163) weight group system, [*MoD, 1989*] to a functional hierarchy, as in SURFCON.

**Section 2** outlines the removal (or addition) of a specified capability in the design. This would be in the form of the removal of blocks, alteration of algorithms and also design constraints, such as required maximum speeds.

**Section 3** then indicates the different aspects of the iterative process to bring the variant design into balance. On the right of Figure 5.4 are examples of the whole-ship numerical balances undertaken. On the left is a summary of the different types of changes to the design that were assessed. These include changes to the layout, to minimise excessive space after removal of blocks, changes to the hull form and overall dimensions plus the re-evaluation of weight groups, not directly linked to the removed capability. An important distinction is shown between "local" and "gross" changes. The removal of different capabilities was expected to have different effects on the ship, with some only causing changes in overall size ("gross"), while others having a significant effect on the detailed layout of the vessel ("local").

**Section 4** in the process diagram indicates the assessment of the balanced design for cost and performance. As described in the introduction (Section 5.2), the costing of the variant designs was not carried out by UCL, so this is included only for completeness.

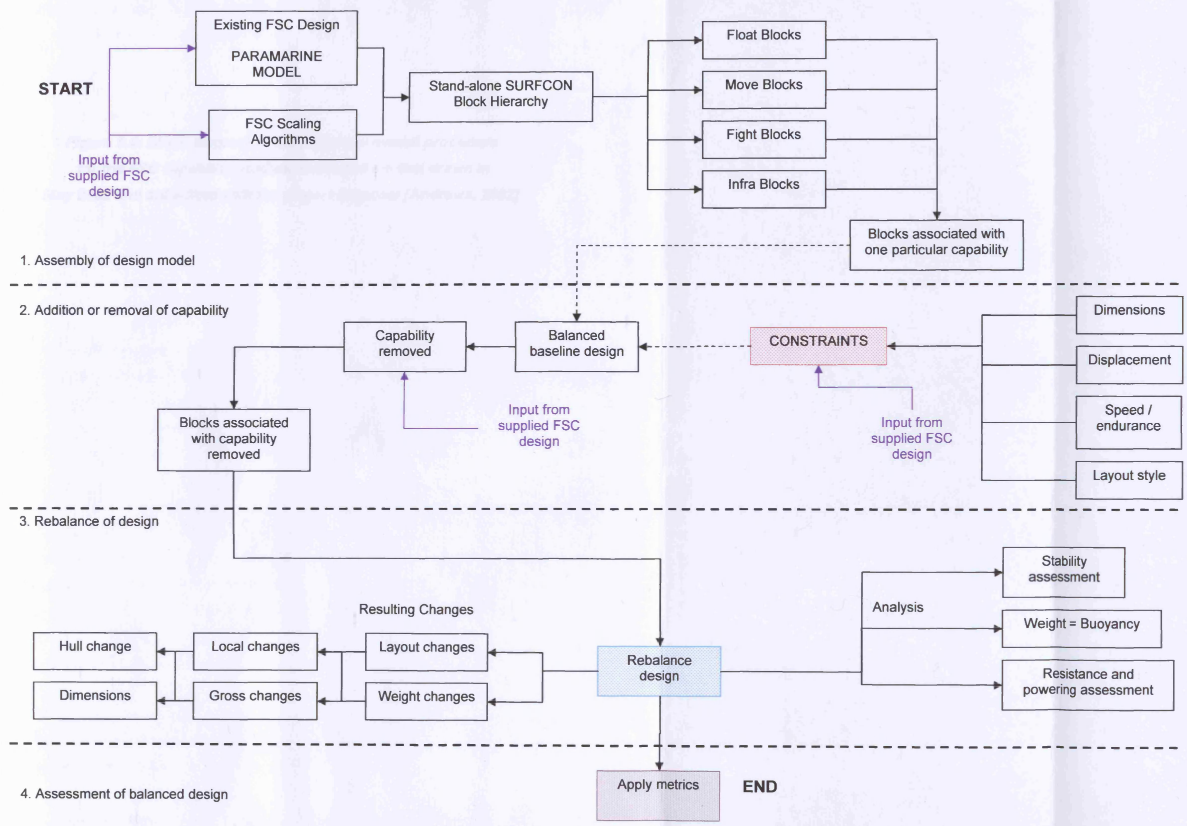



***Figure 5.4: Block diagram of the proposed overall procedure for the FSC capability studies, redrawn from that drawn in May 2002 and submitted with the project proposal [Andrews, 2002]***

As described above, these studies ultimately made use of two parallel models of the vessel, one in PARAMARINE and one in Excel, rather than the single integrated model originally planned. This necessitated an ordered procedure to ensure that data was coherently transferred between the two models:-

1. Identify weight groups that should be changed on the synthesis spreadsheet.
2. Identify space groups that should be changed on the synthesis spreadsheet.
3. Introduce changes in manning requirements to the synthesis spreadsheet.
4. Perform simple numerical balance within the spreadsheet, iterating draught to reach the required displacement to balance achieved weight from the Design Building Blocks.
5. Copy the values of hull shape and size parameters from the spreadsheet into the Paramarine model and recalculate the hullform.
6. Remove or update any blocks corresponding to the changes identified in steps 1-3.
7. Assess and model any overall changes in the layout and principal dimensions of the design in the SURFCON spatial model. This includes upperdeck layout, accommodation flats and blocks plus available bunkerage capacity.
8. Copy any changed spatial measurements into the spreadsheet. This includes overall dimensions and superstructure dimensions.
9. Re-run the numerical balance of weight and displacement to the appropriate level (+/-1%) within the spreadsheet.

In order to avoid excessive data transfer, only those blocks immediately affected by the capability changes were examined initially. Other blocks, such as stores, offices etc., that scale on the gross size of the ship were updated once the overall parameters of the design had been fixed by iterating the steps between 5 and 9. With all blocks updated according to the space requirements, derived from the spreadsheet, the configuration was updated to meet the requirements.

During the iteration process described above, the ship was evaluated for performance in several quantitative and stylistic areas, as shown in Figure 5.4. The quantitative assessments are listed below, in the order that they were typically assessed:-

- Volume or area
    - Supply for each block should be equal or greater to that required. If demand was more than approximately 10% greater than supply, the layout was altered;
- Consumables tankage

    - o The tanks were defined such that supply was sufficient to meet demands (+/- 5%);
- Resistance and endurance calculations were conducted using series data imbedded in the FSC IPT supplied spreadsheet model;
- Weight and centre of gravity for the current layout was evaluated to monitor for large changes, as the design was modified;
- The hullform was updated to use the current displacement, but no changes to hullform shape were made;
- Intact trim, heel and large-angle stability in the Deep and Light Sea-going conditions were assessed;
- Damaged stability, in the Deep and Light Sea-going conditions, was assessed;
- The design was assessed against the NES 109 criteria [*MoD, 2000*] for the shape of the GZ curve. Where possible, the layout was altered to generate a trim between 0.3m and 0.6m by the stern. If this was not readily possible, then this was noted as a problem with the current arrangement.

The design was checked for the following aspects of the layout style:-

- Access routes to all compartments maintained;
- Structural continuity achieved with bulkheads and superstructure;
- Excess space reduced as much as practicable (5%);
- Overall style of baseline layout was maintained in the variants. This meant that spatial relationships between major spaces were kept and the overall configuration of the variants was similar to that shown in Figures 5.2 and 5.3. This reflected the generation of variants from a baseline, as opposed to the development of new designs to different capability requirements, perhaps with radically different layouts.

The process of developing both the baseline and variant designs was recorded by means of a text file containing a log or journal of the decisions made and progress achieved. This was generated by the designer. The "properties" function available in PARAMARINE–SURFCON, described in Section 3.4.1, was used to examine any links and dependencies created in the model.

### 5.2.3 Outputs

Although the aim of the study was to provide a cost-capability model, costing of the designs was not carried out by UCL. The main UCL output was a weight and space breakdown of the design, using the NES 163 systems [*MoD, 1989*], and a single-sheet description of the main features of the design needed for effective cost estimation, which was subsequently undertaken for FSC IPT by the Ministry of Defence Costing Group. Bar charts were also produced comparing the weight and space breakdowns for each of the variants and the baseline, an example of which is shown in Figure 5.5. The main design drivers and features of each of the variants were also described, giving a greater understanding of the solution space.

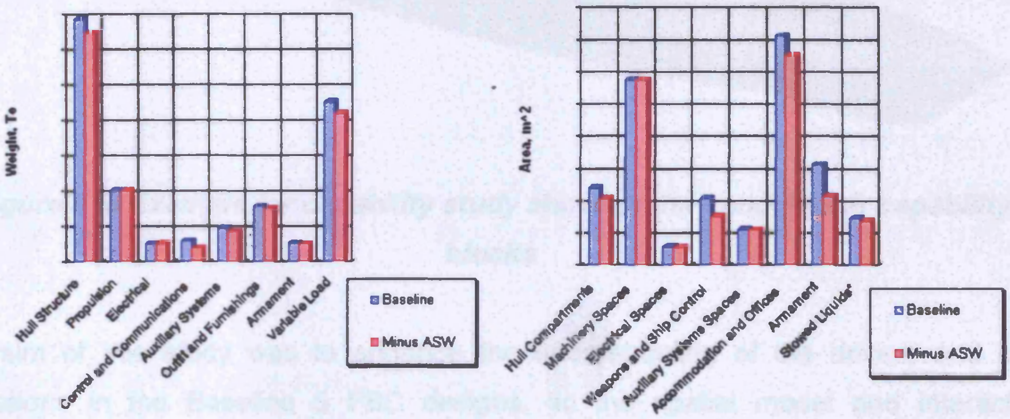



***Figure 5.5: Bar charts comparing weight and internal area of the baseline and "minus ASW" variants of the capability study***

### 5.2.4 Discussion

The functional breakdown of the design used in the Design Building Block approach was found to be well suited to this type of study, allowing assessment of the spatial and numerical extents of each of the capability areas on the design. An example of the land attack function is shown in Figure 5.6.

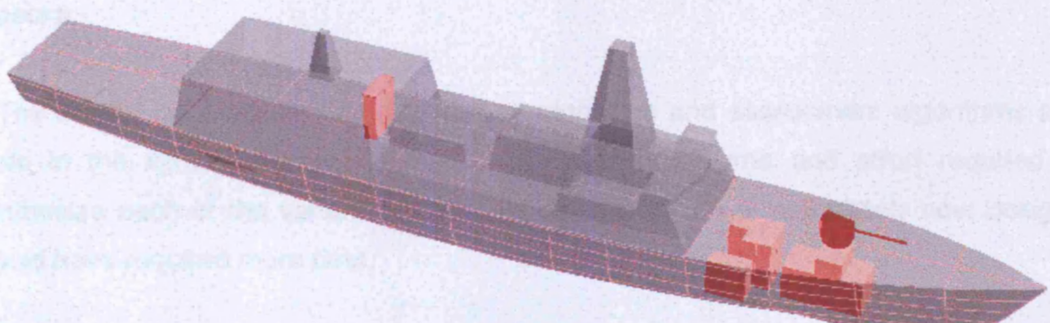


***Figure 5.6: Example for capability study showing the Land Attack capability blocks***

The aim of this study was to enhance the understanding of the drivers and cost allocations in the Baseline 5 FSC designs, so the spatial model and interactive graphical displays were important in identifying the design drivers in the configuration and ensuring that the resulting designs were realistically represented (for example, checking the shape of Design Building Blocks that scaled with the design). The spreadsheet model contained assumptions regarding the arrangement of the vessel and these were checked and, in some cases, altered to properly reflect the actual configuration of the design. The first task in the development of the designs was to update the spreadsheet with areas and volumes read from the spatial model, leading to a baseline design different to that initially supplied by FSC IPT.

The ability to display, in a visual manner, the extent of each identified function in the ship layout, in addition to text and numerical descriptions, conveyed the information and understanding gleaned during the study to the DEC desk officer, who was not familiar with the detailed layout of the ship. This effectively provided context to the numerical values.

Although the Design Building Block approach is primarily intended for *ab initio* design of ships, this study saw the SURFCON tool used in the modification of a design that had been produced using traditional methods. In this respect it did not fully exploit the

Design Building Block approach. In the final reports submitted to FSC IPT [*Andrews & Pawling, 2002a*], [*Andrews & Pawling, 2002b*], it was noted that the retention of the overall layout defined in the baseline design was possibly a restriction on the alterations that could be made to the vessel and was the main driver on the dimensions of the vessel. This "minimum change" approach to the generation of the variant designs, where capabilities are removed from a baseline design, rather than new designs being developed with the reduced capability set, was adopted for two reasons:-

i. The lack of an integrated model, with all modelling and assessment algorithms and tools in the same software, increased the amount of time and effort required to synthesise each of the variant designs, so the generation of completely new designs would have required more time.

ii. The aim of this study was to explore the "local solution space" by conducting sensitivity analyses on the then-current baseline FSC design, with the aim of increasing understanding of that design and allowing more accurate identification of the costs of the different functions required.

The limitation with this approach is that it only assessed the local topology of the solution space for one particular configuration of the design. As was found in the FSC study, this can be dominated by the overall stylistic decisions taken earlier in the generation of the baseline model. Thus the variants generated may not be a realistic representation of a likely ship design, as, if each variant was to be generated *ab initio*, different decisions may be taken which would lead to a different design. These would be genuinely naval architecturally balanced as they would incorporate the effects of the overall configuration (style) in the design solution.

Regarding the objective of producing a cost-capability model of the FSC design, an approach utilising a wider range of variants would provide a more accurate indication of the trade-offs that exist not only between cost and capability but also incorporating stylistic aspects (such as technologies and layout philosophies) which would strongly influence the cost and performance of the design. This would allow a capability based procurement programme to assess the total impact of any required capability on the cost of more representative designs configurations.

To utilise the alternative approach, where different designs would have been generated *ab initio* for each of the capability variants, required a truly integrated model, where all numerical modelling and assessments of the design were performed with reference to a single spatial model. This would reduce time in data transfer between models, reduce the risk of the final configuration being unrealistic and allow the identification of relationships and limitations in the design. Such an approach, where several different styles of solution would be compared, would also require design models more complex than parametric scaling models, as they must not only adapt to the changes in style but to discontinuities in the solution space produced by issues such as:

- The discrete sizes and ratings equipment (e.g. gas turbines);
- The adoption of advanced technologies to permit increased performance at increased cost (e.g. composite structures);
- Discontinuous design features emerging from the design configuration (e.g. the stern arrangements for accommodating waterjets in high speed trimaran designs, explored in the candidate's trimaran LCS study, (Section 5.4) and a later FSC Baseline 7 study by the FSC IPT [*Skarda & Walker, 2004*].

## 5.3 PRELIMINARY DESIGN STUDIES: MOTHERSHIPS

### 5.3.1 Aims of the Study

This study was performed under contract placed by the Defence Procurement Agency's Future Business Group with British Maritime Technology Defence Services Limited (BMT DSL) as prime contractor and UCL Design Research Centre (DRC) subcontracted for some nine weeks to produce nine design studies. The aim of the study was to assess the suitability of the mother-daughter ship concept for the Future Surface Combatant programme. The design study work was jointly conducted by the UCL DRC and, with BMT DSL costing specialists Bertram Martin Consulting Limited estimating the Unit Production Cost of the vessels. Both design partners utilised the SURFCON tool and the Design Building Block Approach, with UCL generating nine of the mothership designs, whilst BMT DSL approached the daughter craft designs and the analysis of more detailed engineering issues of the concept, such as docking interfaces and methods and the overall concept assessment, including costing. The UCL tasks undertaken in the project were summarised in a paper presented at the RINA Warships 2004 conference, which is included at Appendix 6 [*Andrews & Pawling, 2004a*].

### 5.3.2 Procedures Used and the Model of the Design

The overall timeline of the project is shown in Table 5.2, with just nine weeks available for the actual design activity. Prior to this, during the bidding process, the candidate developed an indicative SURFCON mothership representation, based on a past MSc

Ship Design Exercise design [*Winstanly, 1997*]. This model was developed in two working days and illustrated the capability of SURFCON for supporting the production of quick and rough concept designs. The study design process was started with a brain-storming exercise of the UCL and BMT DSL team to propose possible mother / daughter combinations and deployment methods. This initial exercise indicated that the deployment method and number of assets carried were the main "design generators" for these studies, requiring a configuration-led design approach.

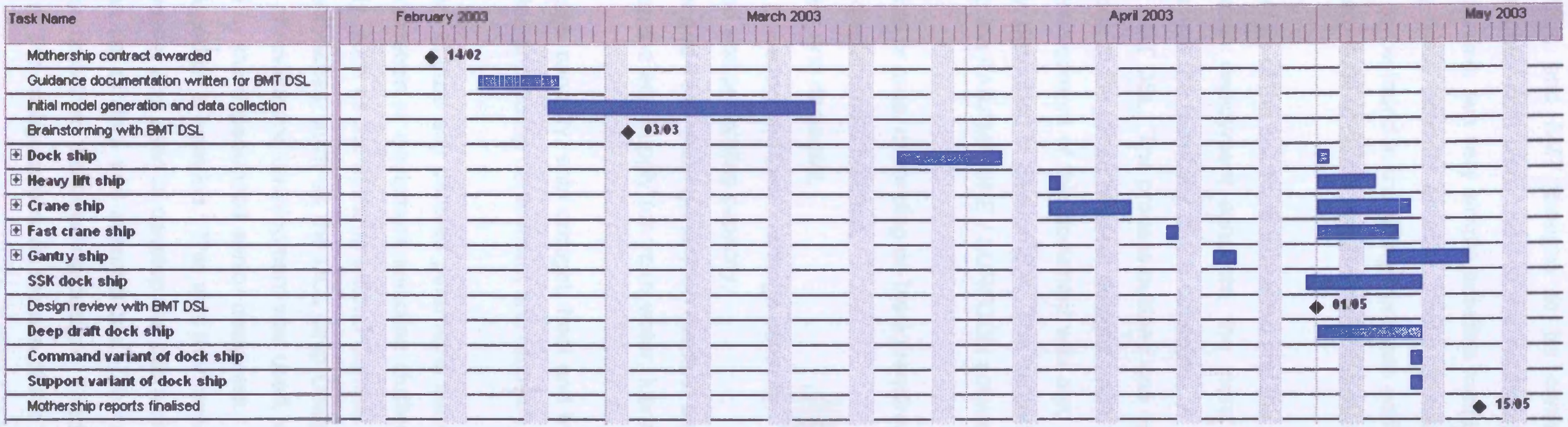



*Table 5.2: Timeline for the UCL mothership studies, showing concurrent studies of different designs*

To allow the UCL and BMT designs to be carried out in parallel, notational "placeholder" daughter craft were used in the mothership studies. In parallel with the brainstorming exercise, two very simple baseline mothership designs were developed at UCL to carry these notional assets. These allowed an early assessment of the difficulties likely to be found in the design process and provided a "first guess" at the likely order of magnitude of displacements and dimensions of the final design solutions.

With the likely scope of the solutions evaluated and the process structured, through the selection of certain deployment concepts, the more detailed design models were developed to assess the feasibility of the concepts. A generalised process document was provided to BMT DSL. The process outlined was deliberately kept general to allow its easy adaptation to the range of asset designs under consideration by BMT DSL. A more detailed development of this document was also subsequently produced for the ONR LCS study, described in Section 5.4. The numerical assessments of the design carried out using the PARAMARINE / SURFCON software were:-

- Space (volume or area, depending on block) required and available;
- Weight and displacement balance;
- Stability, intact and damaged;
- Resistance, powering and Dieso tankage capacity;
- Electrical load and generating capacity;
- Chilled water and fresh water generation demand and supply;
- Tankage demand and supply for fresh water, lubrication oil, sewage and aviation fuel;
- Ballast tankage capacity, ship draught, heel and trim when loaded with daughter craft, unloaded and during deployment and recovery of these assets.

This work did not feature any detailed parametric surveys or optimisation of hullform shapes and parameters or equipment selection studies that would be a feature of a single ship study, such as the trimaran Littoral Combat Ship (Section 5.4) or the more conventional approaches, such as the UCL Ship Design Exercise. [*UCL, 2001a*] An overall process of review and development was used, with the design decisions made being assessed by the experienced senior designers. The first design, a large dock-ship, was developed as a baseline. This was then assessed and improved. The final version of this vessel was used to develop the alternative asset deployment concepts, using a common set of data and assumptions. The alternative solutions were thus developed in less time than the baseline design. Feedback from design reviews was implemented in all the configurations via the use of the "KCL" macro language outlined in Appendix 4. As shown in Table 5.2, this allowed parallel development of the later designs, not only increasing the number of options that could be considered in the available time, but also allowing the lessons learnt in one configuration to be rapidly applied to all the others.

### Rapid Concept Design Development: Motherships Procedure

In addition to applying the Design Building Block approach, this project was also important in that it was the first co-operative project where a partner organisation also used SURFCON. UCL provided training in using SURFCON and the creation of a relatively formalised procedure document. The candidate was located with BMT DSL for three days to train one of their naval architects, who was already familiar with the PARAMARINE software – but not SURFCON. He was then trained in the technical aspects of the use of the SURFCON objects and the overall process of ship design encapsulated in the Design Building Block approach. In addition to these three days of tuition, two documents were produced. The first was a schematic showing how the objects are arranged and connected in the SURFCON file. This illustrated the way objects were organised and grouped within the design file and the main data transfer between these groups of objects.

The second document was a 13-point procedure for synthesising a design in SURFCON. The method described by this document drew from the early work on the SSA ITMC Design for Production studies, outlined in Section 4.2. This method is included as Appendix 7. It describes a preparation stage, where the general structure of the PARMARINE – SURFCON design file is laid out and then a general process of synthesis is performed. The process outlined starts with the design generator blocks – in this case the assets and their deployment method and the main INFRASTRUCTURE blocks – and then moves on to an initial estimate of the hullform dimensions and machinery power. Next the general iterative procedure is employed to work up the design. That document also emphasised that the method outlined is not rigid and aspects of the design thought likely to have a significant impact, or to represent potential risk, needed to be assessed as early as possible. This method was expanded in detail for the Littoral Combat Ship studies discussed in Section 5.4. Sub-Section 5.5.2, which describes the method used in the INEC IFEP studies provides a full description of an important detail of the method that was first conceived during the mothership work but developed in the subsequent studies, namely the need to simplify certain aspects of the design model before numerical iteration. Thus avoiding a divergent iteration where hull size and total weight would increase rapidly with no balance being reached.

**The Design Model**

Figure 5.7 shows the Design Building Block model of the first mothership design, the dock ship. A fully integrated model was used in these studies, in which all modelling and assessment activities were undertaken within a single PARMARINE / SURFCON representation for each variant. This allowed rapid evaluation of changes to the design configuration and sizing algorithms suggested in the design reviews. It also simplified the iterative process, as no data transfer between models of the design was required. Revisions to the design algorithms were carried out using a KCL macro file – a set of instructions generated by the designer that could be executed as a single command from the designer for each of the designs to bring them up-to-date.

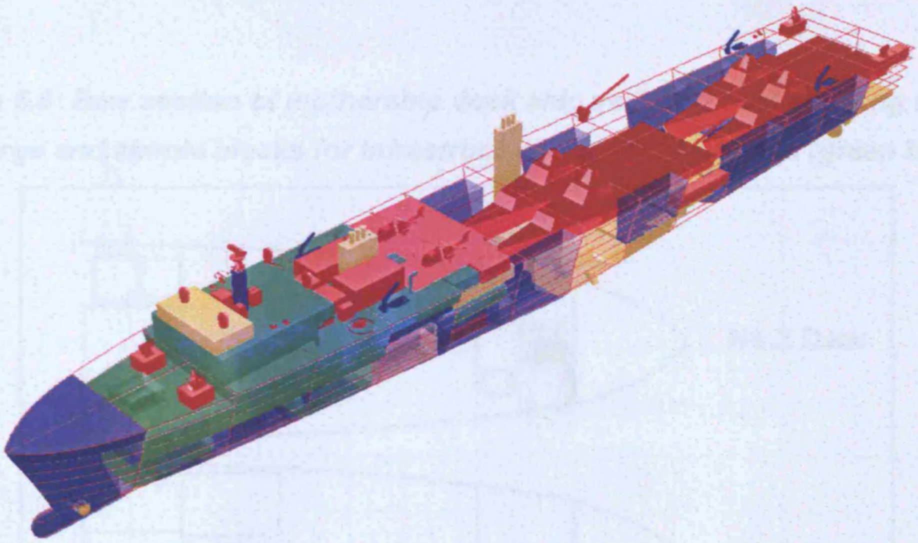


***Figure 5.7: Dock ship mothership model with all Design Building Blocks produced***

Most of the model remained at the "Super Building Block" level, with single large blocks being used to represent areas, such as accommodation and personnel support, rather than modelling individual cabins and interior access. Such a block would typically occupy the space bounded by two decks, two watertight bulkheads and the sides of the ship, as shown in Figure 5.8. Figure 5.9 shows the relevant section of the ship in a 2D General Arrangement drawing. This shows the large blocks used to describe the ship design and the simple cuboid representations of main machinery items in the hull (visible on No 7 deck).

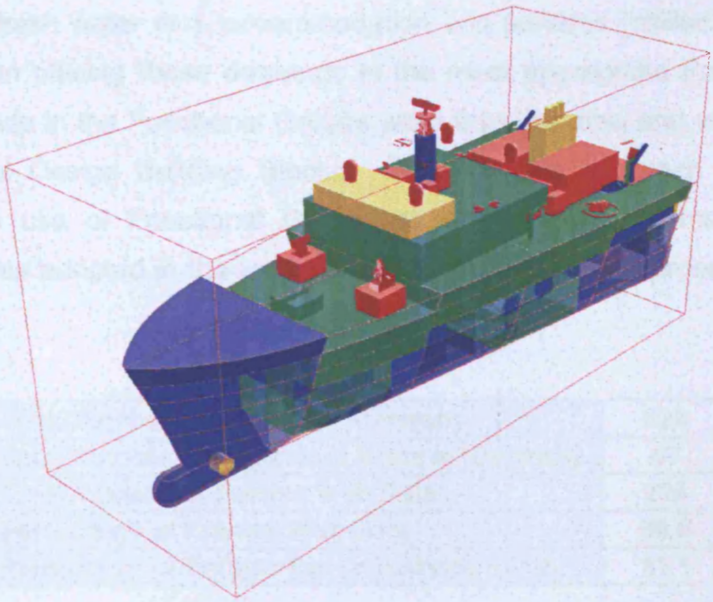


***Figure 5.8: Bow section of mothership dock ship variant model showing use of very large and simple blocks for infrastructure support functions (green blocks)***

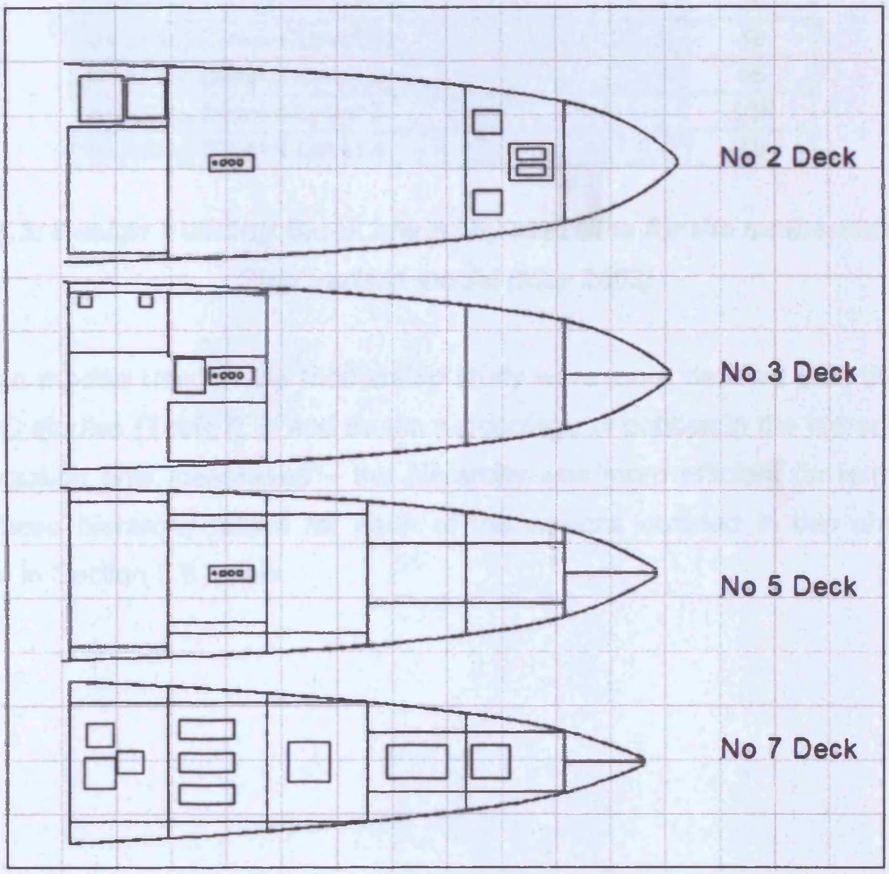



***Figure 5.9: Bow section of mothership dock ship variant model shown in a 2D drawing output file produced by PARAMARINE and viewed in a CAD application***

Each model contained approximately 300 Building Blocks and equipment items. Table 5.3 summarises the use of the blocks for the first mothership design – the dock ship. In this table an additional Functional-Group level block containing the design demands for variables (fuel, fresh water etc), accommodation and services (chilled water etc) was used, rather than placing these demands in the most appropriate Functional Group. The only demands in the Functional Groups were thus the area and volume demands of the individual Design Building Blocks. Although this approach is conceptually opposite to the use of Functional Groups as containers for demand and supply information, it was adopted in the mothership studies to ease the process of review by the design team.

| | |
|---|---|
| **Total Number of Entities in Hierarchy** | 328 |
| **Total Number of Equipment Items in Hierarchy** | 67 |
| **Total Number of Entities With Data** | 226 |
| **Percentage of Entities With Data** | 68.9 |
| **Percentage of Entities For Organisation Only** | 31.1 |

| | |
|---|---|
| **Master Building Blocks** | 1 |
| **Functional Groups** | 5 |
| **Super Building Blocks** | 29 |
| **Building Blocks Level 1** | 59 |
| **Building Blocks Level 2** | 86 |
| **Building Blocks Level 3** | 108 |
| **Building Blocks Level 4** | 40 |

***Table 5.3: Design Building Block hierarchy statistics for the mothership Dock Ship variant model (May 2003)***

The design models used in the mothership study were more detailed than those used in the FSC studies (Table 5.1) and so the percentage of entities in the hierarchy used, for organisation only, decreased – the hierarchy was more efficient (in terms of file-size). These hierarchy tables for each of the designs outlined in this chapter are discussed in Section 5.6 below.

### 5.3.3 Outputs

The mothership designs produced by UCL are described in detail in Appendix 6. Table 5.4 categorises the designs by method of asset deployment and recovery.

| Study | Title | Notes |
|---|---|---|
| 1 | Dock Ship | Assets offloaded by ballasting, e.g. LPD [Ref 12 at Appendix 6] |
| 1a | Command Variant of Dock Ship | Enhanced command of assets |
| 1b | Support Variant of Dock Ship | Enhanced support and maintenance of assets |
| 2 | Heavy Lift Ship | Assets offloaded by ballasting, e.g. Blue Marlin [Ref 13 at Appendix 6] |
| 3 | Crane Ship | Assets offloaded by heavy lift cranes |
| 4 | Fast Crane Ship | Enhanced speed crane ship |
| 5 | Gantry Ship | Assets offloaded by stern gantry, e.g. LASH [Ref 14 at Appendix 6] |
| 6 | Deep Draught Ship | Assets are driven into stern well, no ballasting |
| 7 | SSK Dock Ship | Version of dock ship to carry conventionally powered submarine |

***Table 5.4: Mothership options produced by UCL***

For each of the designs, the final outputs consisted of; a weight breakdown of the vessel, in the NES 163 classification system [*MoD, 1989*], to a 3 digit level; an overview of the design outlining the main features of the configuration; a list of main combat system and machinery items; a discussion of the main design drivers that had been identified and a list of the concerns or problems related to that configuration. The descriptions of the design were illustrated with SURFCON screenshots of the areas of concern or uncertainty in the design.

### 5.3.4 Discussion

The mothership studies required the examination of a concept almost completely unknown to the two design partners (UCL DRC and BMT DSL) and the customer (MoD FBG). Therefore there were no reliable or validated previous designs to draw from. The aim of the study was to gain an idea of the general topology of the solution space and to uncover the design drivers for the mother / daughter concept. This required a tool capable of generating a wide variety of designs that could be readily compared to match the deployment methods identified in the initial brainstorming methods.

The open and transparent nature of the Design Building Block approach and its SURFCON implementation was of great importance in these studies, as it made design decisions clear and auditable. They were open to scrutiny and change so the nature of the design concepts could easily be communicated between the partners in the design team. As just described, this openness allowed significant changes to be made to some design algorithms or features, in some cases during the design review meetings themselves.

There were also other important benefits of flexibility in the design tools; the designs could be modelled to the level of detail needed to provide confidence that the designs were realistic. There was no requirement for all parts of the design to be modelled to the same level of detail, nor was there any limit on the detail that could be added to the design to de-risk a particular feature. This allowed a "naval architectural" balance – one including more than a numerical balance of weight and space demand and supply – to be reached in a short time. A simple example of this variation in detail is shown in Figure 5.9, where the machinery spaces contained Design Building Blocks of diesel generators, uptakes and the largest items of support equipment, while accommodation spaces were simply modelled as large flats.

A more abstract example of this variation of detail levels was first noted in the Type 23-a study, described in Section 4.4, where a process of numerical iteration had been carried out, but the Design Building Blocks for the spaces associated with the scaling algorithms had not yet been placed in the configurational space. In that case, the overall displacement had been assessed, but the design had not been modelled to a uniform level of sub-detail. The overall weight centroid position was at this early stage given by a combination of the positions of the Design Building Blocks and equipment items that had been located in the design configurational space and assumed positions (on a given deck or a percentage of the hull depth) for the more crudely defined items. This allowed stability calculations to proceed to check the practicality of the design, without the need to define all items in detail.

In addition, the flexibility in the design tools meant that the design teams were more confident in their ability to effect changes to the design and assess the consequences, even when the models were effectively complete. This is important in early stage design studies, as should the designer believe that assessing a change will take too long, or will be too difficult to model, then the change is more likely to be left to a second design iteration, so increasing the level of uncertainty in the initial design configuration. This feature also provided confidence in the designer using judgement, as any decision could be readily un-done. Given the lack of similar vessels, incorporating the results of the differing experience of the team-members was vital in this study.

One issue in early stage design that was highlighted in the mothership studies was the applicability of data. The SURFCON models of the motherships typically used the following types of data:

- Simple scaling algorithms from the UCL Ship Design Exercise data book [*UCL, 2001b*], which gave estimates of weight and area for systems and spaces in the infrastructure group, based on overall ship enclosed volume;
- Simple algorithms that scaled to represent a number of separate items, for example the weights and area demands for the accommodation blocks were given by multiplying the values for a single cabin by the numbers of cabins enclosed within a block;
- Point values for payload items whose properties were fixed;
- Geometry related algorithms, which were scaled based on features of the ship configuration (for example the structural weight was based on the size of the ship and superstructure);
- A numerical method, already included within PARAMARINE, was used to estimate the resistance of the hull.

Most of the algorithms and methods used have limits of applicability. For example, the Andersen & Guldhammer method, that was used to estimate the resistance of the hull, has limits based on the shape of the hull, as it is intended for use with high-speed merchantmen. [*Andersen & Guldhammer, 1986*] In the motherships studies, two of the main areas of risk in the calculation methods used were the resistance estimations and details of the structural design, although the identification of likely areas of concern for the latter was greatly aided by the interactive spatial model of the design. Concerns over the applicability of the resistance prediction method to a gantry ship with an unusually shaped stern, or a very high speed vessel indicated a need for more generally applicable estimation tools, perhaps based on simulation, CFD or FEA.

A related issue, which was highlighted in the mothership study, was the extent to which the links between features in the design could be explicitly stated without having first produced a configurational model. Although a detailed parametric survey of the hullform shape was not undertaken in these studies, a limited examination of the effect of changing overall parameters, such as prismatic coefficient, was carried out. It was found that in those designs requiring a lot of ballast, such as the dock vessel (the first design), making the ends of the ship finer led to a design with insufficient ballast tankage to submerge sufficiently. This was entirely due to the configuration of the vessels for the following reasons:

- Flare on the hull increases watertight volume above the waterline, thus increasing the ballast needed to submerge this volume and increasing the draught to that required for daughter craft loading;
- Machinery spaces, unlike ballast, have to be certain shapes, in addition to being at a location, thus the machinery spaces occupied the most voluminous parts of the underwater hull nearer amidships, leading to the ballast being at either end of the ship where the available volume was more strongly affected by changes in hull shape.

This is an example of emergent relationships within a ship design that would not be immediately apparent from a purely numerical model, particularly a parametric scaling model where all relationships are defined explicitly in its construction. Although the model and procedure used in the motherships studies was effective at illustrating this type of relationship, they were not explored in any greater depth with the use of sensitivity studies etc, due to both the limited time available and the nature of the study, which only sought to evaluate the overall nature of the solution space and not its detail.

## 5.4 UNCONVENTIONAL VESSELS: THE NICOP LCS

### 5.4.1 Aims of the Study

The aim of this project sponsored by the US Navy Office of Naval Research (USN ONR) was to evaluate the effectiveness of the Design Building Block approach, as incorporated in the PARMARINE / SURFCON tool, for the early stage design of advanced naval ships. This evaluation covered the method, the tool and the detailed procedure for its utilisation.

To perform this evaluation, a trimaran vessel was designed to meet the threshold requirements for the US Navy's Littoral Combat Ship (LCS) programme, as laid out in the LCS Requirements Document [*LCS, 2003*]. These imply an advanced vessel, capable of accommodating a large modular payload bay, with shallow draught and high speed permitting operations close to the shore, within the range of enemy shore defences. This study was summarised in a paper presented at the RINA Warships

2006 conference, [*Andrews & Pawling, 2006*] at Appendix 8. The following sections build on this paper, providing sufficient detail for the discussion that follows.

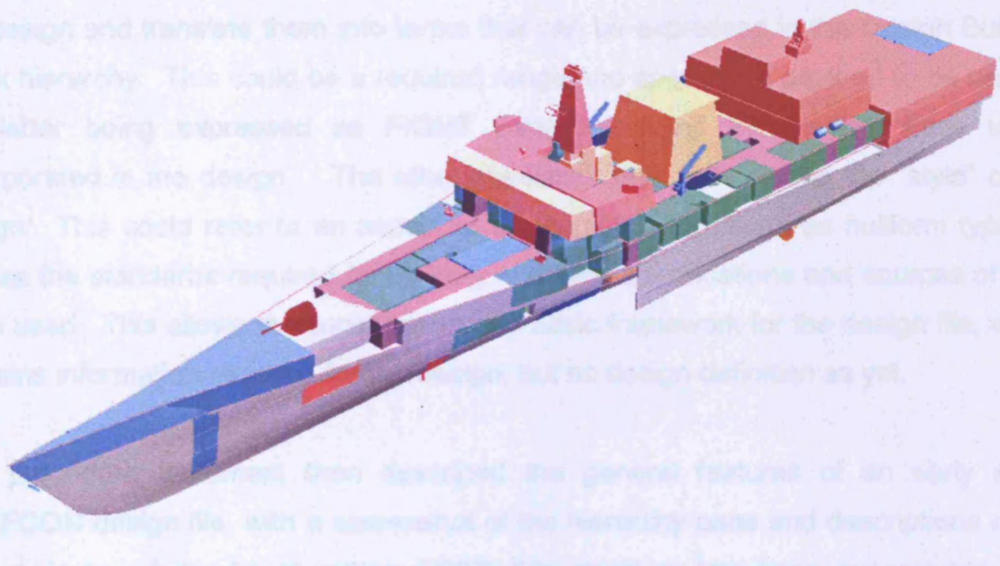


***Figure 5.10: Final UCL LCS trimaran design, showing Design Building Blocks (April 2004)***

## 5.4.2 Procedures Used and the Model of the Design

### The Procedure

This project used a detailed procedure, written at the request of to the United States Naval Surface Warfare Centre Carderock Division (NSWCCD), which explained an approach to designing Trimarans in SURFCON/PARAMARINE. The starting point for this procedure was the document provided to BMT DSL for the mothership studies described in Section 5.3. An initial version of the trimaran procedure was given to NSWCCD in July 2003 and a more detailed version with illustrations was sent via e-mail on the 23rd of October of that year.

This more detailed version is at Appendix 9. It describes the four stages of the Design Building Block approach shown in Table 3.4 with reference to the suggested layout of the design file. Each of the stages is summarised below.

## Preparation Stage

One of the main objectives of this initial stage is to identify the capabilities required of the design and translate them into terms that can be expressed in the Design Building Block hierarchy. This could be a required range and speed or a payload to be carried, the latter being expressed as FIGHT Design Building Blocks that have to be incorporated in the design. The other significant task is to outline the "style" of the design. This could refer to an aspect of the configuration, such as hullform type, as well as the standards required for stability, systems specifications and sources of data to be used. This allows the construction of a basic framework for the design file, which contains information required for the design, but no design definition as yet.

The procedure document then described the general features of an early stage SURFCON design file, with a screenshot of the hierarchy pane and descriptions of the main objects used. As of writing (2007) this structure has been superseded by a template layout constructed by GRC after consulting the candidate. This template file contains the main features described in the 2003 procedure, which divided the design file hierarchy into the following items:

**a) Definitions**

Items that will be used many times in the design, such as items of equipment, weight and space breakdown systems, fluid densities and loading conditions.

**b) Model**

The synthesis of the new design, which itself was divided into:

- Building Blocks – the Design Building Block hierarchy;
- Dimensions and Hullform Coefficients – A centralised folder containing all numerical values used to describe the configuration of the design, e.g. length, beam, deck locations etc;
- Guidance – Visual guidance objects used to assist the designer in understanding the overall structure of the design and placing blocks e.g. datum planes;
- Envelope – The encompassing envelope of the design including the hull and superstructure;
- Margins – Another centralised folder containing controls all margins used in the design (percentage, fractional and absolute values as required).

**c) Audit**

Numerical auditing of the model of the design for any of the numerical properties it contains, including weight, area, accommodation and services.

**d) Analysis**

More detailed analyses of the design making use of specialist objects within PARAMARINE, such as powering, strength and damaged stability.

**e) Results**

Objects providing formatted outputs of the design that can be exported for use in other software (e.g. drawings for use in other CAD tools and tabular reports for use in spreadsheet applications)

## Major Feature Design Stage (MFDS)

In this stage, the initial design is generated and the overall configuration of the design is outlined. This stage allows the identification of the main design drivers and the achievement of an initial numerical balance. In the outline process, the MFDS contained the following steps:

**a) Initial Sizing**

Based on FIGHT blocks and the major MOVE blocks.

**b) Initial Main Hull Hullform Generation**

The generation of an initial main hull with the dimensions indicated by the initial layout.

**c) Resistance Estimation for Main Hull**

Using appropriate resistance estimation tools in PARAMARINE e.g. Series 64 for trimaran main hull.

**d) Service Load and Tankage**

These would be estimated and the main tank groups modelled.

**e) Initial Bulkhead Placing**

At the earliest stages this would tie in bulkheads with major configurational features, such as superstructure blocks and machinery spaces

**f) Assessment of configuration**

**g) Side Hull Design**

The generation of an initial side hull, based on intact stability requirements for waterplane area distribution

**h) Superstructure Design**

The generation of rough blocks of superstructure

**i) Numerical Balance**

The iteration of the design so that the current weight is within 5% of the hullform design displacement and the required internal volume is within 5% of the available volume.

**j) Overall Assessment**

The two "Assessment" actions in this case denote convenient points in the design development where the overall design is assessed for balance, performance and feasibility. One of the fundamental aspects of SURFCON is the provision of an integrated numerical and spatial model, so these assessments could be carried out at any time, as long as the model contains the information needed to make the assessment (e.g. hullform for resistance estimation). At this early stage in the design process, the design could be assessed for the following:

- Propulsive power demand ≤ installed propulsive power
- Fuel required ≤ fuel supplied
- Generator demand ≤ generator supply
- Internal volume required ≤ internal volume supplied
- Weight = displacement
- Upperdeck dimensions = required dimensions
- Intact stability required ≤ intact stability achieved
- Hydrostatics ≈ adequate trim by stern

The concept of "Numerical Balance" in this process requires explanation. The process document was drawn up assuming the existence of a comprehensive database of ship design algorithms and data similar to that used in the UCL MSc Ship Design Exercise [*UCL, 2001b*]. This step in the process would see this standard data set used to generate a more refined displacement estimate for the vessel, to replace that used in the initial hullform generation. The additional weights for systems and spaces would be located at an assumed centroid and any required area would not be allocated yet (e.g. the Design Building Blocks would have weight and location but not dimensions). This issue is covered further in Chapter 6.

### Super Building Block Design Stage (SBBDS)

This stage refines the definition of the design by incorporating the secondary drivers on the configuration. In this stage, the Super Building Blocks in all of the Functional Groups would have been considered. Three main activities were identified as occurring in the SBBDS:-

- Design refinement;
- Parametric Survey;
- Assessment.

The activities of design refinement and assessment refer to the addition of Super Building Blocks representing all the main functions of the design, including infrastructure functions, such as accommodation and supporting functions for the MOVE and FIGHT Super Building Blocks placed at the MFDS.

The Parametric Survey undertaken in this stage is a study of the effects of varying hullform shape parameters on the overall performance of the vessel. Including a numerically based parametric survey, at this stage, allows the impact of changes on spatial features, such as tankage and machinery arrangements, to be assessed. It is also possible to examine alternative configurations of SBBs that could improve the design's performance (such as moving machinery spaces to the upperdeck in an electric ship). In addition to these numerical surveys, alternative system topologies or styles should be considered at this stage, such as the addition of light-weight structures, separate deck houses or breaks in the upperdeck.

### Design Building Block Design Stage (DBBDS)

In this final stage the design is developed to the required level of detail. This will depend on the nature of the study (e.g. a high-level multi-design study, such as the motherships, or more detailed single design, such as that presented here) and the degree of perceived risk or innovation in the design solution. The DBBDS consists of an iterative process of improvement. There are four main methods that were used to structure each stage of the refinement:

a) Commence with those blocks causing design unbalance or conflict;
b) Select the largest blocks before tackling the smallest blocks;
c) Select the most constrained blocks before the least constrained blocks;
d) Start with the FLOAT blocks, then the MOVE blocks, followed by the FIGHT blocks and finally the INFRASTRUCTURE blocks.

### The Design Model

This study used an integrated model of the design, with most modelling and assessment of the design's performance undertaken within a single file and software environment. The following numerical assessments were performed using the PARMARINE software:

- Resistance and powering;
- Stability, intact and damaged in deep and light loading conditions;
- Estimates of structural weight using initially a structural weight density, then an equivalent thickness of material spread over the relevant areas;

- Space (volume or area, depending on block) required and available;
- Weight and displacement balance;
- Electrical load and generating capacity;
- Chilled water demand and supply;
- Fresh water demand and supply.

The only exception to this use of a single file was the second cycle of structural weight estimation, where an Excel spreadsheet generated by Fellows, for the teaching of surface warship structures in the UCL NAME degree was used [*Fellows, 2000*]. The integrated analysis tools allowed rapid evaluation of the effects of changes to the design configuration without requiring export to separate analysis tools.

The LCS synthesis model contained features not previously used in SURFCON designs. Two that made significant use of the integrated spatial model were;

- Structural weight estimation based on the current configuration. Equivalent thickness values for steel and aluminium structures were calculated using the spreadsheet, thus giving an area density for each type of structure. These were then multiplied by the appropriate areas measured directly from the spatial model (e.g. deck areas, or the area of the hull side). Once this part of the model was constructed, the only designer interaction required was to update the thickness values when necessary.
- Void volumes based on hullform shape. The UCL SDE data contains an assumption that void volume is 2.5% of the gross enclosed volume. This is derived from monohull frigates of approximately 4000-5000te displacement and was of unknown applicability to multihulls, or even vessels other than warships. In the LCS study, the major void spaces were modelled with Design Building Blocks so that both the supply and demand values for void spaces were equal to the current volume. This ensured that audits of available and required volume maintained consistency and allowed the amount of void space in the design to be directly monitored. Figure 5.11 shows all void spaces in the model and Figure 5.12 shows the forward part of the vessel with Building Blocks from all Functional Groups visible.

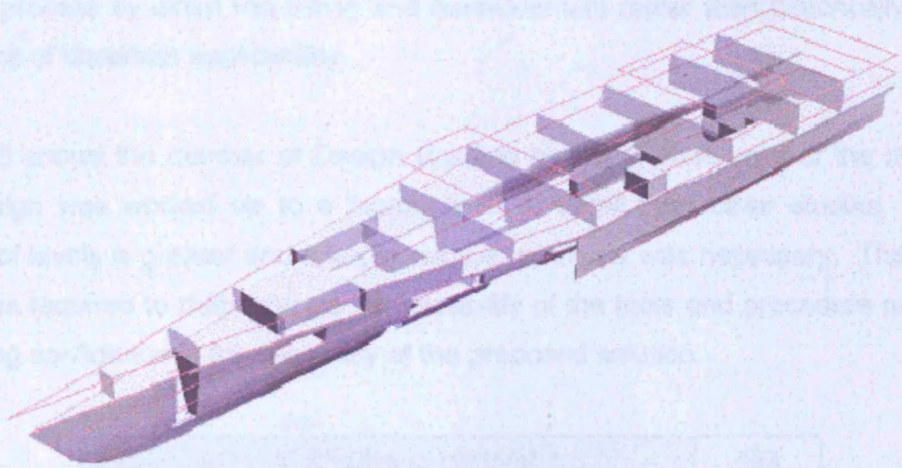


***Figure 5.11: Void volumes in the FLOAT group***

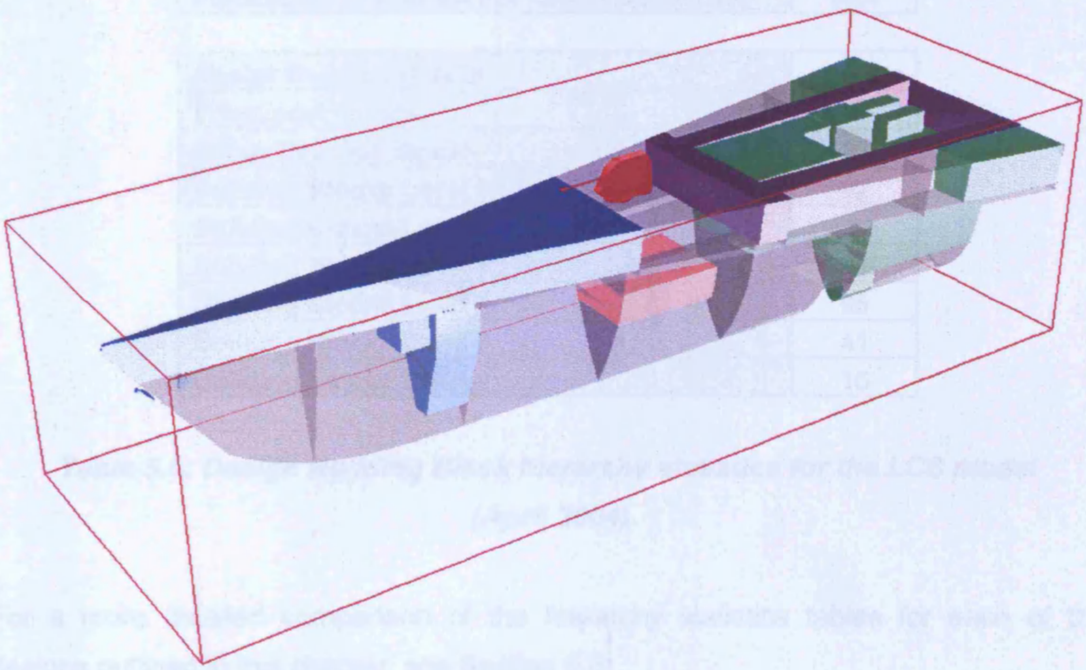


***Figure 5.12: Forward part of the LCS design showing void spaces as semi-transparent with mooring spaces forward (blue), 57mm gun (red) and personnel support space (green)***

In this design the void volume was high – approximately 19% of the gross enclosed volume. The void spaces were found to be driven by functional needs, as follows. Spaces in the side hulls provided buoyancy for seakeeping and damaged stability, while those forward in the main hull arose from the need for a long narrow hull to reduce wavemaking resistance at high speed. Void spaces aft were a consequence of the multiple shaftlines in the confined hull. The flexible, integrated spatial model was vital in identifying these design details and permitting their incorporation into the iterative process by direct modelling and measurement rather than historically derived algorithms of uncertain applicability.

Table 5.5 shows the number of Design Building blocks in each level of the hierarchy. This design was worked up to a higher level of detail than other studies, thus the number of levels is greater and a larger number of blocks was necessary. This level of detail was required to demonstrate the capability of the tools and procedure as well as increasing confidence in the feasibility of the proposed solution.

| | |
|---|---|
| **Total Number of Entities in Hierarchy** | 493 |
| **Total Number of Equipment Items in Hierarchy** | 105 |
| **Total Number of Entities With Data** | 343 |
| **Percentage of Entities With Data** | 69.6 |
| **Percentage of Entities For Organisation Only** | 30.4 |

| | |
|---|---|
| **Master Building Blocks** | 1 |
| **Functional Groups** | 4 |
| **Super Building Blocks** | 25 |
| **Building Blocks Level 1** | 82 |
| **Building Blocks Level 2** | 112 |
| **Building Blocks Level 3** | 118 |
| **Building Blocks Level 4** | 95 |
| **Building Blocks Level 5** | 41 |
| **Building Blocks Level 6** | 15 |

***Table 5.5: Design Building Block hierarchy statistics for the LCS model (April 2004)***

For a more detailed comparison of the hierarchy statistics tables for each of the designs outlined in this chapter, see Section 5.6.

### 5.4.3 Outputs

The main output from this study was a design report describing the trimaran LCS design, the procedure used and major conclusions. This report was subsequently summarised in the RINA Warships 2006 paper, see Appendix 8. The description of the vessel produced included images showing significant arrangement features, graphs of GZ curves for intact and damaged stability cases and a 2D General Arrangement drawing, produced with significant editing in a separate CAD package. The log kept during the design process was used to produce Figure 5.13, which illustrates the progression of the design from the Major Feature Design Stage through the Super Building Block and Building Block Design Stages to the final balanced design. This diagram does not show every stage of the design process, only the most significant iterations of the design.

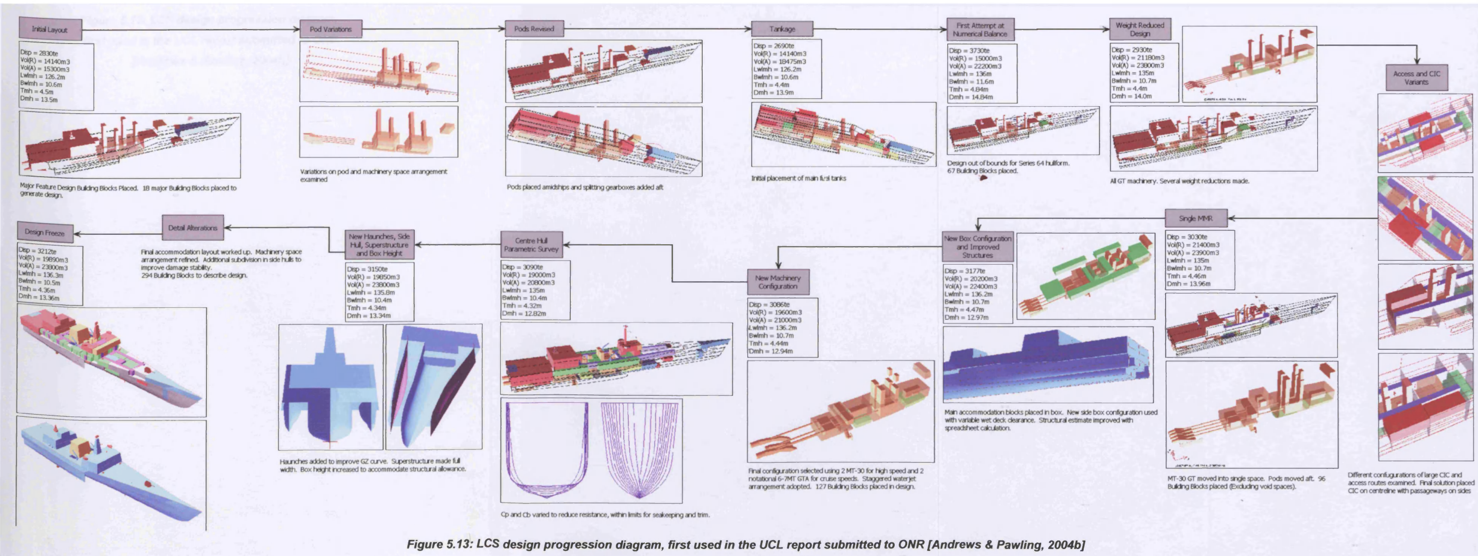



***Figure 5.13: LCS design progression diagram, first used in the UCL report submitted to ONR [Andrews & Pawling, 2004b]***

Although Figure 5.13 summarises the total design process, it concentrates on the Major Feature, Super Building Block and early Design Building Block design stages, as these stages involved the definition of the overall style of the design. The figure shows how the initial design configuration was generated from a small number of simple Super Building Blocks and hows even at the early stages, alternative configurational styles were investigated. Significant changes to these styles were also made later in the design, particularly to the machinery layout, as the more detailed model revealed a potential for interference between functional spaces in the design (uptakes and accommodation). Figure 5.13 also indicates that several weight reduction exercises were undertaken in this study, in the form of design reviews, where different technological solutions, such as composite structures and shafts, were introduced into the design in order to reduce the weight and reach the high speed required. The flexibility of the tool permitted the relatively limited data available on these technologies to be incorporated into the model.

Table 5.6 summarises the increase in the number of Design Building Blocks and Equipment Items used to define the design at each stage of the process.

| | |
|---|---|
| **Start of Major Feature Design Stage** | 18 (in 11 discrete SBBs and grouped BBs) |
| **End of Major Feature Design Stage** | 47 (in 15 discrete SBBs and grouped BBs) |
| **End of Super Building Block Design Stage** | 110 (in 33 discrete SBBs and grouped BBs) |
| **End of Building Block Design Stages (Design freeze)** | 343 (in c. 25 SBBs and 11 grouped BBs) |

***Table 5.6: Summary of the level of detail in the UCL LCS design stages***

## 5.4.4 Discussion

As is discussed in Annex 7, this study led to the production of a viable concept trimaran solution to the LCS requirements. The use of an integrated model of the design featuring a graphical, numerical and logical representation of the current configuration was found to provide a depth of understanding of design drivers and interactions that could not otherwise have been obtained. This also assisted in the identification of areas of uncertainty and technical risk. Examples of such emergent relationships and features, which would not be discovered without this type of model, include the crucial aspect of transom configuration, shown in Figure 5.14, the extensive void volumes highlighted in Figure 5.11 and the limitations on the overall configuration created by the large machinery spaces with horizontal and vertical interactions (drive shafts and trunking, respectively). A summary of the main design drivers identified in the study is given in Appendix 8. The information rich, interactive graphical interface was particularly important in assisting the designer in identifying these, mainly configurational, drivers.

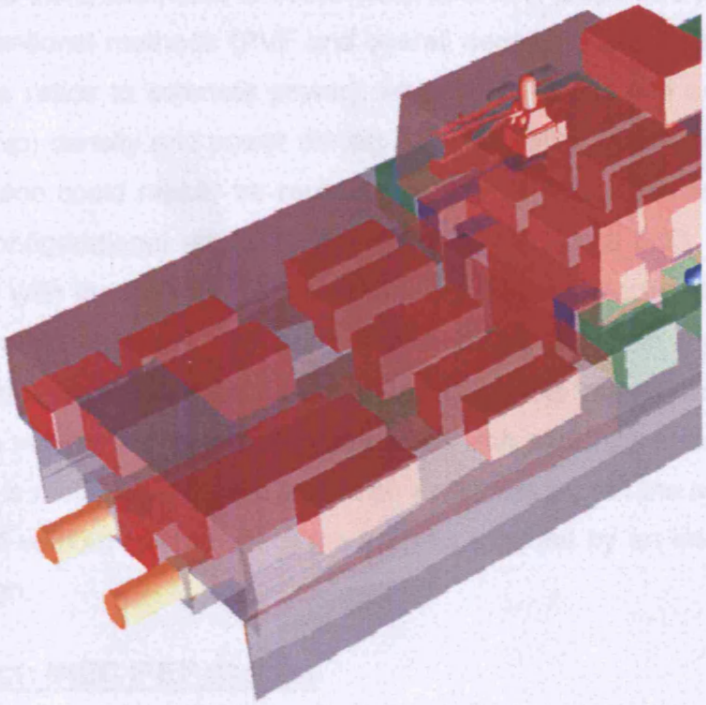


***Figure 5.14: Aft view of the LCS design showing the payload bay over the stern in the box structure and the waterjets in the main hull.***

This study also demonstrated the ability of the new tool to be used in the design of multihull vessels, although a modification to the procedure was necessary to include the sizing process of the sidehulls. This flexibility is also illustrated in the weight reduction exercises, as it was a simple task to change the weight estimation algorithms to reflect alternative technologies and then to assess the impact on the overall vessel design. This does, however, raise the issue of how to assess the applicability and accuracy of such estimates, particularly for radical designs. In the case of the LCS studies, the hullform was developed from a well established series [*Yeh, 1965*] and the weight reducing technologies were implemented as coefficients, derived from the references in Appendix 8, applied to the UCL MSc SDE algorithms. In addition to applicability, there is also the issue of completeness. The LCS used a propulsion system not included in the UCL MSc SDE data book and this introduced the possibility for features, required for the radical solution to be practical, to be omitted from the design unless the designer remembers to include them. In the case of the LCS study, however the solutions adopted were sufficiently well-understood to make such omissions unlikely, but this issue is discussed further in Chapter 6.

Although the choice of a radical trimaran topology had been made at the start of the design process, the initial estimates of overall displacement, propulsive power etc were made using conventional methods (PVF and overall density to estimate displacement and power / tonne ratios to estimate power), which utilised corvette and frigate type ship values for (ship) density and power density. The flexibility of the tool and process were such that these could rapidly be replaced with more accurate values developed from the latest configurational model of the design. As Figure 5.13 shows, as the design developed with the addition of further Design Building Blocks, the overall ship size and configuration changed. At each of the stages shown in Figure 5.13, the design was incomplete, but with sufficient detail to enable numerical analysis and designer decision making. This can be contrasted with a purely numerical method, where the design is numerically "complete" at an earlier stage, but the algorithms used must be assessed without the benefit of the insights afforded by an integrated spatial model of the design.

## 5.5 Design Impact: INEC IFEP Studies

### 5.5.1 Aims of the Study

These studies examined the implications of the adoption of an Integrated Full Electric Propulsion (IFEP) machinery fit on the configuration of modern warships. The designs produced were summarised in a paper presented at the International Naval Engineering Conference (INEC) in Amsterdam in March 2004 [*Andrews, Greig & Pawling, 2004*]. This paper is included as Appendix 10. The concepts behind IFEP and its benefits and development have been discussed in a number of papers and this is summarised in Appendix 10. The specific issue under examination in these studies was the claim that the adoption of IFEP would "release the ship designer from the tyranny of the shaft line", so allowing the adoption of a wider range of machinery and ship configurations.

### 5.5.2 Procedures Used and the Model of the Design

To explore the configurational related issues of the adoption of IFEP, a series of designs was developed, with different machinery architectures but otherwise with identical general ship equipment and performance demands. Six designs were produced, working from a baseline with mechanical transmission and gradually increasing the IFEP sophistication of the propulsion solution. The machinery configurations used for these designs are summarised in Table 5.7.

| Variant | Prime Movers | Transmission | Motors |
|---|---|---|---|
| **Option 1 Baseline** | 2 x WR21 ICR GT & 4 x 1.5MW ICR GTA (hotel only) | Mechanical | (Gearbox) |
| **Option 2 Baseline + IFEP** | 2 x WR21 ICR GTA, 3 x 4.9MW GTA & 1.2MW Battery | Electrical, 6.6Kv | 2 x 30MW AIM |
| **Option 3 IFEP + Pods** | 2x WR21 ICR GTA, 4.9MW GTA, 1.5MW ICR GTA & 1.2MW Battery | Electrical, 6.6Kv | 2 x 30MW PMM, in pods |
| **Option 4 Distributed Prime Movers** | 2x WR21 ICR GTA, 4.9MW GTA, 1.5MW ICR GTA & 1.2MW Battery | Electrical, 6.6Kv | 2 x 30MW PMM, in pods |
| **Option 5 Small Prime Movers** | 4x 13.3MW ICR GTA, 2 x 1.5MW ICR GTA & 1.2MW Battery | Electrical, 6.6Kv | 2 x 30MW PMM, in pods |
| **Option 6 Vertical GTAs** | 2x WR21 ICR GTA, 4.9MW GTA, 1.5MW ICR GTA & 1.2MW Battery | Electrical, 6.6Kv | 2 x 30MW PMM, in pods |

***Table 5.7: Machinery configurations for the six UCL IFEP designs***

The baseline design was developed to represent a multi-role vessel fulfilling the roles specified for the FSC, so was similar in overall size and weapons to the monohull Baseline 5 design that had previously been studied (Section 5.1). Certain payload items were placed in the design to ensure a range of "representative" spatial interactions and features that might be found on modern warships. These were:-

- Medium Calibre Gun (MCG) placed forward;
- Large Vertical Launching System (VLS), split into blocks forward and amidships;
- Inner Layer Missile System (ILMS), split forward and aft;
- Forward superstructure, containing large Operations Room and computer spaces;
- Large foremast supporting Multi–Function Radar (MFR) and aft mast supporting communications gear;
- Upperdeck launchers for Anti – Shipping Missiles (AShMs);
- Double hangar for Merlin helicopter / 15 tonne class helicopter;
- Large crane for handling Special Forces (SPECFOR) boats;
- Magazine Torpedo Launch System (MTLS) in the hull under flight deck and launching through hull side;

- Towed Array Sonar (TAS), in the hull with quarter deck deployment.

In addition, certain features of the INFRASTRUCTURE group were chosen to be representative of modern warship design:-

- Cabin based accommodation leading to Increased accommodation space and space for access routes;
- No accommodation below the damage control deck (No 2 deck).

These features, incorporated into the baseline and thus all variant designs, defined the overall spatial "style" of the design and added certain interactions, such as the conflict between VLS, machinery spaces and accommodation in the midships area of the ship. The choice of features to incorporate was based on the candidate's previous experience of early stage ship concept design in the UCL Ship Design Exercise.

### The model

The Design Building Block model used in these studies was completely integrated – all modelling and assessment of the design took place inside the PARAMARINE / SURFCON software model of the design. The model included sufficient detail and characteristics to allow the assessment of the following features:-

- Total ship weight and displacement balance;
- Space (volume or area, depending on block) required and available;
- Resistance, powering and Dieso tankage capacity;
- Electrical load and generating capacity;
- Chilled water and fresh water generation demand and supply;
- Tankage demand and supply for fresh water, lubrication oil, sewage and aviation fuel;
- Stability compliance with the NES 109 [*MoD, 2000*] criteria, for intact and damaged cases, including trim in the intact condition.

Table 5.8 shows the number of Building Blocks at each level of the hierarchy for this stage. Most of the design was modelled at a very simple level of definition, with large Building Blocks representing, for instance, "flats" of multiple accommodation cabins. However, the main and auxiliary machinery spaces were modelled in more detail, with equipment such as the main salt water pumps and compressors modelled in addition to the prime movers (as this was the focus of the studies). Figure 5.15 shows the aft main and auxiliary machinery spaces of the baseline design, illustrating the placement of support equipment in the auxiliary machinery space and the prime movers with uptakes and downtakes in the main machinery space.

| | |
|---|---|
| **Total Number of Entities in Hierarchy** | 398 |
| **Total Number of Equipment Items in Hierarchy** | 133 |
| **Total Number of Entities With Data** | 276 |
| **Percentage of Entities With Data** | 69.3 |
| **Percentage of Entities For Organisation Only** | 30.7 |

| | |
|---|---|
| **Master Building Blocks** | 1 |
| **Functional Groups** | 4 |
| **Super Building Blocks** | 31 |
| **Building Blocks Level 1** | 90 |
| **Building Blocks Level 2** | 124 |
| **Building Blocks Level 3** | 94 |
| **Building Blocks Level 4** | 32 |
| **Building Blocks Level 5** | 22 |

***Table 5.8: Design Building Block hierarchy statistics for the baseline model of the INEC IFEP studies (April 2003)***

The hierarchy tables generated for each of the designs outlined in this chapter are discussed in Section 5.6.

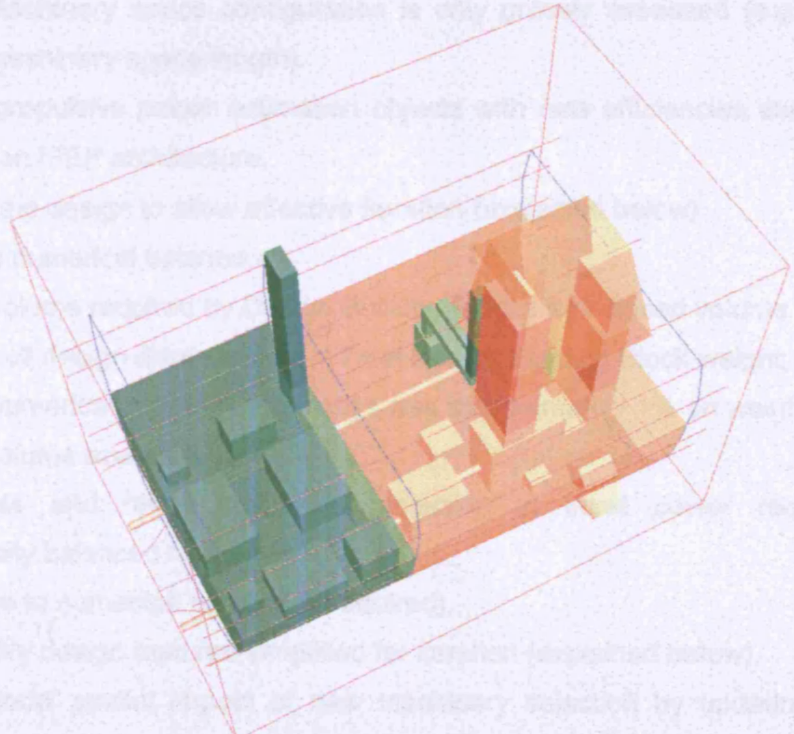


***Figure 5.15: Aft auxiliary space (left) and main machinery space of the baseline design of the IFEP studies***

## The Procedure

The baseline design was developed using the general procedure for monohull design in SURFCON that had been established in the earlier work (i.e. the Type 23-a and mothership studies, Sections 4.3 and 5.3). The development of the IFEP variants used a specific overall process (drawn up on the 28th of October 2003), which is outlined below. This process iterated the design around the machinery selection, the ship configuration and the required propulsion power. The overall performance of the vessel was assessed following the numerical balancing operations and after each variant design was assessed and balanced at the Super Building Block level of detail, it was then modelled to the same level or detail as the baseline. The process was summarised in the INEC 2004 paper (Appendix 10), but is explained in more detail in the following eleven steps:

1. Starting point
    a. Baseline design assessed and balanced in; speed, stability, space, weight and layout.
2. Machinery blocks exchanged by new IFEP configuration, assuming the same propulsive and hotel power requirements as for the baseline design.
    a. This affects items in the MOVE and INFRASTRUCTURE Functional Groups;
    b. Machinery space configuration is only grossly assessed (e.g. changes in machinery space length).
3. Update propulsive power estimation objects with new efficiencies associated with the chosen IFEP architecture.
4. Simplify the design to allow effective iteration (explained below).
5. Iterate to numerical balance:-
    a. Volume required by Design Building Blocks ≤ Enclosed volume available;
    b. Hull design displacement = Total Design Building Block weight;
    c. Numerical balance in this case was approximately 1% on weight and 1% on volume and area;
6. Re-assess and refine machinery selection to meet power requirement of numerically balanced hullform.
7. Re-iterate to numerical balance (if required).
8. De-simplify design features simplified for iteration (explained below).
9. Assess local spatial impact of new machinery selection by updating machinery spaces at the level of detail shown in Figure 5.15.

10. Assess overall configurational impact on the rest of the design by working up the layout at the Super Building Block level of detail, commensurate with the level of detail in the baseline (unless more detailed studies are required).
11. If the overall dimensions need to change to accommodate the new layout, then return to step 4 for numerical iteration.

This procedure is shown in schematic form in Figure 5.16 below. The three main iterative loops used are shown using different colours. These loops occur due to three sources of change:

a. Change of the machinery architecture to the selected configuration for study (BLUE iteration loop)
b. Change in overall propulsive powering requirements to meet the required speed due to the different efficiency of the new machinery configuration and changes in overall displacement (GREEN iteration loop)
c. Changes in overall dimensions (and displacement) due to configurational aspects revealed by the process of updating the rest of the design to accommodate the new machinery selection (RED iteration loop)

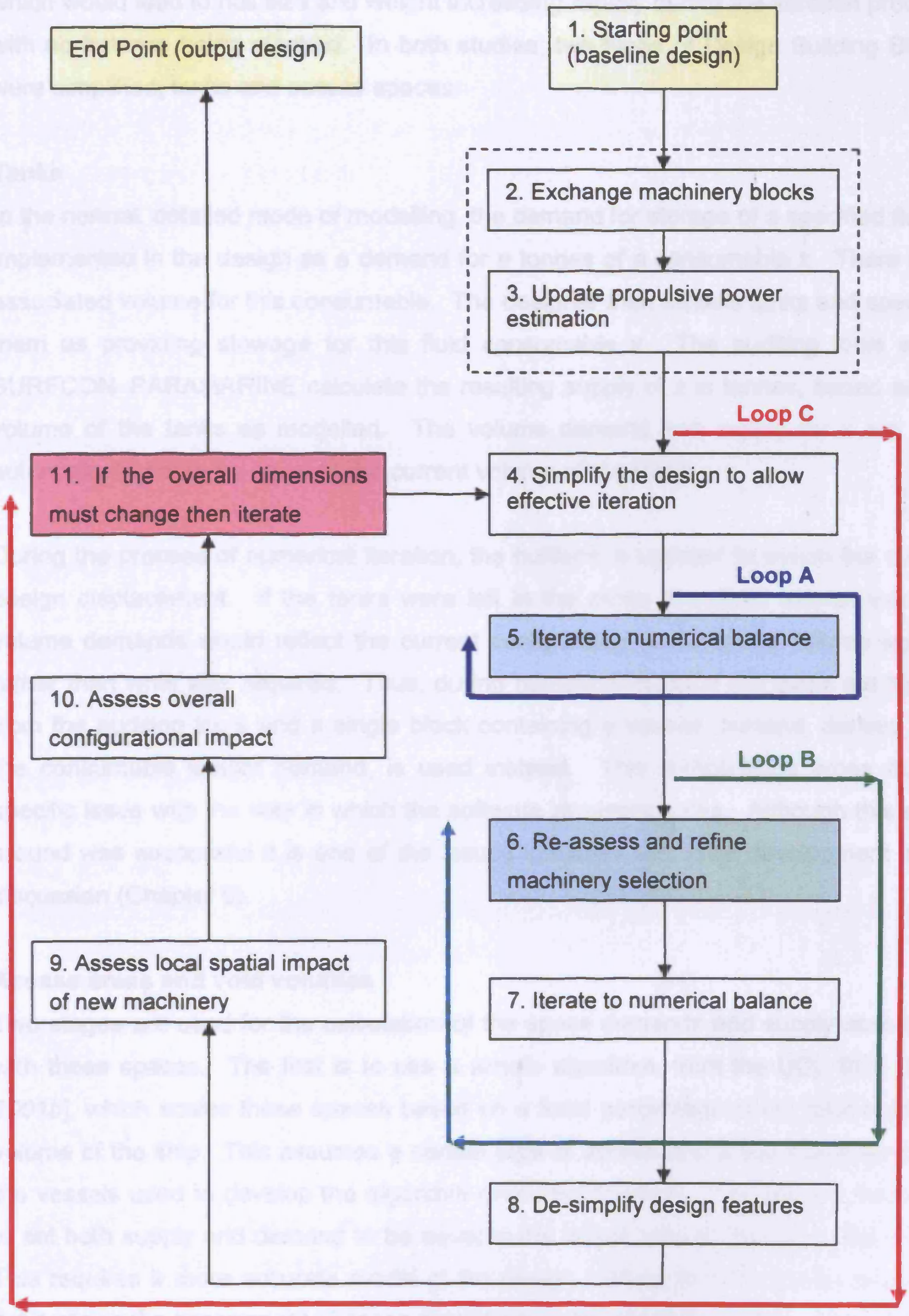



***Figure 5.16: Iterative procedure used to develop the IFEP variants from the balanced baseline design***

As indicated above, the design model was simplified before numerical iteration. As stated in Subsections 5.3.2 (Mothership procedure) and 5.4.4, (LCS discussion), this simplification was a simple approach used to prevent a divergent iteration occurring, which would lead to hull size and weight increasing rapidly during the iteration process, with no balance being reached. In both studies, two types of Design Building Blocks were simplified, tanks and access spaces:

**Tanks**

In the normal, detailed mode of modelling, the demand for storage of a specified fluid is implemented in the design as a demand for *n* tonnes of a consumable *x*. There is no associated volume for this consumable. The designer then models tanks and specifies them as providing stowage for this fluid consumable *x*. The auditing tools within SURFCON–PARAMARINE calculate the resulting supply of *x* in tonnes, based on the volume of the tanks as modelled. The volume demand and supply for *x* are both automatically set to be equal to the current volume of the tanks.

During the process of numerical iteration, the hullform is updated to match the current design displacement. If the tanks were left in the mode described above, then the volume demands would reflect the current configuration (actually the volume supply) rather than what was required. Thus, during numerical iteration the tanks are hidden from the auditing tools and a single block containing a volume demand, derived from the consumable weight demand, is used instead. This complication arose from a specific issue with the way in which the software assesses tanks. Although this work-around was successful it is one of the issues identified for future development in the discussion (Chapter 6).

**Access areas and void volumes**

Two stages are used for the calculation of the space demands and supply associated with these spaces. The first is to use a simple algorithm, from the UCL SDE [*UCL, 2001b*], which scales these spaces based on a fixed percentage of the total enclosed volume of the ship. This assumes a certain style of access and a hull shape similar to the vessels used to develop the algorithm (monohull frigates). The second method is to set both supply and demand to be equal to the actual spaced defined in the model. This requires a more accurate model of the design, with all access spaces modelled, but it allows the assessment of space requirements for any configuration.

As with the tanks, making the volume and area demands dependent on the current configuration presents the possibility of incorrect figures being generated by configurations that may only temporarily exist during the process of numerical iteration. Although the overall design process would later correct for this by changing the local spatial style of the design (shape of fuel tanks etc), unnecessary numerical iterations could be required by the correction. The solution is to switch these Design Building Blocks to use a single algorithm for area or volume demand, based on the overall size of the ship but with a correction applied as required to make this algorithm more suitable for the overall design under assessment (e.g. increasing access areas in a double-passageway configuration).

### 5.5.3 Outputs

As the objective of these studies was not to assign numerical costs to the adoption of IFEP, the results produced were in the form of the descriptive information (subsequently included in the INEC 2004 paper (Appendix 10)) and the associated presentation. These included descriptions of the ship designs, illustrations of the spatial elements of the machinery configurations and their impact on the overall configuration together with a summary chart of ship dimensions, displacement and propulsive power, which could be used to compare the overall ship impact resulting from the progressive changes in equipment. In addition, tables were produced outlining the main design drivers for each variant. These statements provided details on the extent of the machinery spaces, weight and layout of high voltage cables, hullform and stability considerations and the interactions revealed between spaces and equipment for the MOVE function and the other spaces within the vessel. The generation of this type of descriptive data indicates the utility of an integrated spatial model of a ship design to assist in the process of understanding the impact on the whole ship of various design choices (in this case associated with the style and novelty of the propulsion and power generation system).

### 5.5.4 Discussion

In the INEC IFEP studies, the Design Building Block Approach was used to investigate a significant change in the style of a design. This differed from the nature of the mothership studies (Section 5.3) in that the IFEP designs were all variants developed from a common baseline. In such comparative studies, consistency of error is generally more important than absolute accuracy and consistency between models was maintained through the use of a common baseline and the KCL macro based system of updating multiple designs with new information that had been introduced in the mothership studies.

However, this concept of permissible but consistent error cannot be universally applied, even in early stage design, if there are radical features to be included in the design. These stylistic decisions require particular attention and detailed modelling, both to understand the interactions with the rest of the design and to increase confidence in the practicality of any proposed arrangement. In the IFEP studies, the Design Building Block approach and SURFCON tool showed themselves to be flexible and capable of accommodating different levels of detail in the same model. The machinery spaces were modelled at a higher level of definition than the rest of the ship. This would have been more difficult to achieve in a design system with a less flexible approach to the ship definition. The six design studies were also developed very rapidly; in approximately seven weeks.

These studies demonstrated the importance of the integrated model incorporating a graphical representation that revealed the configurational interactions to the designer. The short descriptive tables included in Appendix 10 would have been difficult to generate without such a tool. This can be contrasted with more conventional approaches, such as the UCL MSc Ship Design Exercise, where the marine engineers and naval architects may use different un-integrated modelling tools for the internal arrangements of the machinery spaces and their arrangement within the design, with the potential for the development of two parallel, different models of the same design.

In addition to these advantages, these studies highlight areas for future development. Firstly, Subsection 5.5.2 details how the model was simplified before the process of numerical iteration took place. This required the separation of the numerical and spatial models of the ship and appears to go against the overall logic of the Design Building Block approach. During the investigations described in this chapter this issue was investigated and there seem to be three possible approaches:-

- The first approach is not to have any Design Building Blocks where the numerical supply and demands for space (or weight) are both dependent on their current configuration. This would lose the flexibility illustrated by the LCS example, where the demand for void volume was not estimated with a scaling algorithm, but was instead based on the current size and shape of the void Design Building Blocks, so was numerically identical to the supply of volume for those blocks. Allowing these configuration-based blocks to scale with numerical iteration introduces the potential for them to become the driver in the iteration (as additional void volume, for example, leads to additional steel weight).
- The second is for the designer to inspect these configuration-defined Design Building Blocks at every stage in the iteration to ensure that they are not becoming a numerical driver in the process. This would require more work on the part of the designer.

- The third possible method is more advanced and would require the implementation of limited automation, with certain Design Building Blocks able to change their geometry automatically to meet a numerical requirement. There are several complications and issues to be addressed with any such semi-automation and these are discussed in Chapter 6.

The other area of potential improvement, highlighted by the INEC IFEP studies, is the possibility of the use of more advanced analysis tools at the early stages of the design process. Thus for example, in these studies, no surveys of the effect of a hullform shape optimised for pods were carried out, due to a lack of time and a desire to focus on the machinery layout. Similarly some of the arrangements, such as the vertical gas turbine configuration, with very large holes in No. 2 Deck near amidships, raised issues with regard to structural continuity. Although possible solutions could be suggested (box girders at the hull sides in this case), they could not be readily assessed. Investigating these types of issues is important to gain a fuller understanding of the impact of radical stylistic choices on the overall design. Such choices could have very significant impacts on the design. The issue of structural continuity could even have made the vertical gas turbine design arrangement impractical. However, at this early stage there was insufficient detail in the model or time available for the designer to work up a full structural definition for the sections of interest, using the present toolset. This suggests a need for a set of tools capable of intermediate levels of analysis, that is to say between the very early use of analysis through scaling algorithms and the very detailed worked up design and extensive analysis of structural scantlings etc. Such an intermediate level of analysis could advantage of the rapid spatial modelling capabilities now available in PARAMARINE–SURFCON allowing improved analysis in the early stages of design.

## 5.6 COMPARISON OF DESIGN BUILDING BLOCK HIERARCHY COMPLEXITY

Table 5.9 summarises the tables of Design Building Block hierarchy complexity given for each of the designs presented, including the Type 23-a design described in Chapter 4. Figure 5.17 shows the variation in the number of entities (Design Building Blocks and Equipment Items) across each of the hierarchies and shows after the initial "design" case of the Type 23-a a reasonably consistent level of definition, both in regard to the total number of Design Building Blocks and to their distribution over the six levels of hierarchy.

| | T23-a | FSC | LCS | Dock M-ship | IFEP Baseline |
|---|---|---|---|---|---|
| **Total Number of Entities in Hierarchy** | 522 | 395 | 493 | 328 | 398 |
| **Total Number of Equipment Items in Hierarchy** | 142 | 84 | 105 | 67 | 133 |
| **Total Number of Entities With Data** | 388 | 186 | 343 | 226 | 276 |
| **Percentage of Entities With Data** | 74.3 | 63.3 | 69.6 | 68.9 | 69.3 |
| **Percentage of Entities For Organisation Only** | 25.7 | 36.7 | 30.4 | 31.1 | 30.7 |
| **Master Building Blocks** | 1 | 1 | 1 | 1 | 1 |
| **Functional Groups** | 5 | 4 | 4 | 5 | 4 |
| **Super Building Blocks** | 27 | 29 | 25 | 29 | 31 |
| **Building Blocks Level 1** | 70 | 67 | 82 | 59 | 90 |
| **Building Blocks Level 2** | 148 | 113 | 112 | 86 | 124 |
| **Building Blocks Level 3** | 266 | 123 | 118 | 108 | 94 |
| **Building Blocks Level 4** | 3 | 58 | 95 | 40 | 32 |
| **Building Blocks Level 5** | 2 | 0 | 41 | 0 | 22 |
| **Building Blocks Level 6** | 0 | 0 | 15 | 0 | 0 |

***Table 5.9: Summary of Design Building Block hierarchy complexity for a range of UCL design studies***

Table 5.9 shows the range of detail in the studies presented, from the highly detailed Type 23-a and LCS designs, where only a single design was developed, to the mothership studies, where a wide range of configurations were assessed but at a lower level of detail. Figure 5.17 shows that the distribution of Design Building Blocks across the levels of detail has a bell-curve shape. The peak of the curves lies around Building Block levels 2 and 3, with the high peak in the Type 23-a study due to the flat hierarchy used in that initial study.

This level, corresponding to Building Blocks representing major cabin groups, machinery spaces and weapons, appears to be the reasonable minimum level of detail required, with the further detail defined by the nature of the study.

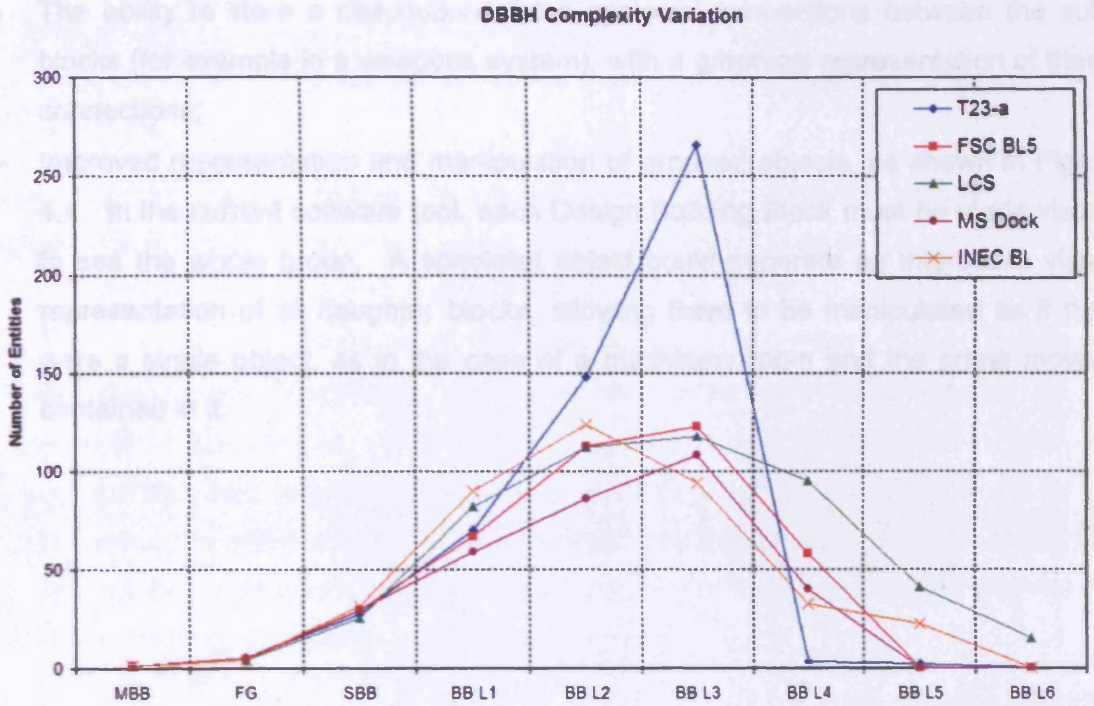



***Figure 5.17: Design Building Block hierarchy complexity variation for the design studies***

The shape of the right side of each of the curves varies between the designs and can be understood by considering the nature of the study. In the case of the IFEP baseline design from the INEC studies (Section 5.5) the higher level of detail overall is due to the modelling of the propulsion system and auxiliary machinery in more detail to evaluate the arrangement of the machinery spaces. In Figure 5.17 this manifests as a "tail" of additional detail at lower levels. For the motherships, however, the equipment contained within machinery spaces were not modelled (other than the prime movers) and so the curve drops off more rapidly.

The final point of note regarding Table 5.9 is that in each of the designs, approximately 30% of the Design Building Blocks added into the design were only used for organisation and did not contain any design data themselves, as illustrated in Figure 3.16. Although in some cases, these would have contained design data at an earlier stage in the design process (for example a block of cabins would be subsequently gain sub-blocks representing individual cabins), this is not always the case. This suggests a requirement for a specialist "organisational" object, which would act as a container for Design Building Blocks within a larger hierarchy containing numerical and spatial data describing the design. This new type of object could have additional functionalities, not available in a Design Building Block, enabling it to function as a specialist "Super Building Block". These functionalities would be:-

- The ability to store a description of the systems' connections between the sub-blocks (for example in a weapons system), with a graphical representation of these connections;
- Improved representation and manipulation of grouped objects, as shown in Figure 4.4. In the current software tool, each Design Building Block must be made visible to see the whole group. A specialist object could generate an interactive visual representation of all daughter blocks, allowing them to be manipulated as if they were a single object, as in the case of a machinery room and the prime movers contained in it.

# Chapter 6: Discussion

## 6.1 REVIEW

Chapter 1 of this thesis defined the area of study as the preliminary design of surface warships and specified the overall aim of the thesis, summarised as:

> ***The aim of this thesis is to investigate the application of the Design Building Block approach to innovative preliminary ship design, to describe the nature of the design process that results from this application and to propose directions for future development, in order to enhance the effectiveness of the Design Building Block approach in the elucidation of the problems presented by preliminary warship design and in developing the design solutions.***

Chapter 2 surveyed a range of implemented and proposed approaches to the warship design task. Chapter 3 outlined the development of a holistic, architecturally centred approach to design known as the Design Building Block approach and described its most recent software implementation, SURFCON, a module within GRC's PARAMARINE ship design system. Chapter 4 described the initial work carried out by the candidate using this tool, both to assess its suitability for early stage design studies and to develop a procedure for the use of the tool in preliminary ship design. Chapter 5 described the use of the tool and procedure in a range of ship design studies with further detailed descriptions of the designs themselves, expanded in appendices. The candidate has applied the PARAMARINE–SURFCON tool to several types of preliminary warship design studies:

- Conventional monohull single design studies: Type 23-a frigate;
- Monohull and trimaran capability variant design studies: Future Surface Combatant Baseline 5;
- Wide ranging monohull multiple design studies: Motherships;
- Trimaran single design studies: Littoral Combat Ship;
- Monohull technology variant design studies: Integrated Full Electric Propulsion.

These studies have investigated different areas of innovation in ship design, from the use of advanced hull topologies such as the trimaran, to the application of technologies such as Integrated Full Electric Propulsion and novel deployment concepts in the Motherships study. For each of these studies, discussions and conclusions are presented in the relevant chapters. This chapter considers the issues highlighted in these chapters with regard to the application of the Design Building Block approach to preliminary ship design, by considering these studies as a group of design investigations. This meets the overall aim of the thesis, in particular by addressing the design process developed in the studies and by proposing directions for future research. Each of the main discussion streams presented in the sub-sections below covers three main areas:

- At the highest level, they consider the impact on the process of ship design of the research into the Design Building Block approach;
- The next level is the effectiveness of the procedure developed in the course of the research;
- The final detailed level addressed is the practical issues of how to use the approach and subsequent developments.

## 6.2 The Design Building Block Approach and the Preliminary Design of Innovative Ships

### Identification of Emergent Design Relationships and Drivers

None of the design studies presented were based on a "type ship", although any innovation in the Type 23-a design was limited, given it was a demonstration of a procedural concept and for the initial development of that procedure. As such, in each case the overall configurational style (topology) of the design solution was unknown at the start of the design process. Although, as warships, the FIGHT function could be utilised as a "design generator" to begin the development of the ship configuration, the design drivers and relationships in the design had yet to emerge. The use of the PARAMARINE–SURFCON implementation of the Design Building Block approach, with its flexible, integrated and interactive graphical display, was instrumental in permitting the designer to determine the design drivers and the relationships between potentially functionally disparate components of the design. Examples of these include: the relationship between hullform shape, machinery arrangements and ballast tank capacity identified in the Mothership study; the conflict between FIGHT and MOVE groups in the LCS (with the INFRASTRUCTURE group being easily accommodated in the resulting configuration) and the summary tables of main drivers, identified for each of the IFEP studies. In addition to the identification of these drivers, the interactive and graphical nature of the tool greatly improved the process of communicating these design drivers to others, be it in design reviews with the supervisor or other members of the project team, or in the form of conference papers.

A particular comparison can be made between the FSC BL5 capability studies and the mothership design studies. In the former, the flexibility of the design model was constrained by it being a combination of descriptions in two software tools (i.e. numerical description in Excel and configurational description in SURFCON). The overall style of the design, primarily the upperdeck layout, was unchanged in each of the variants. Thus these investigations were similar in concept to the numerical concept exploration models described in Section 2.4.2, which are inherently limited in their investigation of the possible solution space by the retention of a single configurational style. However, in the Motherships studies, the use of a more flexible model, with integrated numerical and configurational descriptions, permitted a wider range of variants to be created and investigated. Within this relatively coarse survey of the solution space, the individual designs can then be assessed for the effects of changing requirements by the development of sub-variants. This type of study, when carried out using a method, such as the Design Building Block approach, would assist in the process of requirements elucidation by clearly delineating those design drivers directly influenced by the capability requirements and those that are an emergent property of the selected configuration.

The use of an architecturally – centred approach in the studies outlined has also allowed the definition of a basic taxonomy of relationships in configurationally oriented preliminary ship design, based on the dimensionality of the relationship:

- 1D: Simple relationships, usually linear dimensions, such as the arrangement of the upperdeck layout used to estimate the required overall length (as in the Type 23-a study) or minimum spacing of radar antennae;
- 1D+: A similarly simple relationship, with the addition of limited additional dimensionality in a minority of the items. An example could be the upperdeck layout, influenced by the position of magazines relative to machinery spaces;
- 2D: A two dimensional layout, such as the arrangement of a single deck or block of cabins;
- 2D+: A set of multiple 2D configurations with limited connections, such as early stage deck layouts with connections via engine trunking and magazine lifts;
- 3D: A fully three dimensional layout, frequently with a chain of relationships that forms a loop and requires overall design iteration. An example would be the midships area of an aircraft carrier, where machinery spaces and uptakes, hangar, aircraft lifts, magazines and weapons lifts all compete for space in the hull, whilst being linked through the flight deck arrangement. This is illustrated in Figure 6.1.

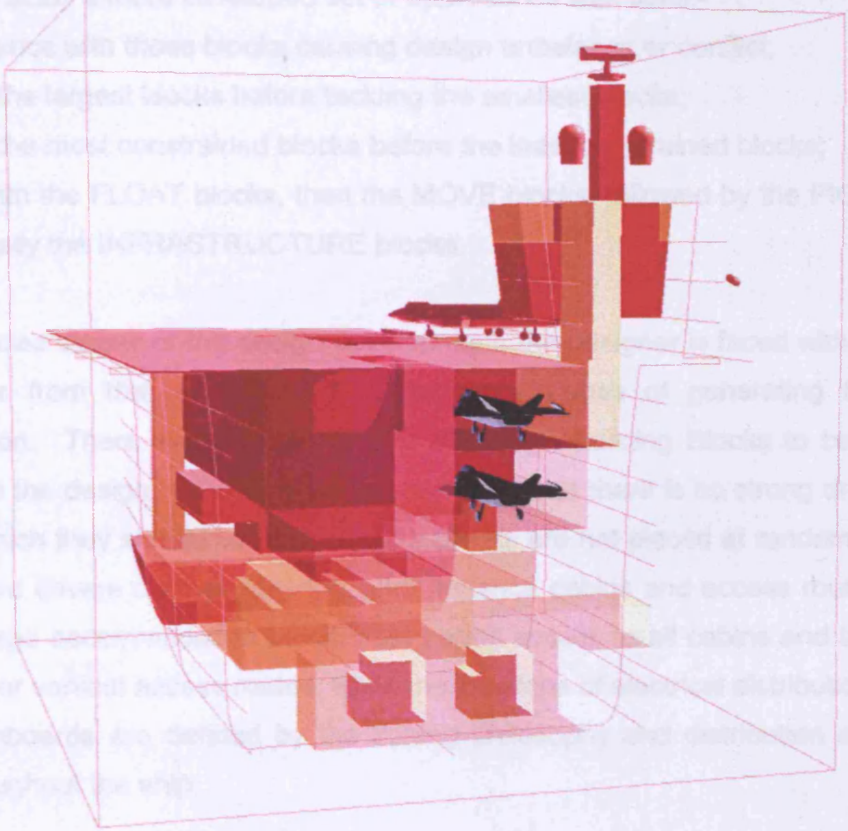


***Figure 6.1: Aircraft carrier midships area showing main machinery spaces, magazines and hangar with vertical connectivity***

## Designer Decision Making

The issue of designer decision making has been discussed regarding several of the designs. This can be addressed at several levels. At the detailed level there is the issue of how to proceed in the later stages of the development of the design (Design Building Block stages), when the main design drivers, previously identified, can no longer be used to guide the assessment process. This issue was primarily encountered in the more detailed studies of the Type 23-a and the LCS, where the general arrangement was worked up to a greater level of detail than for the other studies presented. This is in contrast to those studies, such as the Mothership series, where the level of detail was not found to be significant, since a high level of detail was not necessary to provide the required level of confidence in the practicality of the proposed design. The need for the designer to place a large number of Design Building Blocks by hand was also outlined as a potential disadvantage of the method by Dicks [*1999*].

The initial method of detail design progression used in the Type 23-a study was FLOAT, MOVE, FIGHT and INFRASTRUCTURE

In the LCS study a more developed set of approaches was used:-

1. Commence with those blocks causing design unbalance or conflict;
2. Select the largest blocks before tackling the smallest blocks;
3. Select the most constrained blocks before the least constrained blocks;
4. Start with the FLOAT blocks, then the MOVE blocks, followed by the FIGHT blocks and finally the INFRASTRUCTURE blocks.

In the detailed stages of the design development, the designer is faced with a problem that differs from that encountered in the early stages of generating the overall configuration. There are a large number of Design Building Blocks to be placed in working up the design to the desired level of detail and there is no strong driver for the order in which they should be placed. The Blocks are not placed at random, however, as there are drivers on their location. For instance cabins and access routes defined within a large accommodation block must permit access to all cabins and to the main horizontal or vertical access routes, while the locations of electrical distribution cabinets and switchboards are defined by the zoning philosophy and distribution of electrical loads throughout the ship.

However, these rules can be complex and this suggests that this process of producing a detailed layout may be amenable to automation, perhaps utilizing the ongoing research in using Genetic Algorithms for vessel layout [*Nick, Parsons & Nehrling, 2006*]. Such an approach would take the defined overall configuration at the level of the Mothership studies (i.e. large accommodation blocks) and introduce a level of detail equivalent to that developed in the LCS design (i.e. cabins and access routes). As discussed in Section 2.4, such automated approaches utilize a database of required adjacency values for each compartment being placed and this would be further complicated by the consideration of "ilities", such as adaptability and producability. However, the smaller, more constrained problem presented by the detailed layout of a block of cabins is clearly more easily addressed than overall ship layout.

The second area of designer decision making revealed in the studies presented in Chapter 5 is the higher level process of considering significant changes to the overall configuration. A specific example of this is the change in AAMR location in the Type 23-a design study, while other examples can be found in the LCS progression diagram, Figure 5.13, which compares different machinery configurations. This is a subtly different process from that used in the detailed design development. In the early stages of design, the number of relationships between components is limited (due to the sparsely populated design model) and thus can be more readily considered by a human designer. Importantly, the changes in design configuration are more significant and the total effect of each option considered requires the assessment of the consequences for the overall layout, rather than the constrained detailed layout problem.

This process of exploring options and comparing the resulting configurations was made possible by the provision of a flexible and easily changed configurational model together with the integrated numerical analysis of overall ship performance. Not only does this make it possible to affect and assess such changes, but the increased ease of such editing and increased confidence in the results, afforded by the graphical interface, encouraged such exploration. This was a vital element of the identification of design drivers and design relationships in the innovative designs considered, such as the LCS and Motherships.

## The Nature of a Balance in Preliminary Ship Designs

The concept of a "balanced design" can have many meanings. At the most basic level, a numerically balanced design is one in which the hull design displacement is equal to the design weight and the volume / area required is less than or equal to that available. However, in a broader sense a naval architecturally balanced design is one in which the wider performance of the design, summarised by the $S^5$ characteristics, has been assessed and meets the requirements. This includes the aspect of "style", which can be difficult to define and assess numerically. Thus it could be argued that designs generated from purely numerical models are not truly balanced designs, until they have been developed in more (architectural) detail. Methods such as that used in the UCL MSc Ship Design Exercise, which make use of a large number of historically derived scaling algorithms to reach a numerical balance very rapidly, similarly do not produce balanced designs as quickly as the Design Building Block approach. Stylistic aspects, such as machinery philosophy, must be assessed then described in a numerical form and the model re-iterated to a numerical balance.

The incorporation of a configurational model, from the earliest stages of the Design Building Block approach, allows these stylistic issues to be considered more fully and before a purely numerical balance has been achieved. Similarly the technical assessments of resistance, stability etc can be performed on the initial hullform, which has been generated using early estimates of displacement. In this approach the design is being assessed for its performance before a real numerical balance has been achieved. Instead, estimates of overall size are used and the results of the analysis regarded just as indicators, with associated uncertainties. The key to this is the availability of the configurational model and the speed with which it can be changed. This permits the use of estimates that can subsequently be updated with more accurate figures, without excessive effort being expended on re-working the design or transferring detail between definitions of the design, often held in different software tools.

A comparison of these two approaches is shown in Figure 6.2, which utilises the simple representation of a design in a notional n-dimensional design space used by Andrews [*Andrews, 2003c*]. A numerical approach generates a point design with an associated uncertainty that subsequently moves around the solution space, while the Design Building Block approach generates a more approximate design that refines as the design progresses. Set-based numerical approaches proceed in a similar manner by analysing a wide region of the solution space and then selecting a design from within it, but they suffer from the limitations already discussed, of being relatively inflexible, once configured to a certain design style.

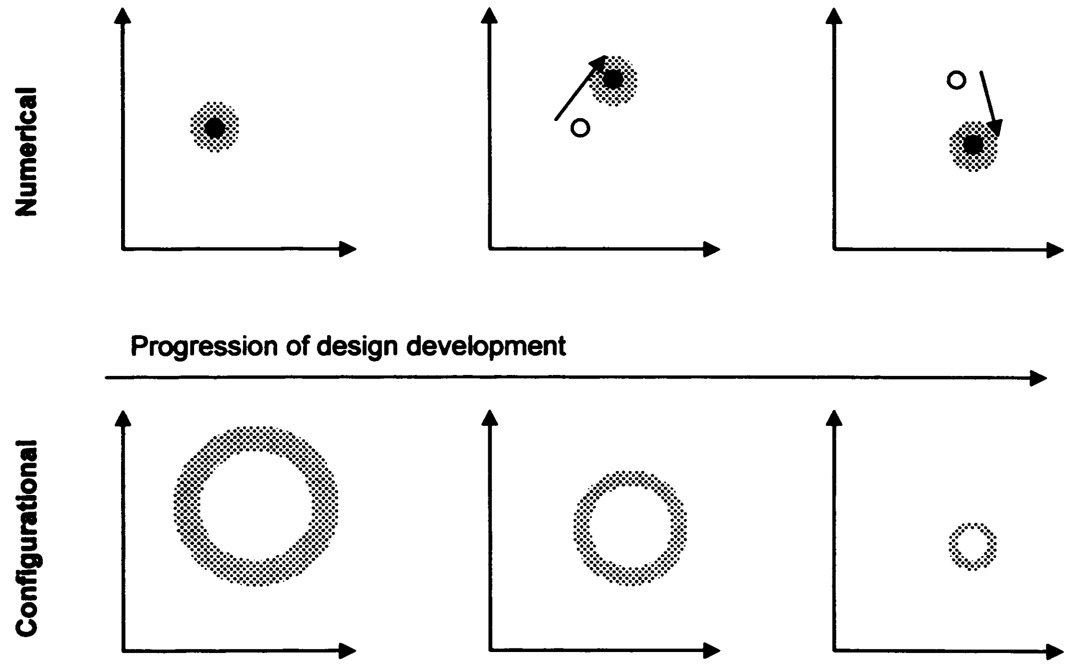



***Figure 6.2: A diagrammatic (solution space) comparison of the progression of designs in numerical and configurationally led design approaches***

## Completeness in preliminary innovative ship designs

An issue raised by the more radical designs, such as that produced in the LCS study, is how to ensure sufficient completeness when undertaking such innovative preliminary ship designs. In the design of type ships or variants of previous vessels, the equipment, systems and features that should be included in the design definition to achieve a satisfactory degree of certainty are normally well understood. Methods, such as the UCL MSc Ship Design Exercise [*UCL, 2001a*], provide a "checklist" of such items in the form of a weight breakdown system and historically derived scaling algorithms. The checklist will be suitable for any vessel with the same overall style (such as a common machinery type), but when considering innovative vessels the historically derived solutions may not be appropriate. The functional hierarchy used in the Design Building Block approach was introduced to assist in the incorporation of innovative solutions by encouraging the designer to consider the functions that must be performed, rather than just selecting the systems and equipment used in previous designs. However, this raises the question of how the designer can assess the completeness, practicality and certainty of the proposed design when adopting novel systems and configurations.

A simple example of novel choice is the use of azimuthing podded propulsors rather than conventional shafts. The UCL SDE data book contains a breakdown of the items required for the traditional design solution, including the shafts and their supports (bearings and structural supports), rudders, steering and control gear etc. However, the azimuthing pods will require a different set of supporting systems, such as cooling for the electric motors and possibly additional structural support, due to the concentration of weight in the pod. Innovative solutions may also lead to improved performance, which may not be accurately reflected in regression-based tools. In the pod example, improved propeller efficiency can be attained if the pods are positioned correctly and the hullform is appropriately shaped (see Appendix 10). In the studies presented, the flexibility of the PARAMARINE – SURFCON implementation of the Design Building Block approach allowed the designer to incorporate alternative systems and to use different coefficients and efficiencies etc, but the accuracy of the system architecture modelled was dependent on the designer.

This issue leads to two main proposals and areas for discussion. The first is that more interfaces between the SURFCON model and the type of first principle analysis tools described by van Oers and Stapersma [*2006*] would allow the assessment of the performance impacts of innovative design solutions. However, this raises issues of their usefulness and applicability in the preliminary design stages. The second proposal is that tools for the definition of systems linking the Design Building Blocks, numerical analysis and design infringement analysis could be used to assist in ensuring a better degree of completeness in innovative designs.

## Applicability of Analysis Tools in Preliminary Innovative Ship Designs

One of the advantages of the PARAMARINE–SURFCON tool, that has already been identified, is that it integrates the flexible configurational model with numerical analysis tools. This then raises issues regarding the limits of applicability of these tools in assessing innovative ship designs. Analyses, such as intact and damaged stability in the equilibrium state, are concerned with the shape and attitude of the vessel and thus only require a tool capable of correctly auditing the submerged volumes and calculating their geometric properties. This can be reasonably well assessed using simple geometric models, although in such a tool, the location of the centroid of weight would have to be assumed. For aspects, such as resistance, structural weight and, more significantly, seakeeping and manoeuvring, the issue is more complex, as not only do they require a certain level of detail in the design definition to be available, but the numerical methods used can have limits on their applicability.

In considering the issue of the level of detail required, there seem to be three main points:

- Some issues can be assessed with quick, low resolution methods, early in the design, and then reassessed with more accurate methods once further information is available. An example of this is the structural weight, which for the LCS was initially assessed using an assumed structural weight fraction and later, once the main structural elements have been identified, with an equivalent thickness based approach.
- The level of detail to which an analysis needs to be taken may vary both between designs and within the same design. In the INEC IFEP studies in Section 5.5, for example, the hullform was a derivative of a conventional frigate hull and so the Taylor-Gertler [*Gertler, 1954*] method for resistance estimation was appropriate. However, in the vertical gas turbine variant (Option 6) the structural arrangement in way of the machinery spaces was identified as a potential problem and so further structural analysis was deemed appropriate. In the Type 23-a design, the location of the after diesel generator space in the hull would have affected the underwater noise signature. As this is significant for an ASW oriented vessel, this decision could have benefited from more detailed underwater signature analysis at an early stage. However, the otherwise generally conventional style of the Type 23-a design reduced the need for detailed analysis of other aspects of performance.
- For some analyses sufficient detail may not be available, although this problem is reduced in SURFCON. For instance an initial structural analysis requires a concept

of the structural style and estimate of the longitudinal weight and buoyancy distribution to calculate bending moments, if any preliminary structural design is to be undertaken. Such features can be generated early in the design using the Design Building Block approach, due to the availability of the integrated spatial model of the design. However, dynamic analyses, such as structural response to underwater shock, require more information on structural detail and equipment mountings than is likely to be available in preliminary design.

Possible future developments of advanced analysis tools that may be able to make estimations of performance, based on the low level definition existing in preliminary design, are beyond the scope of this thesis, but an important point can be drawn from the work presented. Any analysis tool should make clear to the designer the limits of its applicability and it ought to notify the designer when these are reached or exceeded. The resistance estimation objects within PARAMARINE perform this by checking the assigned hullform geometry for its compliance with the published limits for each of the different estimation methods. Depending on the exact nature of the method and its limits (absolute or recommended), the software either refuses to perform the calculation and informs the designer which limit has been exceeded, or carries out the calculation but warns the designer of when the limit is exceeded. This type of on-line communication of applicability and limits is far more useful in the rapid development of designs than an off-line manual that relies on the designer being aware and conscientious enough to stop on-line "designing" to check the manual.

## The Design Building Block approach and Systems Engineering

Section 2.3 briefly summarised the systems engineering approach, with reference to its application to ship design. Comparing the systems engineering approach to the Design Building Block approach, there are several similarities, particularly with regards to the focus on a functional description of the design and a requirement to integrate many different technical issues. The studies outlined in Chapter 5 have shown that the Design Building Block is ideally suited to addressing the four basic ideas of systems thinking, as described by Checkland [*1993*].

- Emergence: SURFCON and the Design Building Block approach have demonstrated their effectiveness at revealing the emergent relationships and properties of new design configurations.
- Hierarchy: The concept of a hierarchical definition of the design is a fundamental part of the Design Building Block approach.

- Communication and Control: The capability of SURFCON to represent both spatial and functional connections between Design Building Blocks allows the representation of explicit connections between design entities and systems.

In addition to providing an environment for integrating and assessing the whole ship impact of the many specialist technical aspects of ship design, SURFCON and the Design Building Block approach also offer a way to address the "wicked problem" aspect of ship design, which makes it a "soft system" process as defined by Checkland. The enhanced understanding of the problem of ship design, provided by the application Design Buidling Block approach, would allow the exploration of the consequences of requirements and lead to the "requirements elucidation" approach proposed by Andrews [*2003b*].

The incorporation of objects for the definition of systems could also assist in reducing the reliance on "checklists" for design completeness. Such systems would be composed of not just Design Building Blocks but also numerical performance requirements derived from the analysis tools. A possible approach is to identify the supply chains formed by each system. For the example of the propulsive machinery, this gives:-

- Propulsive system provides propulsive power;
- The requirement for propulsive power originating from the resistance estimate based on the current hullform;
- The power must be brought onto the ship (as energy in fuel) and stored, it must then be converted from energy into power and this power must be converted into propulsive power;
- The resulting chain is:
- Energy storage in fuel tanks → power generation (e.g. gas turbines, diesel generators) → power transmission (e.g. shafting, high voltage cabling) → power conversion to propulsive power (e.g. propellers, waterjets)

Each of the main components in the supply chain could be an established system (such as gas turbines) or an innovative solution (e.g. fuel cells). The use of a systems based approach would assist the designer in ensuring that all aspects of the integration of the innovative features have been considered. It may be that assumptions or historical data are used with an associated degree of uncertainty, but this is acceptable in preliminary ship design if it is made explicit and easily evaluated, later in the design process.

## 6.3 The Design Building Block Approach and the Interaction of the Designer With the Design

### Human Computer Interfaces

As described in Section 2.5, the user interfaces used by preliminary ship design software changed considerably over the latter part of the 20th Century and early years of the 21st. The PARAMARINE – SURFCON tool now offers a graphical user interface based on a commonly used layout (that of the Microsoft Windows Explorer program) and, importantly, provides an interactive graphical display of the design elements generated from a spatial model linked to the numerical analysis. The graphical display of the Design Building Block configuration and the equivalent informational display in the "hierarchy" pane greatly eases the "Seven Stages of Action" outlined in Section 2.5. The designer and any reviewers can more easily understand the current state of the design and engage in the reflective design dialogue, akin to sketching. However, there are some areas where the interface could be improved to reflect the domain specific needs of preliminary innovative ship design when using the Design Building Block approach.

This domain specivity would reduce the Gulfs of Execution and Evaluation (see Section 2.5), as the software tool itself would become more transparent by reducing the level of abstraction required to turn the designer's intent (e.g. model a faceted mast) into a set of actions that the software can carry out (e.g. create a series of planes controlled by variables containing the dimensions, then use these as the bounds of a solid body). This example is shown in Figure 6.3 and is representative of the current need to turn a stylistic choice (i.e. re-use the Type 45 Destroyer's mast) into a series of relatively abstract geometric modeling actions (i.e. requiring 49 objects to create one mast as a "solid body" object).

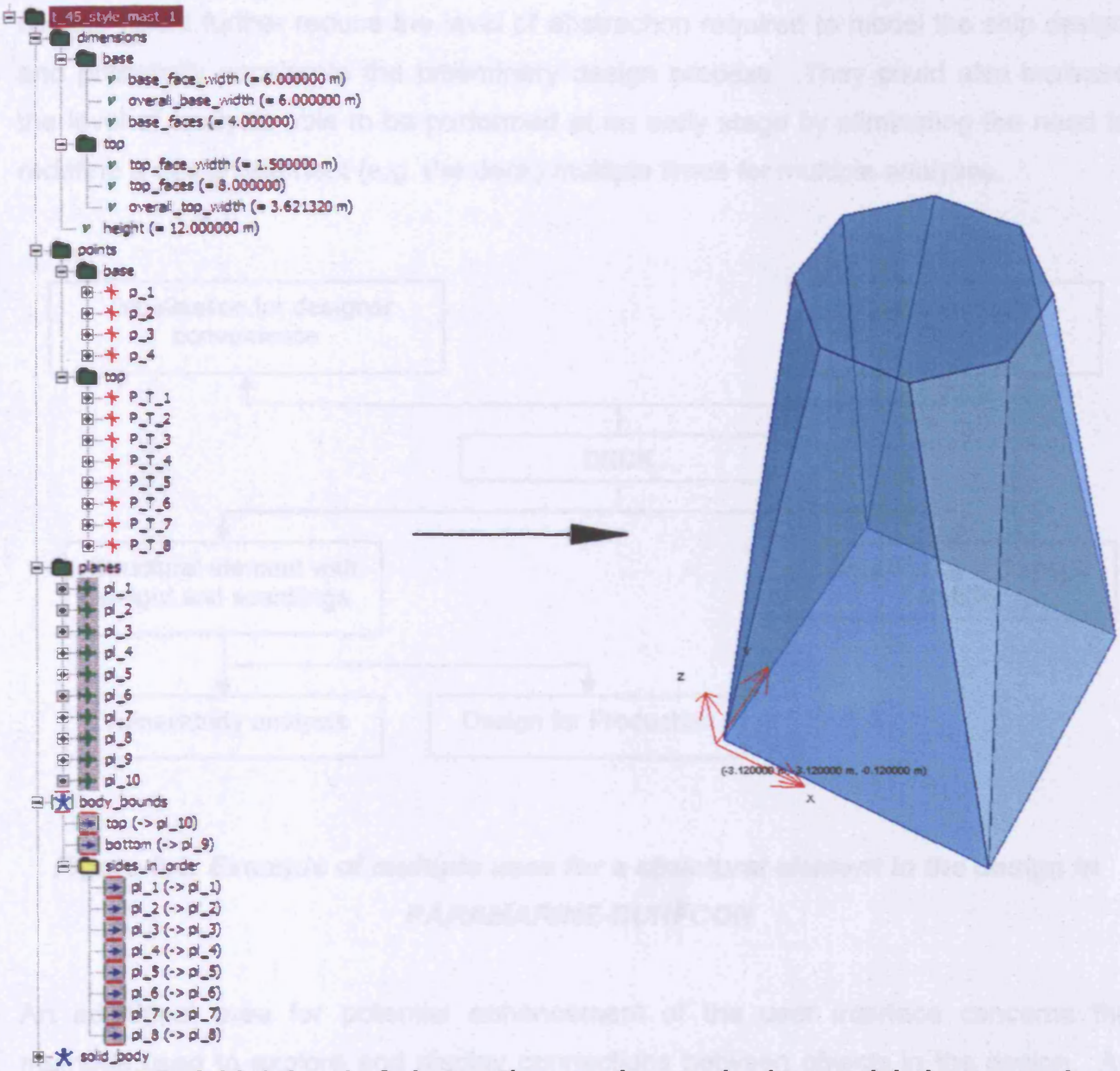



***Figure 6.3: A high level of abstraction can be required to model shapes such as faceted masts***

Another area of abstraction that could be usefully reduced is the use of objects for visual guidance just to the designer. Figure 4.21 shows two examples of this. In the current software implementation in PARAMARINE-SURFCON, visualisation objects such as the "layout grid" and a "polyline" object are used to display the current positions of decks and bulkheads. However, both decks and bulkheads are elements of the design definition. There is thus potential for a new type of object that could represent a deck or a bulkhead, able to be generated at the early stages of design for visualisation and location purposes. Design Building Blocks could then be placed directly onto the deck object and used in the more detailed stages for component structural weight estimation and even scantling design of those elements. This synergy, between different uses of the same design object, is shown in Figure 6.4 and represents an extension of the functional Design Building Block description to include additional hierarchies, such as structural design and subdivision. Such multi-purpose objects would further reduce the level of abstraction required to model the ship design and potentially accelerate the preliminary design process. They could also increase the level of analysis able to be performed at an early stage by eliminating the need to redefine a design element (e.g. the deck) multiple times for multiple analyses.

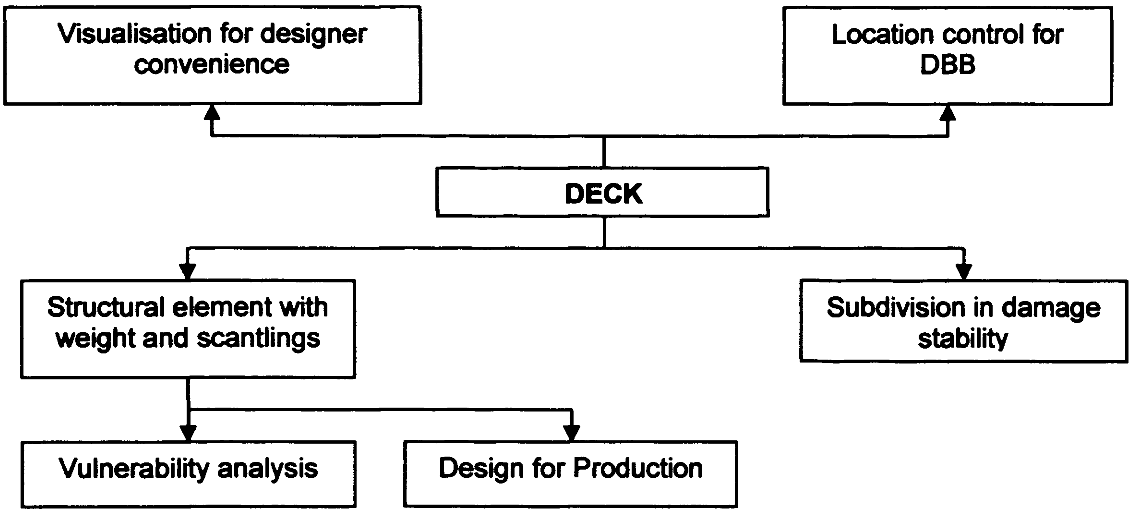



***Figure 6.4: Example of multiple uses for a structural element in the design in PARAMARINE-SURFCON***

An additional area for potential enhancement of the user interface concerns the methods used to explore and display connections between objects in the design. As was noted in Section 3.4 the hierarchy view is not representative of the direct links created between objects in the design, other than by the use of a common icon scheme to indicate required information sources. Just as in the SSA ITMC Design for Production studies and the Type 23 model, where three different hierarchical representations of the spatial model were used (i.e. constructional block, watertight subdivision and design building block), so alternative representations of the design could be added to the interface. These would go beyond the list based approach of the "properties" dialogue box shown in Figure 3.18 and could include the connection diagrams presented by Andrews [*1984*] and Dicks [*1999*]. This raises questions regarding the level of complexity to be displayed on such a diagram (e.g. should every linked object be shown at once, or in an expandable hierarchy?) and whether it should be possible for the designer to annotate them with emergent relationships (i.e. an additional layer of connections superimposed over the direct parametric relationships) and contextual information (e.g. why the link was formed). This type of user interface development can only come about with direct involvement from users to determine the most useful methods of information display and interaction with the software.

Examples of the connection diagrams produced by Dicks are shown in Figure 6.5 and 6.6. Figure 6.5 shows the spatial (solid lines) and combat system (dotted lines) connections between the main spaces and equipment items in a frigate design. Figure 6.6 shows the same design with the Design Building Blocks also illustrated (the coloured areas). Although these diagrams permit the display of several types of design relationship simultaneously, any software application would require careful design to ensure that the designer is not overwhelmed with information and can control what is displayed.

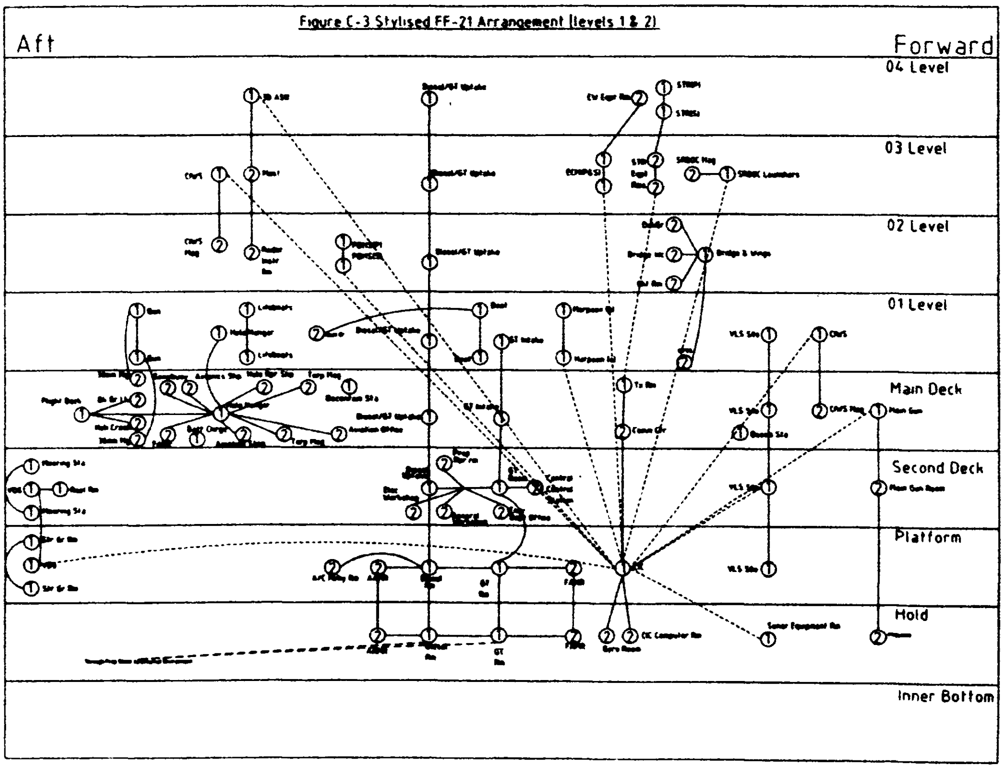



***Figure 6.5: Connection diagram for frigate general arrangement [Dicks, 1999]***

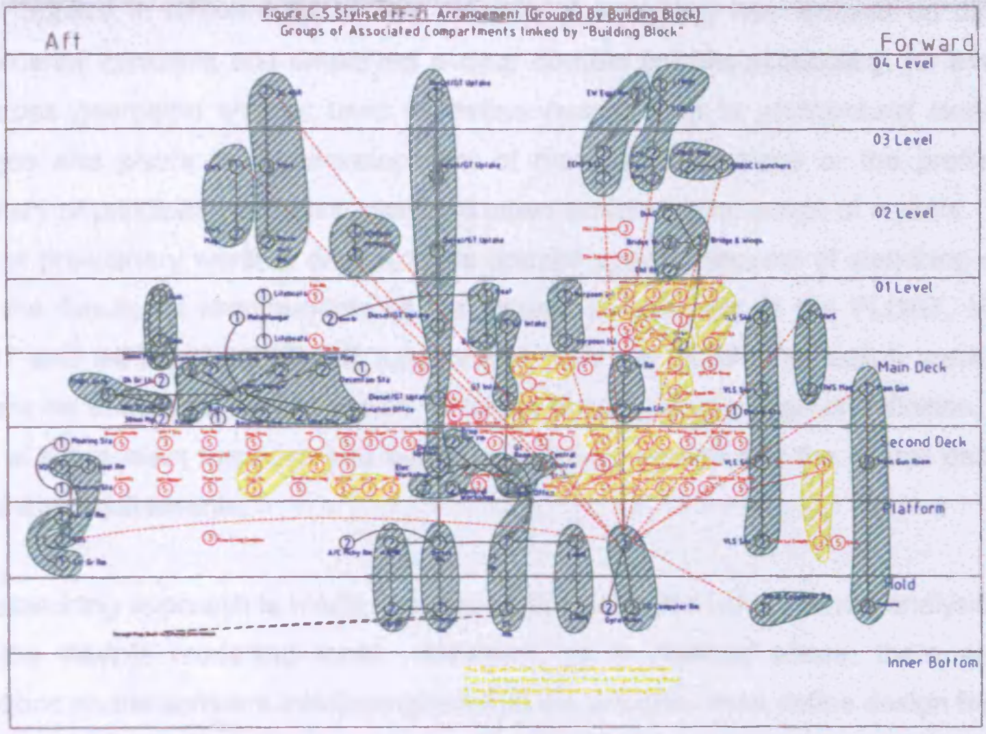



***Figure 6.6: Connection diagram for frigate general arrangement showing groups of associated compartments linked by Design Building Blocks [Dicks, 1999]***

## Sketching and the Design Building Block Approach

Comparing the previous discussions on designer decision making with the summary of the properties of sketches and the process of sketching presented in Section 2.6, it becomes clear that the use of the Design Building Bock approach in the preliminary design process can be seen to be akin to the process of sketching. The Design Building Block model, particularly at the early stages of design definition, is used by the designer to explore options and suggest new ones. All three types of sketches previously outlined are identifiable:

- The talking sketch: Best represented by the descriptions of the design in the conference papers included as Appendices 5, 7 and 9. Such summaries were also used in design reviews.
- The thinking sketch: This is the sparsely populated, highly flexible model used in the Major Feature and Super Building Block design stages (on the upper left of Figure 5.13, or Figures 3 and 5 in Appendix 8).
- The storing sketch: This functionality was provided by a combination of the inherent ability of the PARAMARINE-SURFCON tool to store the design "as is", without requiring a particular structure or level of detail, and the textual and graphical design journal kept by the designer.

When applied in different fields, the process of sketching has focused on different fundamental concepts and employed a clear domain specific vocabulary, for example the gross geometric shapes used to define overall form in architectural sketching, linkages and pivots in the development of mechanical systems or the profile and summary of principal particulars, provided when sketching the design of a yacht. In the case of preliminary warship design these domain specific aspects of sketching derive from the functional requirements of the vessel, summarized in the FLOAT, MOVE, FIGHT and INFRASTRUCTURE functional groups. A SURFCON sketch would thus typically be in the late Major Feature or Super Building Block stage of definition, when each of these main functions has been assessed, to ensure that the overall design is meets the requirements.

This sketching approach is made possible by the integration of numerical analysis tools with the flexible modelling tools. However, as is outlined above, there are still limitations on the software interface given that the designer must define design features in an abstract manner. This increases the time invested in creating the model, thus reducing its "disposability", in that the designer will be more likely to adopt a "minimum change" approach. Despite these current limitations, the sketching nature of the SURFCON implementation of the Design Building Block approach potentially represents a significant shift in the practice of preliminary ship design. The integration of numerical analysis tools, with the graphical description, reduces the effort the designer must expend on *modelling for analysis purposes* and permits he or she to focus on *modelling for exploration*, where creativity and innovation can be more fully employed and understanding of the problem greatly enhanced.

## 6.4 The Design Building Block Approach and Analysis of Designs

### Use of the Design Building Block Approach and Numerical Design Tools

Although the PARAMARINE – SURFCON implementation of the Design Building Block approach encourages exploration of the preliminary design space through the provision of a flexible model and interactive graphical display, it does not currently support the highly structured studies of the nature of the solution space that can be performed using the numerical methods and tools described in Section 2.4. As has been previously suggested in this discussion, future developments of SURFCON could incorporate certain types of numerical parametric survey. This includes both more extensive use of UCL SDE type surveys of hullform coefficients and also wider surveys varying the overall dimensions of the vessel, as described in Section 2.4.2. The SURFCON tool could be used to overcome the limitations of the numerical models, when dealing with ill-structured problems and fostering innovative designs, by allowing an early assessment of the potential solutions, of several different topologies (overall configurational styles). These could then be assessed using set-based numerical design tools to reveal the nature of the possible solution space, for each of the major options or variants. This would allow assessment of the design topology selected and reduce the pre-determination of the design form, identified by Dicks [*1999*] as a potential problem with the application of the Design Building Block approach.

For example, a study which could have used this type of hybrid approach is the Mothership study, where the seven radically different initial configurations were generated using PARAMARINE – SURFCON. These models could have then been represented in a parametric form, similar to the concept exploration models described in Section 2.4.2, using the knowledge gained on the relationships and drivers in each design. A large set of variants could then have been produced from each of these point designs. The use of weighted assessments of the performance of each variant design could then provide a wider evaluation of the potential solution space and how this relates, not just to the direct performance requirements, such as speed, but also to the relative importance attached to these requirements. As with all weighted assessment methods, it would also be vital to undertake sensitivity analyses of the weightings themselves. The Design Building Block approach could be of great assistance in this area, due to the enhanced understanding of the design provided by the interactive graphical display. This could lead to a common environment for improved communication between all individuals involved in the weighting and design evaluation process. This is particularly important when considering complex hierarchical descriptions, such as that shown in Figure A1-3.

## 6.5 THE PROCESS MODEL

### Development of the Process Model

A significant part of this thesis has been the development of a process for utilising the Design Building Block approach in the preliminary design of ships. As explained in Section 4.5, the initial process developed was based on the previous work by Andrews [*1986*], Dicks [*1999*] and the candidate's own experience of the UCL MSc Ship Design Exercise approach [*UCL, 2001a*]. This initial process was then developed through the design studies outlined in Chapter 5, with the most recent development, applied to trimarans, being included as Appendix 9. The detail procedures used in each of the studies varied, as the nature of the design model and objectives of each of the studies was different and a common detailed procedure was found to be impractical. Similarly, for studies of vessels with different roles or different configurational styles, it may be required to develop a slightly different process. The integration of set-based numerical models and methods may also require a modification to the approach. Reviewing the applications described in Chapters 4 and 5, it is possible to produce a generic illustrative diagram for progression of a design using the Design Building Block approach, as is shown in Figure 6.7.

This figure shows the different stages of variant generation and comparison used in the process. The early variants developed in the MFDS represent significantly different overall layout configurations and are not developed to a high level of detail, so they are akin to rough sketches. One of these layouts is then taken forward to the SBBDS. However, as shown by the dotted arrows, it is also possible to develop several variants to a higher level of detail, as was done in the Mothership studies (Section 5.3). Given that the process of design is iterative, feedback mechanisms exist not only within the processes of comparison and selection, but also between the stages of design development, allowing information to be fed back into an earlier stage, as was also shown in Figure 4.28.

In the SBBDS, several variants are developed, based on the same overall configurational topology, but each is examined in more detail for a fuller comparison. As before, one variant is selected and taken forward, usually with a parametric survey of hullform shape coefficients. In the INEC studies (Section 5.5), multiple SBBDS variants were taken forward, one for each of the propulsion options investigated. In the BBDS, there are several stages of design development. The earliest will involve the generation of alternative configurations, but with more limited variation than at previous stages in the process. Much of the BBDS involves the addition of detail to the design without the generation of significant variants. There is also the possibility of performing further numerical parametric surveys at this stage of the design.

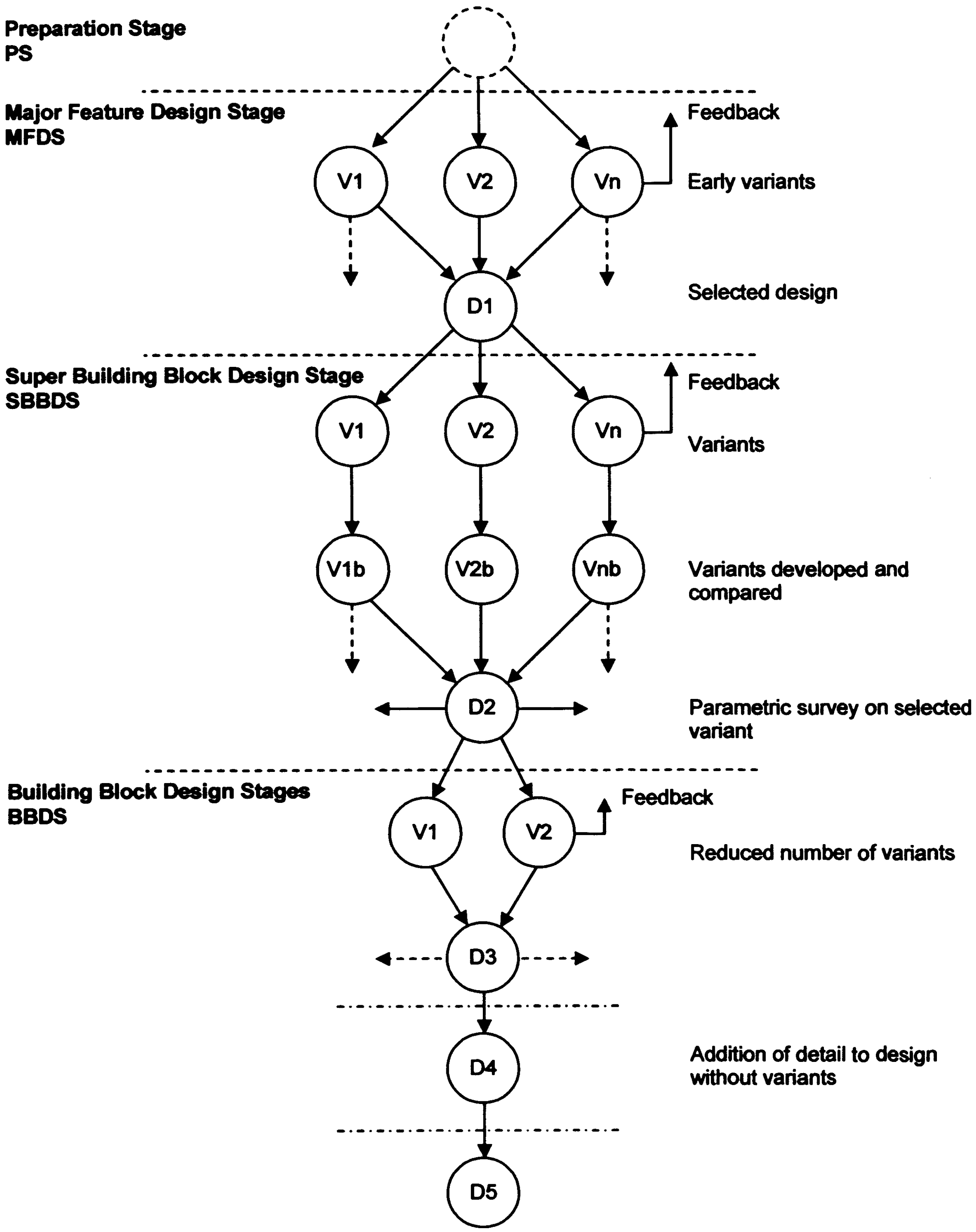



***Figure 6.7: Illustrative diagram showing the progress of a design using the Design Building Block approach***

## Advantages of the Design Building Block Approach

Figure 6.7 shows a key aspect of the Design Building Block approach – the multiple stages of generation of alternatives and evaluation, with the ability to split the variants off for further study. Each of these stages involves the manipulation of the overall topology of the configuration and so not only incorporates innovation and creativity but also allows the consideration of a fundamentally wider range of variants than a purely numerical survey. However, the utility of such numerical parametric surveys cannot be ignored, and they can be incorporated within the Design Building Block approach. As discussed in Section 6.4, the later parts of the BBDS, where the design is worked up to a suitable level of detail, are amenable to automation, given the comparatively linear nature of the process. However the major problem with implementing such numerical approaches is providing the logic that can be used to populate the design with detail. This could be in the form of stylistic rules (e.g. *n* ATUs per damage control zone) or tables of required adjacencies.

Although the procedure described in Appendices 6 and 8 and illustrated in Figure 6.7 is focussed on the configuration of the vessel, this does not necessarily mean that technical assessments of performance are neglected. As discussed in Section 6.3, the integration of the spatial and numerical analyses in a single tool, using a single model of the design, has reduced the time required to reproduce definitions of the design for detailed analyses. Also, as shown in Figure 2.3, all the major technical aspects of the performance of a design are directly linked to the configuration, so this must be modelled (or otherwise assumed) for any analysis to take place. As illustrated by Figure 6.3, there are limitations in the current software implementation that increase the time and effort required to create the spatial model and, similarly, there are limitations in some of the analysis tools. However, this is purely a limitation of the software available during the studies presented, rather than of the approach itself. From a philosophical point of view, Figure 6.7 shows that there are many "hooks" within the approach such that more detailed numerical analysis or parametric surveys could be added. These would make use of the flexible spatial model of the design, to expand their applicability beyond the configurationally limited type-ship applications described in Section 2.4.

# Chapter 7: Conclusions and Future Research

## 7.1 OUTLINE

The discussions presented in Chapter 6 have covered a wide range of issues informed by the design studies outlined in Chapters 4 and 5. There are several key conclusions that can be made from the discussion on the application of the Design Building Block approach to innovative ship design. This chapter presents these conclusions and then outlines proposed future development paths. These are oriented towards the wider, philosophical and procedural aspects of the approach, rather than detailed issues of GRC's PARAMARINE software. A more general conclusion is that the overall aims of the thesis, as stated in Chapter 1 have been met.

## 7.2 MAIN CONCLUSIONS ON THE APPLICATION OF THE DESIGN BUILDING BLOCK APPROACH TO INNOVATIVE SHIP DESIGN

The features of the PARAMARINE–SURFCON implementation of the Design Building Block approach that were found to be key to its use in the studies, were that it provided a flexible configurational model, integrated with numerical analysis tools, and an information rich interactive graphical display. The software tool, when utilised within a suitable procedure, was instrumental in revealing emergent design drivers and relationships in the innovative vessel types considered.

The flexibility of the model allowed a wide range of designs to be investigated, encompassing a range of basic design topologies. The flexibility and relative ease with which major features of the design could be modified encouraged the exploration of a wide range of alternatives.

The interactive graphical display made the process of design modelling and analysis more transparent than with purely numerical models and reduced the level of abstraction required to translate from the designer's intent to computer model. Not only did this facility in the Design Building Block approach demonstrate the importance of continued development of naval architecture specific user interfaces, but it also allowed a more integrated dialogue to develop between the designer and computer. This process was seen to be akin to sketching in product or architectural design, namely, a creative, reflective process, where the sketch (the Design Building Block model) is part of the creative process and assists in the internalisation and understanding of the problem. Crucially, the integration of the configurational model and numerical performance assessment tools allows this creative process to occur, without sacrificing the technical accuracy required in preliminary ship design.

Similarly, it is proposed that the flexibility and holistic nature of the approach, implemented in a tool with robust performance assessment methods, makes it ideal for the integration role in the Systems Engineering approach to ship design. In particular, this research has led to the suggestion that the exploratory, revelatory nature of the approach, tool and procedure have synergies with the concept of "Soft Systems", appropriate to problems which may be ill-defined and where exploration is necessary to acquire understanding of the problem and appropriately explore potential solutions. Such an approach would also aid in addressing the "wicked problem", presented by preliminary ship design, by opening up the solution space to greater exploration, thereby challenging the requirement outline and assumptions of what is achievable and affordable.

The studies presented here have also demonstrated that two key levels of designer decision making occur in the Design Building Block approach. The higher level is concerned with large scale issues, such as the overall layout of the vessel, stylistic issues and the interplay of design drivers and design relationships. The more detailed level concerns those decisions required to develop the design to a greater level of detail, particularly addressing aspects such as systems layout and the arrangement of accommodation blocks. It has been proposed that potential exists for automation of the detailed stages, allowing the designer to concentrate on the high-level, stylistic issues, while numerical methods can be used to develop the designs to the required level of detail. It has also been suggested that this hybrid approach could be used to conduct wide ranging parametric surveys of the solution space, as these can be based on overall design topologies, which very crucially have been defined by the designer. Developing any such methods, however, must avoid the danger of "black boxes", where the design becomes opaque to the ship designer and such an outcome would be potentially detrimental to the revelatory nature inherent in the philosophy behind the Design Building Block approach.

## 7.3 Future Development

### User Interfaces to Encourage a Sketching Approach

One area of development that emerges strongly from this research is how to encourage a sketching-like approach of exploration and innovation in design. The main features of the SURFCON implementation of the Design Building Block approach that assist in sketching are the flexible modeling tools and the graphical interface. Future developments could reduce the "gulf of execution" (see Section 2.5) by reducing the degree of abstraction and duplication needed to represent ship features. A central issue of such developments would be how to balance flexibility and simplicity. Another area where development would be appropriate is in the storage and representation of contextual information, such as design logs, summaries of the design and explicit and emergent relationships. Such interface development concerns more than new objects for modelling spatial features, it also needs to address the implementation of a naval architecturally relevant visual vocabulary, within the graphical user interface of the software (For example, using traditional symbols for amidships, greater representation of ship systems and ship features such as decks, bulkheads and superstructure blocks).

### Links to Numerical Tools

A crucial feature of the Design Building Block approach is that numerical analysis of the technical aspects of the design is not sacrificed in the desire for greater designer interaction with the spatial model. This analytical emphasis is maintained through the provision of the embedded analysis tools and further development of these, along with links to emergent simulation tools, such as personnel movement [*Andrews et al, 2007*], freight movement [*Tian, 2005*] and potentially survivability and topside arrangements [*Bayliss, 2003*] is strongly encouraged. A related development would be the incorporation of semi-automatic numerical synthesis tools, based on methods such as Genetic Algorithms, that could be used to perform wider parametric surveys and to accelerate the process of naval architectural oriented design development. This acceleration of the initial design process may become more urgent given the increased use of analysis and simulation tools, which require a greater level of definition in the preliminary design model [*Andrews et al, 2007*]. There are seen to be four main issues in this development:

- Development of databases and rule sets, particularly for layout and detailing of the engineering design tools;
- User interfaces, which would ensure that the automatic components do not produce a "black box" process and that the assumptions underlying these components, as well as their databases and applicability can always be assessed;
- Procedural integration to ensure the new tools are used in the most effective manner;

- Software integration, to ensure that the numerically and graphically integrated approach to synthesis is retained so that the numerical tools are used as a part of the design development, not as a post-processing operation.

**Systems Engineering Integration**

The SURFCON implementation of the Design Building Block approach has been proposed as an ideal method to underpin any integration tool as it is seen to be consistent with the application of Systems Thinking to preliminary ship design. To make the best use of the approach and any tool based on it in this manner, it will almost certainly be necessary to add additional functionality. This could be in the form of improved representation of ship systems and in the on-line notation tools referred in Section 4.4.4.

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# Appendix 1: Approaches to Computer Aided Preliminary Ship Design

This appendix contains more detailed discussions of the approaches to computer aided preliminary ship design outlined in Section 2.4.

## A1.1 Preliminary Numerical Models

Numerical ship models have been used in a range of preliminary ship design investigations. These models have variously been known as Concept Exploration Models or Parametric Models. The overall approach is that the vessel design is described through a series of parametric relationships, generally linear in nature, which have been summarised by Parsons [*2003*]. Parsons also divides the overall strategy adopted into point-based and set-based design.

### Point Based Parametric Design Models

These models require the designer to make decisions about the configuration of the design, within the limits of the model and algorithm flexibility. The designer develops the design through a series of specified steps, considering each aspect of the design (payload, overall dimensions, machinery fit etc) in turn. These processes lead to a single design solution, although limited studies may be carried out to assess the impact on the developing design of detail choices such as hullform shape parameters. A wider survey of design options (for example, changing the machinery type or weapons fit) would be carried out by generating a new design.

Tools such as the US Navy's Advanced Surface Ship Evaluation Tool (ASSET) [*Heidenreich, 2002*] use linear algorithms to estimate weight and space demands for a new vessel, based on historical data and scaling from selected characteristics of the new design. ASSET is type-ship based, using a modular approach, with different modules of sizing algorithms for ships such as frigates, destroyers [*Levedahl, 1993*] and aircraft carriers [*Calkins, 1988*], [*Heidenreich, 2002*].

The CONDES system, developed and used by the UK MoD adopts a slightly different approach to ASSET, in that the designer enters the sizing algorithms to be used in developing the new design [*Hyde & Andrews, 1992*]. Hyde and Andrews describe studies for a fleet of MCMVs, using CONDES to develop a range of designs, each leading to different fleet size to accomplish the same mission. A similar designer led approach was utilised in the experimental DESIGNER tool developed by MacCallum [*1982*]. Although it utilised a very simplistic model of the ship design, this tool featured the additional functionality to automatically assess and present to the designer the strength of relationships between parameters in the design. This was carried out by varying input parameters and recording the effect on the outputs, in an attempt to understand the relationships in the design.

Specialised numerical models have been developed for a number of investigations. Reeves [*1983*] describes a series of such numerical models developed to assess Surface Effect Ship designs, where the algorithms used were suitable only for that specific example and made use of an assumed overall configuration of the design. An example of a similar tool, for application to merchant ships, was presented by Schiller et al [*2001*]. This also limited the application of the tool to a specific type of ship (container ships), thus permitting the use of a stereotyped configuration. Balasubramanian and Lavis [*2001*] described the Parametric Analysis of Ship Systems (PASS) tool in a focussed study on the ship impact of payload, structural and propulsion technologies on high-speed transport ships, where the designer was required to define these aspects of the otherwise configurationally constrained design, to develop a range of design options.

A common feature of these tools is their very limited graphical display of the design, if at all. The system described by Schiller et al [*2001*] used diagrams to illustrate the dimensions being selected at each stage of the process. ASSET features a more detailed representation of the current configuration of the design, but this is limited to a profile section view and a plan view of the machinery arrangements. In all these tools, the graphics are a display of the current configuration and are not interactive – they cannot be manipulated directly by the designer. A type of parametric model with more advanced graphical representation and spatial modelling is described by Bole [*2005*] using GRCs PARAMARINE software. In this case a detailed spatial model is constructed with dimensions controlled by numerical parameters, which can then be varied to improve the design's estimated performance. However, the model only represents a single overall configurational style (topology) and the graphical display is still for information only.

### Set Based Parametric Design Models

Compared with the tools outlined above, which require interaction with the designer and produce a single design or a limited range of designs, numerical models have also been used in a different manner, to automatically produce a very wide range of variants of a design. This goes further than the limited parametric surveys of hullform shape coefficients, based on a single baseline design, used in procedures such as the UCL Ship Design Exercise [*UCL, 2001a*]. Daman et al [*1997*] present a similar approach to the UCL one, where a configurationally restricted type ship model is used to generate the baseline design (of Ro-Ro vessels in the example presented) and then a parametric survey is carried out by varying the service characteristics such as speed and payload.

More generally in set based design approaches, the variation in design parameters investigated includes a wide range of characteristics, such as overall dimensions, payload and performance where each combination of options is used to generate a design solution. Nethercote and Schmitke [*1982*] described a model for SWATH ships where, for a defined overall configuration, a large number of variants are generated from inputs, including dimensions, structural type and propulsion efficiency and a post processor is used to allow the designer to view and assess the results for overall trends. Numerical methods can also be used to search the solution space for the design that best meets a given performance requirement. This allows a process of iteration to take place with the designer editing the numerical model to direct the design development. The design system described by Lamb and Kotinis [*2003*] illustrates the main limitation of set-based approaches, which is their restriction to type-ship vessels, with little configuration change between variants and simple measures of performance to allow optimisation via conventional numerical search methods.

Although the design solutions in set based methods are generated using models similar to the point-based approaches, (i.e. employing linear relationships) different methods have been used to evaluate the resulting densely populated solution space. Multiple criteria decision making approaches have been adopted to allow the performance of each candidate solution to be assessed, using a method, such as weighted preferences, as described in Section A1.2. Some set based methods use Genetic Algorithms to direct the development of the design solution (see Section A1.3).

## A1.2 MULTIPLE CRITERIA DECISION MAKING

### Overall Approach

A summary of Multiple Criteria Decision Making (MCDM) was presented in the IMDC 1997 Design Methodology state of the art report [*Andrews et al, 1997*]. MCDM is differentiated from mono-criterion decision making in that the optimal solution is not immediately clear from the problem and a trade-off must be made between possibly conflicting criteria. The overall hierarchy of terms within the field is included as Figure A1-1 below. This figure differentiates between Attributes, such as length or weight and Objectives, which are Attributes with direction, such as *minimum* weight or *minimum* cost. Goals are composed of Objectives with Constraints. Within MCDM there are decision making processes based on the attributes, Multiple Attribute Decision Making (MADM) and objectives, Multiple Objective Decision Making (MODM).

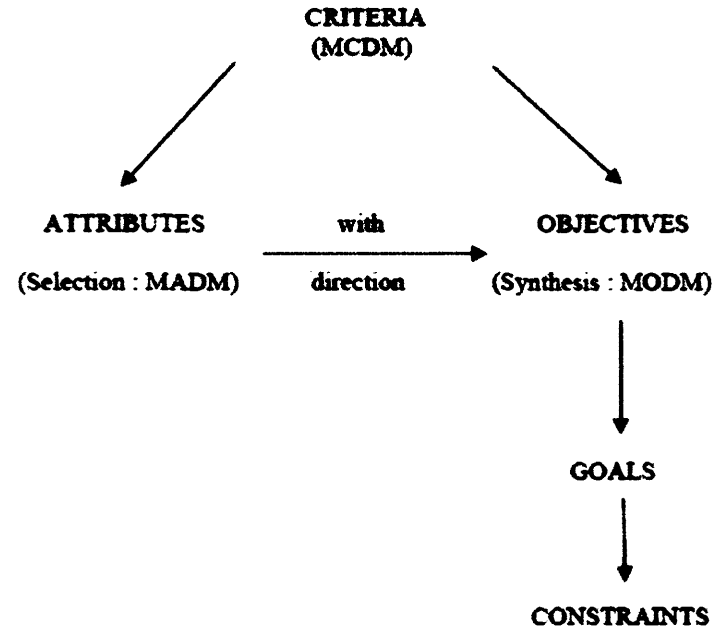


***Figure A1-1: Definition of terms within MCDM [Andrews et al, 1997]***

There are many different numerical methods and overall approaches that have been used in MCDM and there is no overall classification scheme [*Andrews et al, 1997*]. As noted in Section A1.1, MCDM is a method of ship design that requires the development of a large set of candidate designs and their evaluation. A parametric model of the ship is used to generate these designs and their performance is evaluated by numerical tools. Thus a solution space is generated containing many different possible designs, each with attributes corresponding to the objectives (such as minimum weight).

This solution space can then be searched using a range of numerical methods, as summarised by Keane et al [*1991*] and more recently by Parsons and Scott [*2004*] and Hootman and Whitcomb [*2005*]. The aim of these methods is to meet a range of objectives whilst respecting the constraints, the latter being the edges of the solution space. The type of search to be employed is determined by issues such as the numerical nature of the solution space, the possibility of local maxima and minima which may cause a search routine to miss a global "optimum" solution and the calculation time available [*Parsons & Scott, 2004*]. A representative example of a solution space showing two variables and a range of possible design alternatives is shown in Figure A1-2. This shows three main regions; the dominated, or inferior alternatives, the non-dominated extreme alternatives and a frontier of non-dominated compromise alternatives. This represents the "Pareto-Front" [*Whitcomb, 1998*], the set of solutions in which no aspect of effectiveness can be improved without detrimental effects on the others.

Genetic Algorithms, discussed in more detail in Section A1.3, can be used as a form of MCDM and have advantages such as a resistance to the local optimums referred to above. In GA approaches, rather than populating the entire solution space prior to any evaluation, the search is directed, by the evaluation of each generation of designs and the selection of those determined to best meet the objectives to create the next generation.

An important aspect of the application of MCDM is how to perform the effectiveness evaluation of the design alternatives and how to turn technical evaluations of performance, such as maximum speed or payload capacity, into a single measure of effectiveness (MOE) such as that shown in Figure A1-2. This issue has been discussed by Whitcomb [*1998*], Brown and Thomas [*1998*] Brown and Salcedo [*2003*], Brown and Mierzwicki [*2004*] (considering specifically the issue of risk in naval ship design) and Hootman and Whitcomb [*2005*].

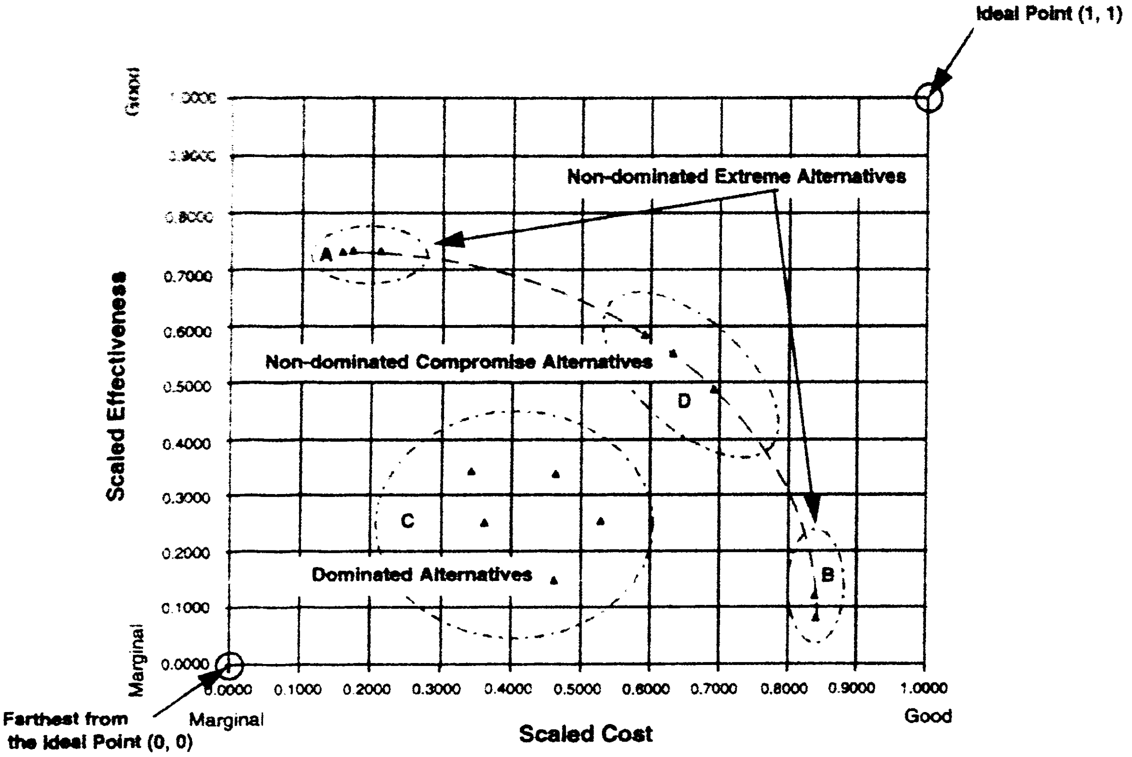


***Figure A1-2: Cost – effectiveness trade off regions [Whitcomb, 1998]***

A general process for the development of a single measure of effectiveness could be summarised as:

- Evaluate a candidate design's measures of performance (MOP) in each field to be considered (speed, limiting sea state for helicopter operations etc)
- Non - dimensionalise this against the target value (to produce a measure of the degree of effectiveness) (MOE)
- Combine these non-dimensionalised effectiveness measures via a weighting system (Overall MOE, OMOE).

The weighting system adopted can be very complex, with a hierarchical structure as shown by Figure A1-3.

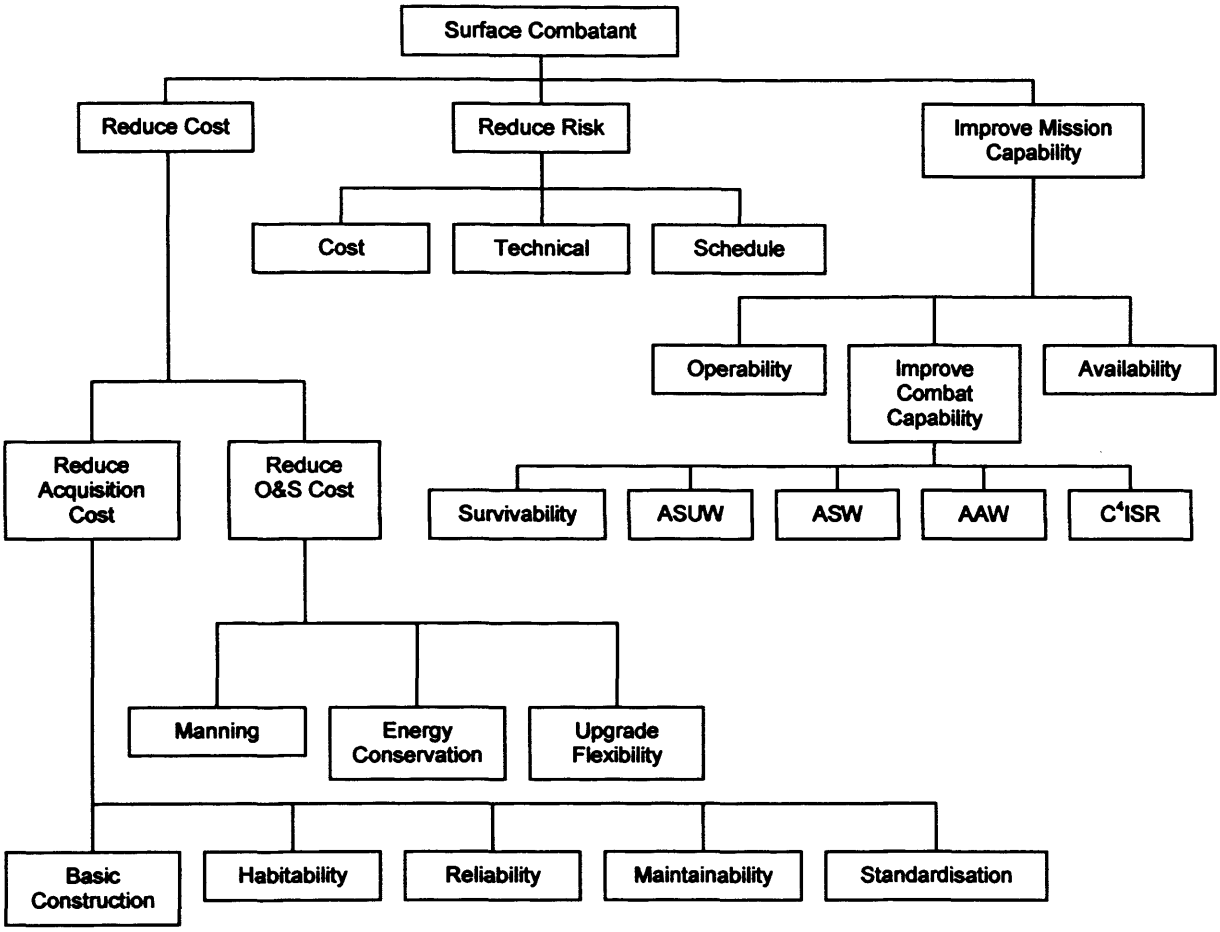


***Figure A1-3: Objective hierarchy (after Whitcomb, [1998])***

There is also the issue of how to describe performance in areas such as "operability" as a single figure and how to evaluate a complex aspect such as risk, which can originate from many sources and be highly subjective. Brown and Mierzwicki [*2004*] address this issue by considering the impact on the design of developmental technologies not coming to fruition.

## Applications

MCDM approaches have been applied to the problem of preliminary ship design in many ways. An early application was by Mandel and Leopold [*1966*], who considered the selection of principal dimensions and hullform shape coefficients for cargo ships and tankers based on type-ship parametric models. Their optimisation technique made use of weighted performance parameters and a random numerical search method. Similarly, Nowacki et al [*1970*] considered the selection of tanker overall characteristics based on economic measures and used a directed search method to locate the optimum point in the solution space. Lyon and Mistree [*1985*] addressed the problem of selection of container ship overall characteristics and included in their numerical method a parametric survey around the selected design point to confirm it was the optimum. This system was later enhanced and demonstrated in a simple case of a barge [*Smith, Kamal & Mistree, 1987*].

The detail design issue of the selection of heat exchanger type was used as the example by Bascaran, et al [*1989*], in a system that relied on the designer to construct the numerical problem to be solved, by specifying the attributes, objectives, constraints and evaluation scales. Warship design was then considered [*Mistree et al, 1990*], for the case of a corvette. Although this utilised a more advanced mathematical model than the early container ship studies, it retained the basic concept of using a configurationally constrained parametric model of the design for subsequent numerical optimisation. The more recent tool described by Artana and Ishida [*2003*] makes use of the commonly available Microsoft Excel software for the selection of container ship main dimensions and power requirements and notes that the approach is not difficult to implement if the problem and optimisation model can be fully defined.

Peri and Campana [*2003*] consider the detail problem of reducing hullform resistance and use a Genetic Algorithm based approach to generate the candidate hullforms. However, their approach is notable for the provision to the designer of scatter plots of the solutions to allow the designer to assess whether the constraints are too restrictive and are reducing the investigated solution space. The example of a destroyer, similar to the DDG-51 class, was used by Brown and Thomas [*1998*] and Brown and Salcedo [*2003*] to demonstrate a hierarchical structure of MOEs leading to an Overall Measure of Effectiveness. This work also utilised a Genetic Algorithm based approach to produce the range of candidate designs. In evaluating a new risk metric, Brown and Mierzwicki [*2004*] considered an advanced vessel carrying Unmanned Combat Air Vehicles (UCAV) and featuring a range of advanced weapon, propulsion and hullform technologies.

## Application to Preliminary Ship Design

Multiple Criteria Decision Making methods in general have been demonstrated by application to a range of problems encountered in preliminary ship design. The effectiveness of mathematical methods in finding the optimum point, as defined by some measure of effectiveness, in a numerical solution space is long established. The use of hierarchical weighting systems allows the incorporation of a wider range of performance aspects than just speed and payload capacity. Where a problem can be expressed in a numerical form, MCDM can provide a robust and rapid method of solution. However, there are several significant limitations to the application of the methods in preliminary ship design, particularly of innovative ships.

In order to generate the large number of alternatives required for an effective search of the solution space, a configurationally constrained parametric model must be used, so limiting the range of solutions that can be considered to those with well-understood spatial relationships. This limits the application of the approach to well-structured and broadly understood problems, such as tankers or monohull corvettes, with clear measures of effectiveness and suitable tools to analyse performance. Even within this constrained region of applicability, there remains the issue of how to evaluate issues such as operability, producabilty, survivability, adaptability and risk, which require more detailed modelling of the configuration of the design. Another aspect limiting their applicability is whether they can address innovation and novelty. For a novel concept to be assessed by MCDM, it must be included as part of the problem to be solved. (For example, using a new hullform design or machinery type.) Novel solutions to problems that might emerge in the design development will not arise in a numerically optimised parametric solution, thus limiting, but not completely removing, the applicability of MCDM to innovative preliminary ship design.

## A1.3 GENETIC ALGORITHMS

### Overall Approach

Genetic Algorithms, sometimes referred to as Evolutionary Algorithms, are a method of solving search and optimisation problems that is based upon the principles of natural evolution [*Sommersel, 1997*]. The main steps in the process of using Genetic Algorithms in the analysis of a system or design can be summarised as follows:

- The design phenotype (physical design) must be mapped to the genotype (collection of chromosomes) by describing the design as genes (design parameters) and arranging these genes as chromosomes (collection of design parameters).
- The fitness of each chromosome (set of design parameters) must be evaluated, by evaluating the fitness of the corresponding phenotype (physical design).
- The chromosomes (set of design parameters) are then ranked according to the fitness evaluations.
- A new population of chromosomes (collection of design parameters) is created by both combining the characteristics of the highest ranked chromosomes and by introducing small random changes to the chromosomes themselves.

At each stage of the evolutionary process a large number of chromosomes will be created, but the method of evaluation would allow a single solution to be reached. An alternate approach however is to use the Genetic Algorithms to produce a wide range of solutions and then to select from this range using multi-criteria decision making methods (discussed in section A1.2).

In addition to the applications of Genetic Algorithms to ship design described below, Genetic Algorithms and evolutionary principles in general have also been suggested as an analogue to the overall design process. Bercsey et al [*2001*] suggest that the method of improvement of the design used in the approach is a closer model to the flexible iterative methods used by human designers when considering constrained detail design issues in engineering design.

### Applications

Genetic Algorithms have been applied in a wide range of detailed ship design problems. Lowe and Steel [*2003*] consider the use of Genetic Algorithms to generate faired hullforms early in the design process. Partial Differential Equations are utilised to generate a range of hull surfaces that fulfil specified dimensional criteria, with other dimensions allowed to vary. (For example for specified internal volume, draught and freeboard, solutions would be generated with varying length and beam.) The Genetic Algorithms are used to identify those hullforms that match the geometric requirements. As this leads to a wide range of candidate hullforms, an additional algorithm is used to identify "clusters" of similar solutions and select the design that is closest to the centre of the cluster. This reduced range of hullforms is then presented to the designer, so that they can be assessed for performance. Although Lowe and Steel's research demonstrates the potential for the GA in exploring an unknown, but mathematically describable solution space, it is limited by the difficulty in numerical hullform generation and thus many of the hullforms generated, whilst fulfilling the numerical criteria, are not realistic.

Gammon and Alkan [*2003*] again consider the problem of hull design, attempting to produce a hullform with the minimum resistance whilst meeting an internal hold volume constraint. In this approach, the selection takes place in two stages, with two separate 'species' used – the first describes the overall parameters of the hull, such as the length and beam and the second describes the offsets of the hullform itself. As well as hullform design, Genetic Algorithms have been applied to the problem of watertight bulkhead spacing [*Boulougouris & Papanikolaou, 2004*]. In this case, the Genetic Algorithm is utilised due to its ability to assess the design against multiple criteria and to operate within multiple constraints. In this case the relative importance of the fitness parameters is decided by the designer and a large set of possible designs generated can be post-processed to find the solution that best meets the given objectives.

Brown and Thomas [*1998*] and Brown and Salcedo [*2003*] consider the application of the approach to wider evaluations of mission effectiveness and gross ship characteristics such as overall dimensions and payload. Their studies focussed on the selection of major equipment items and performance aspects such as speed and range to meet several overall mission objectives. Again, they utilise the Genetic Algorithm for its ability to assess a design against multiple criteria and to meet multiple objectives. The vessel designs considered were produced using a simple derivative of the ASSET model leading to estimates of ship speed and cost. The effectiveness of the designs was evaluated from the specified payload for the variant and the performance of the design resulting from the synthesis model.

Genetic Algorithms have also been applied to the problem of layout of ships. Sommersel [*1997*] describes the use of Genetic Algorithms to generate the layout of an Offshore Support Vessel (OSV), but in this case the level of detail is much less, with the smallest entity in the model being the volume of a single deck between two consecutive watertight bulkheads. In this case, the model is highly specialised for the analysis of OSVs of a conventional configuration and is used to arrange the many storage tanks that are typical of these vessels.

The problem of warship arrangements has also been examined by Kyu-Yeul et al, [*2002*]. These studies considered only a single deck of a frigate type vessel and led to an arrangement almost identical to that generated by human designers, although in this case the required adjacency between spaces was derived from a baseline ship, so illustrating only that the Genetic Algorithms can be used to replicate the baseline. The difficulty in defining the required adjacency values limited the application of the tool to a single deck.

The Submarine Concept Aid (SCA) described by Biddell [*1998*], [*2000*], [*2001*] applies Genetic Algorithms to the problem of preliminary submarine design. In this case, the configurational model of the submarine is simplified, describing the vessel as a series of "slices" with required adjacencies and absolute positions. The software attempts to produce an order of "slices" that satisfies these requirements. Ballast is added in the process to meet transverse stability and longitudinal trim requirements. The notable feature of SCA is that the submarine definition is part of a larger tool designed to examine the effects of the application of different technologies, such as air-independent propulsion, to a fleet of ships. SCA is able to incorporate features such as new hullform shapes into the model, but this is in the form of new data tables used in sizing the propulsive machinery etc of the submarine and the use of a very simple configurational model means that the total impact of such a feature on the design will not be assessed. The solutions produced are assessed for a range of aspects including signatures, cost and risk (represented as a development cost). The relative importance of these factors in determining the overall performance of each option generated is determined by weighting factors obtained by questioning experts in each domain. The lack of a complete configurational model prevents the SCA from producing designs with the wider naval architectural balance described in Section 2.3, when compared with a tool such as SUBCON described by Andrews et al [*1996*] and outlined in Chapter 3.

More recently, development work on a more advanced approach to the use of Genetic Algorithms in warship layout has taken place. Daniels and Parsons [*2006*] and Nick, Parsons and Nehrling [*2006*] describe different aspects of a hybrid approach using Genetic Algorithms and software design agents. The overall approach is shown in Figure A1-4.

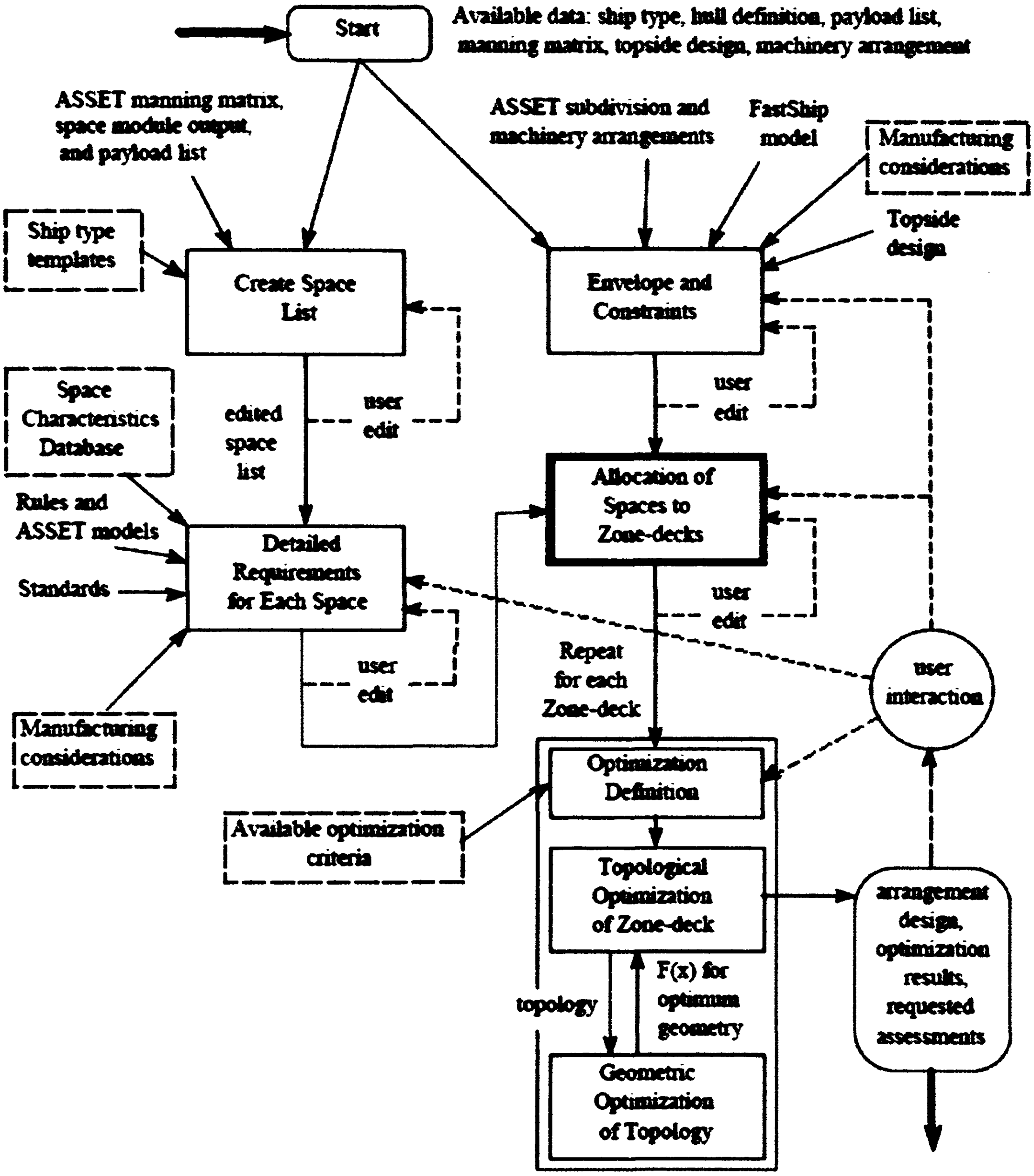


***Figure A1-4: Overall schematic of proposed general arrangements system [Nick, Parsons & Nehrling, 2006]***

The developmental system takes a series of inputs, generated by a human designer, from existing tools as constraints. The ASSET tool provides a machinery space definition, main bulkhead and deck positions and space requirements for internal compartments based on a ship template (frigate, destroyer, corvette etc). The FastShip tool is used to generate a hullform model. The topside arrangement is provided by an unspecified tool. Within these constraints a three stage approach to detail layout is adopted. Spaces are positioned in a zone (coarse longitudinal position), deck (vertical position) and then within the "zone-deck", are more precisely located (fine longitudinal and transverse positions). An important point to note in Figure A1-4 is the inclusion of user interaction, via a tool that permits the user to review the generated arrangement and suggest changes and additional constraints, which can then be implemented. Nick, Parsons and Nehrling suggest that this tool could additionally be used to capture designer experience for future use in automated layout generation.

The general approach outlined by Daniels and Parsons [*2006*] uses a Genetic Algorithm to generate a large range of candidate solutions, which are then assessed by "agents". This hybrid approach was chosen due to its increased speed and the capabilities of the agents to control the search for a solution. These agents have four main roles. Each of the spaces to be placed in the design is represented by a design agent, which evaluates the current position against a database of required absolute and relative positional criteria. These agents then request changes to the configuration (if required to meet the criteria). These requests are passed to a series of domain agents, which evaluate the design and proposed changes for aspects such as survivability, habitability etc. If the changes are accepted by the domain agents, then they are passed to each member of the design agent population. Two further agents are used to discard unfeasible configurations generated by the Genetic Algorithm (e.g. having every space in one zone-deck) and a Genetic Algorithm agent that performs the mutation operations used to generate candidate solutions.

The ongoing study presented is of a small frigate or corvette, containing 17 zone-decks and 100 configurable spaces, represented by 100 genes. Only the zone-deck allocation task was presented and this was not outlined in detail so currently it would seem no comparison with general arrangements generated by a designer can be made.

## Application to Preliminary Ship Design

The application of Genetic Algorithms to the ship design process has several difficulties and these are summarised by Sommersel [*1997*] as:

- Design a ship model and determine how to represent it in the form of a chromosome;
- Find an evaluation function that can be used to rank the instances;
- Construct a Genetic Algorithm that can be applied on the chromosome.

The third of these issues is one of mathematical methods and is beyond the scope of this thesis. However, the first two issues are worthy of more detailed examination.

Regarding the definition of the design model itself, the design (phenotype) must be expressed as a finite number of parameters (genes), which must be independent of one another, to allow the process of random mutation to occur [*Sommersel, 1997*]. Just as the level of complexity in a design increases with time, so the number of parameters and the connections between them will increase, making the identification of independent parameters much more difficult. This problem has been addressed in the studies discussed above by either focussing on a single constrained detail aspect of ship design, or by greatly simplifying the model. In the two most recent papers [*Daniels & Parsons, 2006*] and [*Nick, Parsons & Nehrling, 2006*], the subdivision of a ship into a grid of possible locations appears to resolve this issue. This particular simplification may not be a limitation in early stage ship design, however, when the design definition is inherently simple. However in general the studies leading to a design solution feature a fixed overall layout topology, with the mathematical investigation determining the overall dimensions and proportions.

The second issue is that of how to evaluate the fitness of the chromosomes and is potentially more significant. Firstly, each aspect of the overall performance of the design controlled by the Genetic Algorithm must be analysed. In the case of stability, or resistance, this can be performed using established methods, just as for a design generated by a human. However, for more complex issues such as adjacency and overall position in layout, this assessment requires large databases of the required positions. Obtaining this data from past designs is one possibility, but as with any process of numerical interpolation, the database must be large enough to avoid being dominated by single solutions. Additionally, this will only indicate how ships *have been* laid out, not necessarily how they *should be*. An alternative approach that could improve this is to interview ship operators and illicit their preferences on arrangements. This was carried out by Andrews [*1984*], leading to a matrix of desired spatial relationships. With the introduction of more complex issues, such as producability, survivability, habitability etc, as shown in Figure A1-4, such simplifications would become less appropriate and more detailed analysis and simulation would be required, the complexities of addressing producability issues alone being illustrated by Andrews, Zhang and Burger [*2005*].

The introduction of the "ilities" adds further complexity due to the need to trade-off between potentially conflicting requirements. This introduces the concept of multiple-objective optimisation to the numerical Genetic Algorithm method. Brown and Thomas [*1998*] and Brown and Salcedo [*2003*] use an 'Overall Measure Of Effectiveness', or OMOE, a single figure made up of assessments of different performance aspects, weighted by their relative importance. The difficulty is in deciding the weighting factors to be used in the calculation of the OMOE. The wider use of multiple-objective methods was discussed in Section A1.2.

## A1.4 ARTIFICIAL NEURAL NETWORKS

### Overall Approach

Artificial Neural Network systems attempt to emulate the process of learning that it is believed takes place in the biological brain. Inputs and outputs are connected by multiple layers of neurons or nodes, each of which applies a simple mathematical transfer function to its' input to generate an output [*Parsons, 2003*]. The neurons are connected in a network with weightings applied to the links. The system "learns" during a period of training where the weights applied to the links are defined. This training is performed using a back-propagation algorithm, which adjust the weightings until the output matches the known correct output for a specified input. Figure A1-5 shows the general form of a very simple ANN, with a single internal layer of four neurons and the backpropagation algorithm providing feedback during the training process to alter the weightings.

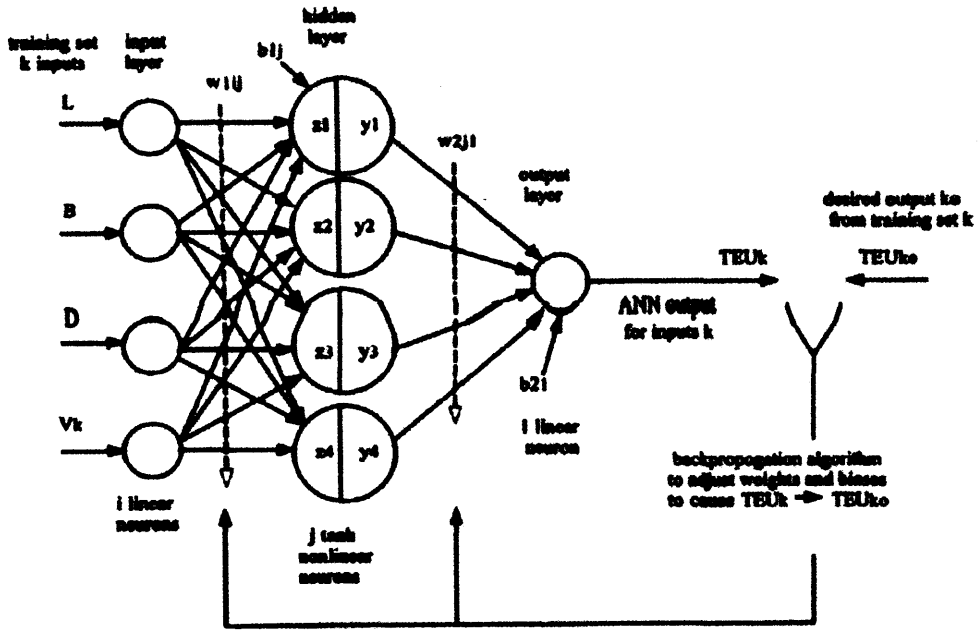


***Figure A1-5: Schematic of a simple ANN [Parsons, 2003]***

After this training is complete, the ANN is capable of generalisation – it can apply the same mathematical operations to a set of inputs that may be different from those used in the training. The ANN can also increase its effectiveness by repeating the training with new data – it can be improved once in use. The main advantages of ANNs are adaptive learning; large error tolerance in the examples; rapid real-time execution and ease of implementation. The main disadvantages are the impenetrableness of the resulting network and the large number of training and test examples required [*Jensen et al, 1997*]. Effective training of the ANN is central to its performance and the examples must contain sufficient information to allow relationships to be recognised. The training process requires a certain level of knowledge about the environment in which the ANN is to be used; the training inputs and outputs selected must be appropriate and there must be some way of recognising when the most effective structure (weightings) has been reached.

## Applications

An advantage of ANNs is that the parallel nature of the trained system permits the analysis of non-linear relationships. Alkan and Gülez [*2004*] describe the use of an ANN to estimate the intact stability characteristics (KM, KG, BM) based on the overall dimensions and hullform shape coefficients of the new vessel. In this case, a database of 22 naval ships was used to train the ANN, modifying the weightings until the outputs matched the actual values in the database.

Neural Networks have been demonstrated for use in making early estimates of the dimensions and weights of container ship designs by Clausen et al [*2001*] and Parsons [*2003*]. These systems allow a designer to use a limited set of defined dimensions to select the other main dimensions and form parameters, based on the historical data of a large number of examples. In this respect the Neural Network is acting as an advisor to the designer, or an 'expert system' as described in section A1.5. Ray [*1998*], presents a different approach, where the Neural Network is 'trained' by a supervisor to produce acceptable designs from limited inputs.

### Application to Preliminary Ship Design

As these above examples show, the main application of ANNs has so far been to the analysis of specific detail aspects of ship design and to the estimation of overall dimensions of specific types of ships. This is a result of the requirement for a database for the training process, as these highly constrained analyses are more amenable to the collation of large databases. This requirement for a training database has so far prevented the wider application of the ANN to more complex problems such as ship internal layout or the initial synthesis of new (non type-ship based) ship designs. That they are essentially tools for extrapolation and interpolation also raises the question of their suitability in assessing innovative and unconventional solutions, where data from previous designs would be lacking. This would be less significant for the design of type-ships, particularly most merchant vessels, where ANNs could be successfully used to produce initial estimates of overall dimensions based on the payload requirements.

## A1.5 Expert Systems and Knowledge Based Systems

### Overall Approach

Expert Systems and Knowledge Based Systems are two methods of utilising computers to draw upon past designs and design experience in the generation of new designs. Together they encompass a wide range of approaches to the problem of incorporating past knowledge into future designs and are both examples of the "Decision Support Systems" outlined by Andrews et al, [*1997*]. This is not to be confused with Multi-Criteria Decision Making, which is a more specific mathematical approach discussed separately in Section A1.2. Halvacioğlu and İnsel, [*2001*] note that interest in expert systems reflects a failure to produce intelligent machines and a new focus on specific problems, to which the application of current artificial intelligence approaches may be more amenable.

Figure A1-6, a schematic of an Expert System structure, shows the three main elements of the Expert System - the knowledge base, containing information on previous designs, rules and regulations; the inference engine, which must apply these rules to the new design; and the designer, or more correctly, the interface with the designer. There are several challenges to be overcome in the development of effective Expert Systems, particularly for a complex subject such as ship design. These are outlined below.

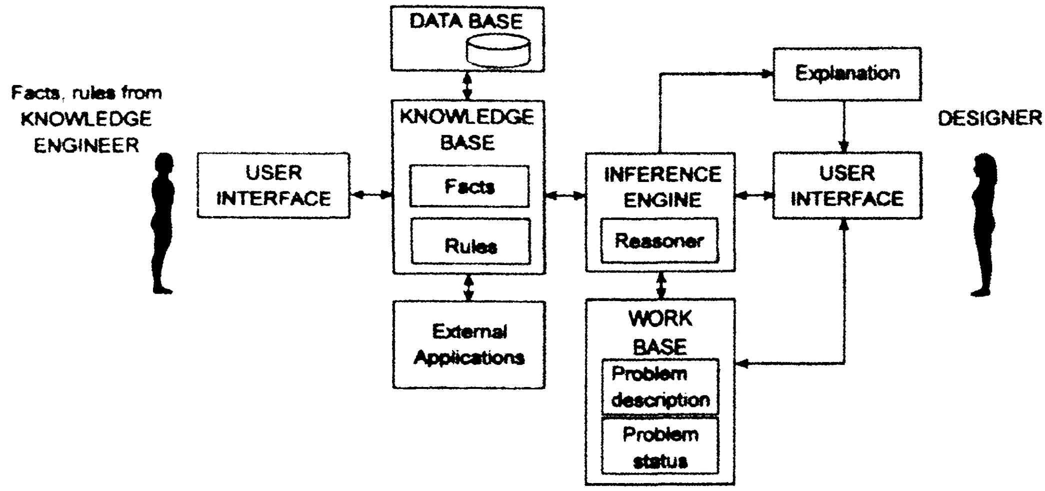


***Figure A1-6: Schematic of the QUAESTOR Expert System [van der Nat, 1999]***

The Knowledge Base is a database of knowledge which may or may not be relevant to the current design. This can take the form of explicitly stated rules, for example for stability standards [*MoD, 2000*]. Alternatively, the database can consist of numerical descriptions of previous designs, a concept also known as "Case Based Reasoning" (CBR) [*Delatte & Butler, 2003*]. As MacCallum recognised when writing on the importance of understanding relationships in design, designers use both codified and explicit methods as well as their own implicit knowledge of ship design, gained through experience [*MacCallum, 1982*].

Although these two approaches are different, some Expert Systems research utilises both. For example Halvacioğlu and İnsel, [*2003*], in approaching the problem of container ship design, use specified rules for some parts of the design while more general relationships are inferred from a database of past ship designs. Alkan and Gulez [*2004*] describe a system that uses Neural Networks (described in more detail in Section A1.4) to determine a relationship between intact stability characteristics and hullform parameters for a database of hullforms.

The Inference Engine is the central component of the Expert System. It must be able to recognise features in the new design and determine which rules should be applied to them. If the new design is constructed in a very restrictive format and the Knowledge Base consists of explicit rules, then this may be relatively simple. However, if the database consists of descriptions of previous designs, then the Inference Engine must be able to derive practical non-trivial design relationships from this information and then determine which are to be applied to the new vessel. The Inference Engine utilises forward and backward reasoning to identify those parameters required to calculate the output. Figure A1-7 shows a general process used for forward and backward reasoning to search within a database of rules and relationships for those connected to the goal parameters.

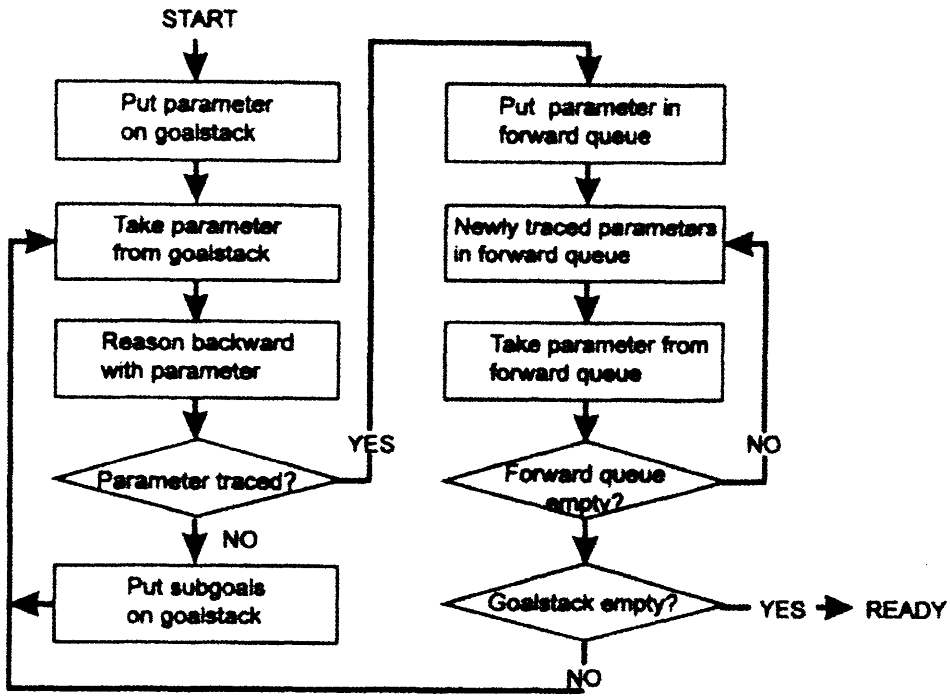


***Figure A1-7: Forward and Backward reasoning [van der Nat, 1999]***

The user interface is important as it must not only present the information gathered from the database in a format that can be used by the designer, it must also allow the inference engine to recognise the new features in the design.

## Applications

Early design applications of Expert Systems were based on simple rules and were thus limited to constrained problems such as mechanical part design. [*Calkins, 1988*] They have been applied more recently in a research context, to the space layout problem in architecture, using Genetic Algorithms to recognise features and extract them for use in the database [*Gero, 1998*].

Van Hees [*1992*] describes the application of the QUESTOR tool, previously used in specific areas such as propeller design, to the problem of preliminary ship design. In this application, the knowledge base contains parameters (such as length), relationships between these parameters (with limits of validity), constraints and a "parameter – expression" covering any of the ratios frequently used in ship design (such as the length/beam ratio), which are used by the designer as parameters but mathematically are relationships. This results in a network model linking parameters and parameter – expressions via relationships. When used in the development of new designs, this network is used to arrange the design algorithms to calculate unknown properties from those that are known. This tool was subsequently used by van der Nat [*1999*] to address the problem of preliminary submarine design.

Andert [*1993*] describes the development of a tool to address the problems of equipment specification and the generation of design requirements for individual vessels classes based on the overall fleet capability requirements. This is a knowledge based approach, where explicit rules are used to relate the overall requirements of the ship, as a unit in a taskforce, to output requirements for speed, armament etc.

Halvacioğlu & İnsel [*2003*] have worked on the development of a knowledge-based system for the early stage design of container ships, using a combination of explicit rules, rules inferred from interviews with designers and an object-based database. However, this application is limited to ships of a specific type and overall configuration together with a simple measure of effectiveness (e.g. Required Freight Rate, (RFR)).

The system developed by Delatte and Butler [*2003*] was applied to very simple models of submarines and cargo vessels and is notable for using geometric features as the design elements to be included in the database. However, the system was limited in that only the principal particulars, such as length, speed and cargo capacity, were used to search the database.

A recent development is the application of the Semantic Web approach to expert systems for ship design by Ando et al [*2003*]. This uses a Resource Description Framework (RDF) to describe the data (ship designs) in a machine readable manner. The user interface displays the connections between entities in the database in a graphical web, with specialist displays of the data extracted from the database generated as required. This developmental tool is notable for the use of a graphical display to present the connections in the database in an intuitive manner, thus allowing it to describe a design process, in addition to design information.

## Application to Preliminary Ship Design

When the Knowledge base consists of previous designs, problems arise concerning exactly which characteristics are to be recorded and how this information is to be effectively represented. Different methods have been proposed, but all the systems presented are limited, in that they can only store those properties and characteristics that have been explicitly defined and extracted from previous designs. Difficulty is also experienced in acquiring data on technical decisions that are not explicitly stated as rules. Interviews with designers have been used for the problem of container ship design [*Halvacioğlu & İnsel, 2003*], however the same problems remain regarding storing these in a practical format and relating them to the new design. The practical limitations on the ability of the Inference Engine to recognise features in the designs and relate them to the database, mean that the new design must be developed in a format that is the same as, or similar to, the database used.

The submarine design tool described by van der Nat [*1999*] has potentially wider application, since the main purpose of an Expert System is to change the order the algorithms used to allow the calculation of any unknown parameter from any start point. However, even here the system is limited in application due to the parametric geometrical description being defined specifically for submarines. To produce a more widely applicable tool, a more flexible geometric model would be required.

The Expert Systems approach has demonstrated potential for storing and applying more knowledge than a single designer could hope to accumulate through experience or learning. However, many of the systems developed to date use highly simplified models of the design, or can only accommodate "type" ships with known and explicit relationships between the components of the design. This would seem to limit the applicability of the Expert System approach in the overall design of innovative vessels without the incorporation of a more realistic synthesis tool that produces sufficiently balanced concept solutions.

The main problem with explicit design rules used in Expert Systems is that they frequently have a limited scope of application and they attempt to show how design *is* done, not how it *should* be done [*Bras et al, 1990*]. This combined with the reliance on type-ships, to enable the inference engine to recognise features in the new design, risks inhibiting creativity in the design process and reducing possibilities for innovation.

## A1.6 VIRTUAL REALITY AND SIMULATION BASED DESIGN

### Overall Approach

Simulation has been defined by Clarke et al [*1986*], quoting Gagn'e [*1976*], as "an experiment using a computer model". Simulation Based Design (SBD) is an emerging multidisciplinary subject that can be applied to a wide range of aspects of warship design as shown by Figure A1-8

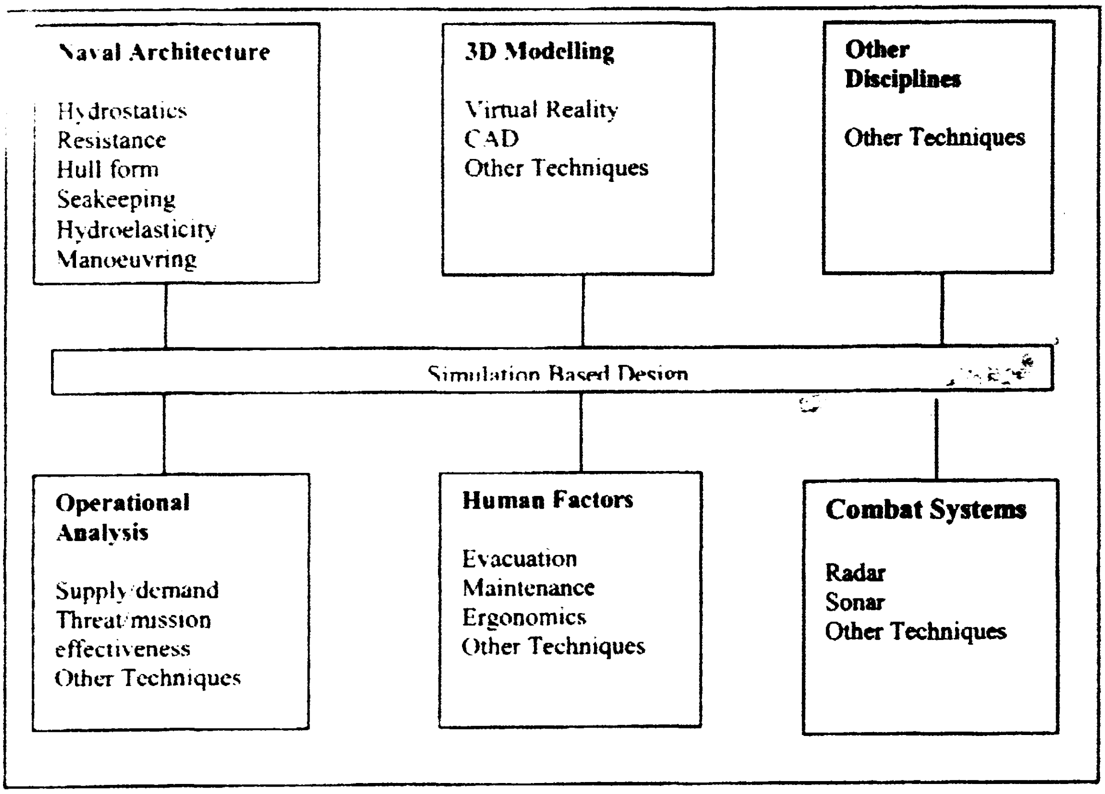


***Figure A1-8: Disciplines and analysis areas in warship SBD [Francis, Lee & Duncan, 2002]***

Virtual Reality (VR) technologies are differentiated from the wider field of SBD by the more realistic graphical representations used and the ability to move within the simulation environment [*Martin, 2002*]. VR can be fully immersive, where the user utilises a headset viewing system or the graphical display can be viewed with conventional desktop monitors or large-format projected screens using stereo projection systems to create the illusion of depth. [*Martin, 2002*], [*Johansson, 2001*]

Tibbitts et al [*1993*] presented simulation and virtual reality technologies as the key to the future US Navy ship design process, as shown in Figure A1-9.

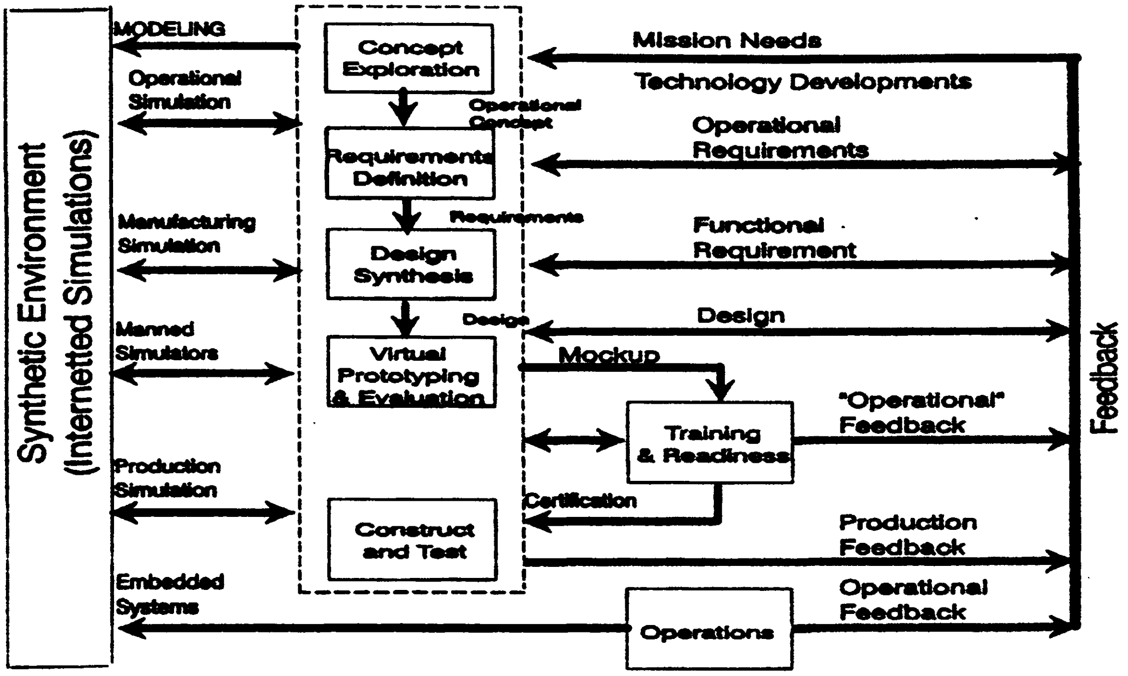


*Figure A1-9: The US Navy's future ship design process, showing the role of simulation [Tibbitts et al, 1993]*

As this wide application suggests, the range of tools used for SBD can be extensive and a federated approach can be adopted to allow different domain-specific tools to communicate with each other in a real time environment as demonstrated by Boudreaux, [*1995*] and discussed by Anderson, [*2000*]. An example of such interaction for the warship design case is shown in Figure A1-10.

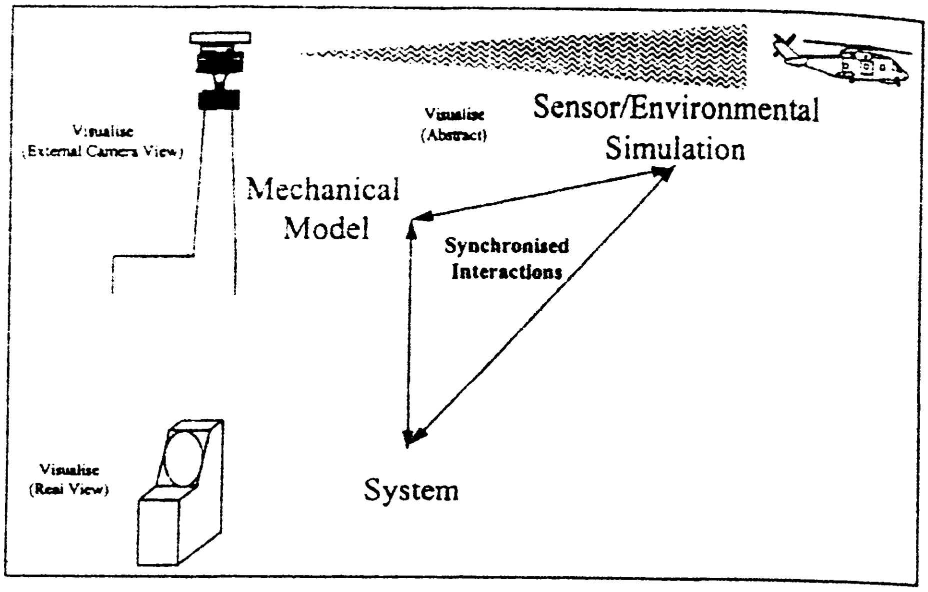


*Figure A1-10: A combination of multiple simulation types [Anderson, 2000]*

This communication requires not only the identification and application of suitable domain-specific simulation tools, but also the development of suitable standard interfaces, a substantial task that has been outlined by Boudreaux [*1995*] anderson [*2000*] and Francis, Lee and Duncan [*2002*], the latter with regard to the UK "Virtual Ship" initiative and Hurwitz [*2001*] on the US Navy's LEAPS project.

## Applications

Research into and application of VR and SBD has been surveyed by Andrews [*2005*], [*2006b*]. Simulation and Virtual Reality tools have been applied to many aspects of ship design, both in the form of developmental tools, such as the ongoing UK "Virtual Ship" project [*Anderson, 2000*] and operational systems, such as the VR design assessments described by Martin [*2002*]. These aspects have included detail technical issues of performance, interfaces with the operating environment and with in-service operations. Two areas that have seen extensive use of simulation are fluid flow, with Computational Fluid Dynamics (CFD) and structural response to loading using Finite Element Analysis (FEA), as outlined by Jensen et al [*1997*].

Personnel movement and evacuation has been assessed using automated "agents" to model the behaviour of crew and passengers, both for cruise liners and ferries [*Galea et al, 2002*], [*Vassalos et al, 2002*] and more recently warships [*Andrews et al, 2007*]. Interactive VR techniques have also been applied to this area of analysis, allowing the designer to view the current design configuration from the perspective of a passenger [*Kostas et al, 2003*]. VR has also been used to assess the aesthetic aspects of cruise liner interior design and layout [*Peverero & Zini, 2003*]. Similarly, flight deck operations on aircraft carriers have been assessed with software links to flight simulators used by pilots [*Martin, 2002*]. VR and line of sight analysis has recently been used during the preliminary design of dredgers, to evaluate the layout of operator positions [*Sonneveld & van Schothorst, 2003*]. In this example, the issues examined ranged from the detail layout of the operators console to the overall configuration of the cranes and control rooms, whilst the vessel was still in a preliminary stage of design.

Simulation tools have been used to evaluate vehicle movements in an aircraft carrier hangar, including an interface to a Genetic Algorithm based tool to evaluate the order in which vehicles should be loaded [*Zini et al, 2003b*], an analysis that requires only the overall configuration of the hangar and vehicle ramps to be determined. Such loading simulations have also been applied to the design of advanced port-ship interfaces for fast intermodal freight transport vessels. This has been investigated using simulations that include vessel and port overall layout and vehicle "agents" that load and unload containers [*Ottjes & Veeke, 1999*].

## Application to Preliminary Ship Design

Examples of development work specifically addressing the integration of simulation tools into preliminary design have been presented by Andrews et al [*2007*] for the case of personnel movement and van Oers and Stapersma [*2006*] for hydrodynamics performance prediction tools. The primary problems raised are the high level of detail required to perform many types of simulations and the requirement for extensive human interaction to pre – and post – process information. Also significant is the issue of assessing the reliability and applicability of the numerical methods adopted in the simulation, particularly if the design definition is uncertain, as is the case in the preliminary stages. The application of VR techniques, as a subset of simulation generally, is less problematic in that it is, in essence, an interface technology and thus all that is required is a spatial model of the vessel to be displayed. As has been discussed above with regards to the many types of numerical model employed in preliminary ship design, even this less representative level of detail may not always be available.

Despite these difficulties, a number of advantages have been proposed for the introduction of SBD into warship design. Tibbitts et al, [*1993*] suggests that SBD will provide the designer with the ability to rapidly assess the impact of changes on the overall ship and Boudreaux, [*1995*] describing early research in the USA, lists the main advantages as:

- Increased concurrency in design processes;
- Increased opportunity for creativity in design;
- Elimination of hard (physical) prototypes;
- Possibility of reduction in design process costs of up to 30%.

However, it has also been noted that changes in the procurement process will be required to fully realise the advantages offered by SBD [*Anderson, 2000*] and Andrews [*2006b*] proposes an approach centred around interactive graphical representations of the design configuration that would allow a more holistic assessment of design performance.

# Appendix 2: Summary of the SURFCON Functional Specification

This appendix contains a summary of the SURFCON Functional Specification as presented to the UK Ministry of Defence as a proposal for a new Computer Aided Preliminary Ship Design System. [*Dicks, 1998*]

The main capability requirements were:

- Create and manipulate graphical representations of a ship design at the concept design stage.
- Provision and modification of hullform descriptions.
- Integrated design and analysis of major features.
- Short and long term storage of design specific and design independent data.
- Analysis of overall design performance and design balance.
- Overall project data management.
- Data output.

A modular system architecture was then suggested to accomplish these tasks. The modules and their short descriptions are included below in Table A2-1. Figure A2-2 shows the overall relationship between these modules. The functional specification included flow charts to show how typical operations would be carried out by interactions between the modules, but these are not included in this summary.

| | |
|---|---|
| **MODELLER** | An integrated two and three dimensional surface and solid modelling system |
| **TOPINT** | Integrated Topside Design and Analysis Tool |
| **SURFHULL** | A Rapid Hullform Generation Method |
| **SURFDATA** | A Relational Database Management System (or other method of data storage) with modular data storage |
| **SURFBAL** | An automated design balance assessment tool |
| **MODELANALYSIS** | A Model to Analysis programme conversion management and interface program and a suite of analysis tools (SURFANALYSIS) |
| **SURFPROJ** | An integrated master control program and project data management system |
| **SURFOFFICE** | Standard desktop publishing and office support software suite including SURFWORKBOOK |
| **SURFINT** | Interface programs to Simulation Based Design tools |
| **SURFOS** | Operating System and system management tool |
| **SURFPLOT** | Naval Architecture Output Program |

***Table A2-1: Short summary of the SURFCON modules outlined in the Functional Specification***

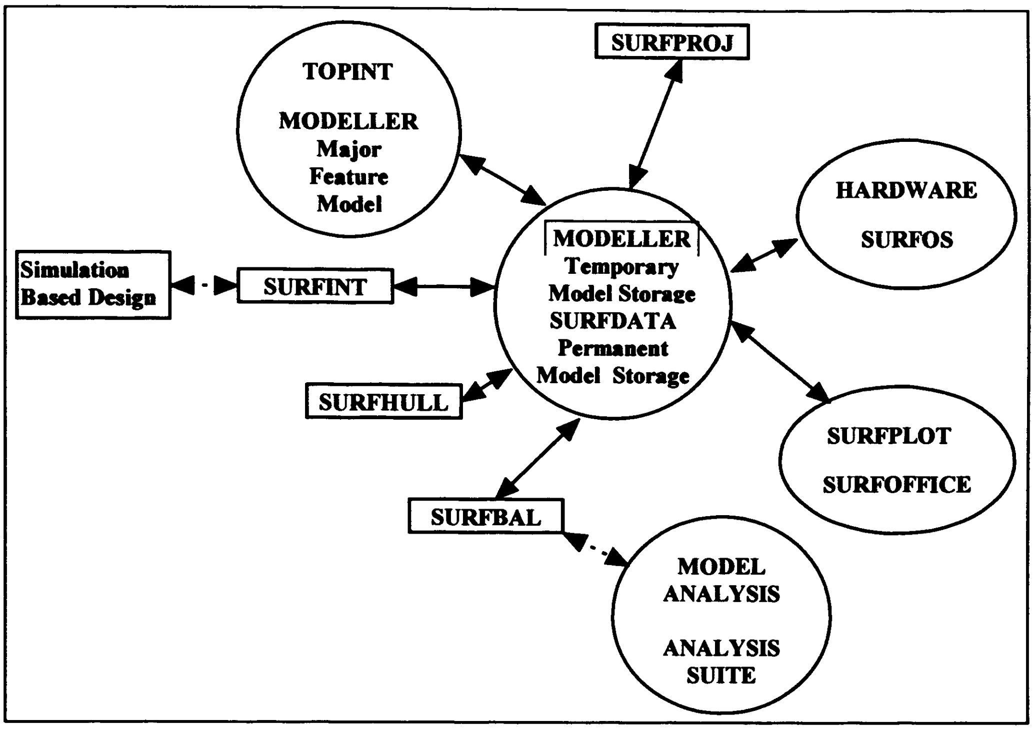


***Figure A2-2: SURFCON system major interactions [Figure 6 of Dicks, 1998]***

Several key capabilities and requirements arise from the overall functional specification, and these are summarised in the sections below.

## Core Graphical CAD System

The functional specification stated that the graphical CAD tool is fundamental as the core of the SURFCON system, and that it should be the interface for all graphical design functions. This core module would provide the user interface with all other modules via the use of dialogue boxes for specialised operations and analyses.

Named MODELLER in the module list above, this CAD system would be based on a commercial CAD tool, and would be capable of displaying 3D views of both solid models and surfaces (for the hull) in a shaded or wireframe representation. The ability to display multiple views of the model and 2D deck plans was also required. In order to differentiate blocks and functional groups, a system of user definable colour 'layers' would be required.

In addition to these requirements for graphical representation, the MODELLER core would have to support parametric models, in which the spatial model is controlled by numerical variables, and in turn the spatial model itself would be used to generate numerical outputs for further analysis.

## Rapid Hullform Generation

An important feature of the notational SURFCON system specified was the ability to rapidly and semi-automatically generate a hullform. This hullform should be representative of the overall dimensions and form coefficients chosen, but would not have to be a production quality, fully faired hull. To allow flexibility in modelling unconventional vessels, the resultant hullform was to be open to manipulation via numerical and graphical means.

## Parametric Survey Tool

In addition to the ability to rapidly generate hullforms, the functional specification also described a parametric survey tool called SURFBAL. This would allow parametric surveys to be performed at the end of a balance or analysis process. The objective of this parametric survey would be to assess the impact of changes in any hullform parameters that were not otherwise constrained by the layout of the vessel.

The SURFBAL tool would use simple estimates for changes in resistance, seakeeping performance and structural weight to produce graphs of changes in design performance as the dimensions or coefficients of the hullform were altered. These graphs, representing the overall shape of the permissible solution space, would allow the designer to select a combination of dimensions and coefficients where no other explicit constraints or selection criteria were available. This configuration would then be used to develop the design.

## Tool Command Language

The availability of a tool command language was specified to allow the designer to develop small 'macros', a short program that would carry out a group of operations upon a single command. This would give the designer flexibility to add additional simple functions and analysis methods to the SURFCON components without recourse to complex software coding.

## Analysis Tools

A wide range of analytical tools would be required in addition to the graphical layout tool. These would have to be capable of the same basic analyses as the GODDESS ship design system, and would include analysis of stability, seakeping, powering and resistance and structural estimations. The use of extant, validated code from GODDESS was recommended. An important feature of these tools was that their operation and the display of results to the designer should be rapid, and reflect the current level of definition in the design.

## Balance Tools

In order to develop a balanced design, the functional specification mandated the use of a set of design balance tools that could interrogate the current design configuration for performance data and requirements, produce reports on the results for the designer, and detail the dimensions or characteristics of the next iterative step in order to improve design balance or performance. Characteristics to be considered in the design balance were to include: Weight, displacement, overall volume, specified dimensions, ships services (Air conditioning, electrical), complement and accommodation, stability, propulsion power, resistance and fuel consumption and seakeeping requirements.

## Data Management Issues

An important area of the computing requirements was the issue of data management. As several alternate designs would normally be developed to the same requirement, the functional specification suggests the use of a 'Ship Project' container for these variants. Automatic documentation of the design history, including notes from the designer to explain decisions, would be required for the variants.

The data types and structures established in the CONDES system were to be replicated in the new SURFCON tool. These would allow the regression of data from previous designs. Similarly, the ability to re-use blocks from previous designs would be required. Some blocks and data would be stored separately, such as that describing weapons systems, sensors and prime movers. This would form a reference database that could be imported into the design as needed, but would not be a part of the design variant itself.

The main design database, including the regression data, would be stored in a separate data file or files. The SURFDATA database tool would control access to this information. The current status of the design would be loaded into MODELLER at the start of a session and then saved at the end. This would be separate from the historical database, and user access controls to restrict access to classified data etc would be required. However, the functional specification stated that a "computer literate naval architect" with appropriate user access could inspect the database directly.

A notable feature of the proposed data storage system is that the very early stage modelling of the overall configuration would be saved in a separate major feature design file, within the larger 'Ship Project', rather than being incorporated into the more detailed designs directly.

## Outputting Results

A method of reporting the contents of the design databases would be required, adhering to normal naval architectural conventions of data formatting. The functional specification mandated the use of a "standard commercial word processor and spreadsheet" as a component of the SURFCON system. The ability to produce drawings of the design configuration and Design Building Blocks would be required, and the SURFWORKBOOK module would document all changes made to the design.

## Development Path

The functional specification envisioned that the initial system would be limited to monohulls, and more radical types, primarily SWATHs and Trimarans, would rapidly follow. The SURFCON tool should be capable of designing vessels for all roles, although Submarines would specifically be excluded, as this capability already existed in the SUBCON tool. The applicability of modelling and analysis procedures to the more radical design was considered, with the conclusion that most are widely applicable, and that those requiring most modification would be powering and seakeeping analysis and structural weight estimation algorithms.

In view of this development plan, the notational SURFCON software should use an open architecture, written to support future updates, with a central modelling and analysis system using external analysis code modules for more detailed calculations, as is indicated in Figure 3.10. One such external analysis tool specifically identified for future development was the topside integration tool expected to arise from Bayliss' research work at UCL. [*Bayliss, 2003*]

# Appendix 3: The Early Development History of PARAMARINE

This appendix contains a summary of the early development history of PARAMARINE. Information on the technical developments of the software was provided via e-mail by Charles Forrest (formerly) of GRC on the first of December, 2004. This text is based on his e-mail.

- First ideas were put to MoD in September 1996 but were rejected as MoD had just completed migration of GODDESS from VAX to UNIX operating systems at exorbitant expense.
- First development started September 1997 as a technology demonstrator for object orientated behaviour and expression evaluation. Graphical User Interface consisting of split tree pane and graphics pane created by end 1997.
- Pilot program "Aquamarine" developed with "HullMaker" (an early capability that attempted to perform the Quickhull task) released to DERA in March 1998. This was not considered a great success.
- Further development of the Paramarine Kernel undertaken during 1998. Parasolid evaluation undertaken, leading to first successful import of a GODDESS outer hullform in June 1998. Remainder of 1998 spent determining correct way to recreate subdivision of the hullform using Parasolid.
- MoD tasked GRC to evaluate the future of the GODDESS New Stability software in early 1999. The development of facet model based hydrostatic calculations lead to a GRC proposal to use Paramarine and solid modelling for the New Stability role. By end of 1999 the Paramarine Kernel had matured sufficiently to provide a stable environment consisting of object oriented database, reliable recalculation, saving and loading, and undo and redo capabilities.
- Early 2000 MoD tasking to develop the SRD for Paramarine stability calculations. Spring 2000 saw a number of GRC-led workshops introducing the Paramarine software to potential users from the UK defence community. BAE Systems Astute took the first Paramarine license in about April 2000.
- From summer 2000 QinetiQ was involved in validating the Paramarine stability functions leading to V1.3 release of Paramarine approved by MoD for stability calculations in October 2000.
- Autumn 2000 was spent developing the first elements of structural definition, including panel generator. Early 2001 saw GODDESS pressure hull structural analysis interfaced to Paramarine structural definition, and later in the spring the Weidlinger codes for blast and fragmentation also integrated.
- From May 2001 work on SURFCON began at the suggestion of Prof. Andrews using funding from UCL; the first round of this was completed around August of the same year. From August to December 2001 we began discussions with SENER regarding interfacing Paramarine with FORAN. We also interfaced Paramarine with CADRCS, MATHMAN and TRIMAN, and the Powering capability was also begun this year. The online help system was also created this year leading to V2.0 release in November 2001.
- A pilot of Seagoing Paramarine was trialled in HMS EXETER during 2001.
- Meanwhile the Naval Architecture side of GRC was migrating the major surface ship GODDESS models to Paramarine during the first half of 2001.
- In December 2001 we began discussions with BAE Systems CVF project on developing SURFCON to address Design for Production (DfP), and also were encouraged to consider developing a concurrent version which we codenamed Ultramarine. A demonstrator of Ultramarine was shown at a user group meeting in the spring of 2002. We interfaced Paramarine with W. S. Atkins' S4 submarine manoeuvring predictor in August 2002. At the same time we were working on the

DfP capability and beginning to consider systems (automatic 3D routing of connections). I presented our work on Paramarine DFP at ICCAS in September 2002.

- From September 2002 onwards we were beginning to address interfacing Paramarine to the Tribon production system as a commitment to the SSA DfP project led by UCL and Prof. Andrews. A necessary first step was to provide a production-level hullform definition which began as the Hull Generator project late 2002. Hull Generator continued intermittently through 2003 as an R&D exercise, finishing in January 2004. Although the technological problems were solved, the tool was not completed. Meanwhile Paramarine was interfaced with the hullform generation code "IntelliHull" produced by Marcus Bole which provides a more elaborate version of QuickHull for commercial vessel hullforms.
- 2003 saw the first production release of Seagoing Paramarine which was distributed to the major RN surface warships. Take-up of SURFCON also began in earnest this year. There were also interfaces from Paramarine to SURVIVE and FREDYN.
- August to December 2003 was spent integrating the Paramarine DfP code with Tribon Hull in a joint collaborative effort with Tribon Solutions. This resulted in a pilot capability which was presented to UK industry in December 2003.
- 2004 has been spent supporting the development of Seagoing Paramarine to consider ship structures, with bulkhead analysis and ultimate strength assessment being added (the latter is an interface with the NS94D code from QinetiQ Rosyth.

# Appendix 4: The KCL Macro Language

All actions taken by the designer in constructing or assessing the design are recorded during the PARAMARINE session and saved as a 'log' file. This uses 'Kernel Command Language', which is the language used to instruct the core software kernel in modelling the vessel. The saved log of actions can be viewed in text format, or even re-played as a 'macro' file to recreate the actions described. An example of the KCL format is shown below. This particular file will create the 'shaft_power' object shown in Figure A4-1. The notes in square brackets explain what each line of instructions means.

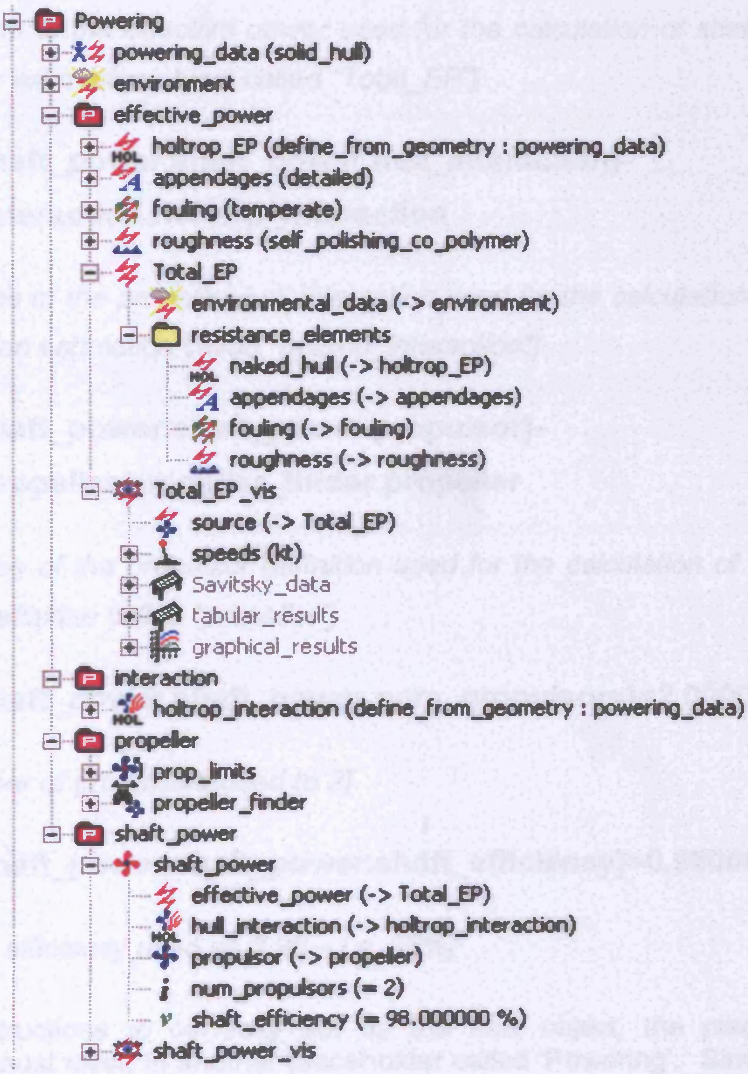


***Figure A4-1 Resistance and Powering prediction objects from PARAMARINE for MCMV study***

**deselect all**

*[De-selects all objects, returning the focus of the software to the upper level of the design model]*

**{Powering.shaft_power} new shaft_power shaft_power**

*[Adds a new object, of the 'shaft_power' type (Calculates shaft power from effective power), called "shaft_power", inside the object "Powering.shaft_power". The full stop demarcates a level in the hierarchy, so this refers to the pink powering placeholder called "shaft_power" which is itself inside the powering placeholder called "Powering", as shown in Figure A4-1]*

**{Powering.shaft_power.shaft_power.effective_power}->Powering.effective_power.Total_EP**

*[Sets the source of the effective power used for the calculation of shaft power as the effective power estimation object called "Total_EP"]*

**{Powering.shaft_power.shaft_power.hull_interaction}->Powering.interaction.holtrop_interaction**

*[Sets the source of the propeller-hull interaction used for the calculation of shaft power as the interaction estimation called "holtrop_interaction"]*

**{Powering.shaft_power.shaft_power.propulsor}->Powering.propeller.propeller_finder.propeller**

*[Sets the source of the propulsor definition used for the calculation of shaft power as the propeller definition called "propeller"]*

**{Powering.shaft_power.shaft_power.num_propulsors}=2.000000**

*[Sets the number of propulsors used to 2]*

**{Powering.shaft_power.shaft_power.shaft_efficiency}=0.980000**

*[Sets the shaft efficiency used as 0.98 – i.e. 98%]*

For these instructions to correctly set up the new object, the placeholder called 'shaft_power' must exist, in another placeholder called 'Powering'. Similarly, the other objects referred to must already be in existence in the correct locations in the design file. This macro language is useful in several ways; it provides a back-up, recording the current work session in case of software failures that lead to a loss of data. It can be used to transfer information to older versions of the software, should this be necessary. The most important aspect is that it provides a description of the processes used to produce the design configuration that can be easily read and understood by the human designer. Any software capable of editing a text file can be used to create and read the macro files. This means that readily available tools such as spreadsheets and word processors can generate macros to perform repetitive tasks, such as setting up the many damage stability assessments to be carried out in a detailed design. This can also be used to facilitate communications between PARAMARINE and other software tools, where pre-programmed interfaces are not already included.

Figure A4-2 below shows part of an Excel spreadsheet used to generate a series of damage definitions for damaged stability assessments task. The entries in column "A" read the case number from cell "B2". As this is incremented, so the text changes to describe the compartments that are to be flooded in each damage case.

| | |
|---|---|
| select Analyse.Stability.Damage_cases | |
| new damage_summary Case_3 | 3 |
| deselect all | |
| select Analyse.Stability.Damage_cases.Case_3 | |
| new damage DS_1 | |
| deselect all | |
| select Analyse.Stability.Damage_cases.Case_3.DS_1 | |
| ->Analyse.Stability.Damage_spaces.Symmetric.Case_3.Compartment_1.attributes.solid | |
| deselect all | |
| select Analyse.Stability.Damage_cases.Case_3 | |
| new damage DS_2 | |
| deselect all | |
| select Analyse.Stability.Damage_cases.Case_3.DS_2 | |
| ->Analyse.Stability.Damage_spaces.Symmetric.Case_3.Compartment_2.attributes.solid | |
| deselect all | |
| select Analyse.Stability.Damage_cases.Case_3 | |
| new damage DS_3 | |
| deselect all | |
| select Analyse.Stability.Damage_cases.Case_3.DS_3 | |
| ->Analyse.Stability.Damage_spaces.Symmetric.Case_3.Compartment_3.attributes.solid | |
| deselect all | |

***Figure A4-2 Excel spreadsheet used to generate KCL macro for adding damage cases for stability assessment***

# Appendix 5: Summary of Objects Available in PARAMARINE and SURFCON

## INTRODUCTION

This appendix describes the objects written by GRC to provide the SURFCON functionality within PARAMARINE. Also outlined are the objects already implemented in the PARAMARINE software that are key to the SURFCON tool. Each of these objects can be placed in one of the three regions shown in Figure A5-1 (Figure 3.19 in the main text);

- Green: Libraries and References,
- Blue: Design Definition,
- Red: Design Auditing and Analysis.

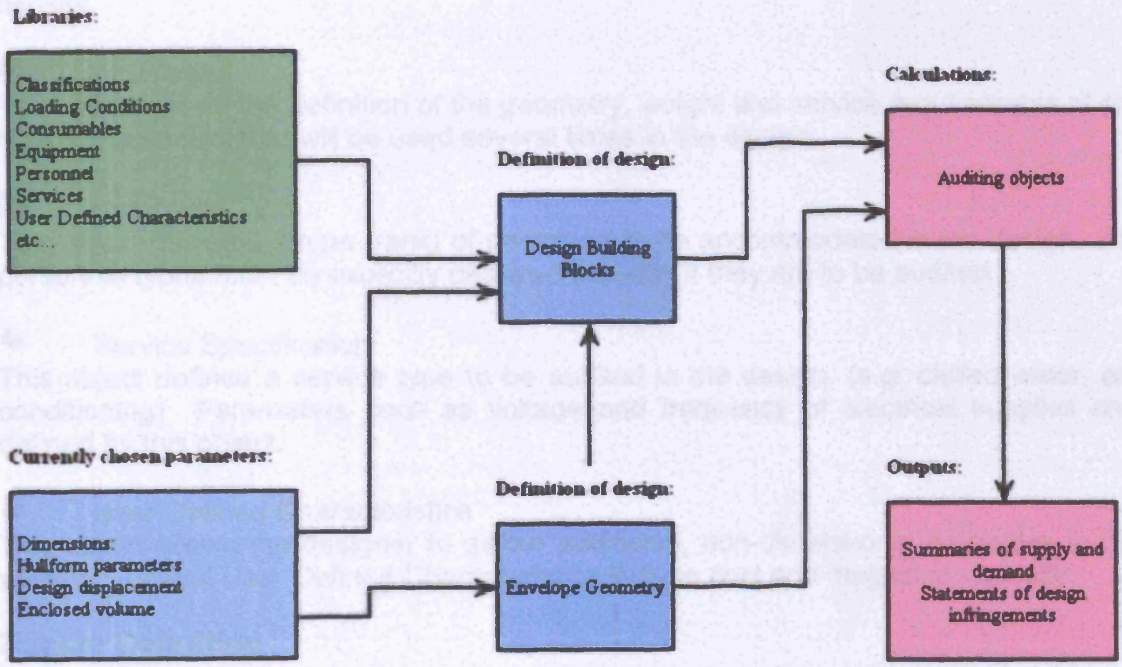


*Figure A5-1: Data flow diagram for a generic SURFCON design file*

This appendix is not, however an exhaustive list of all the objects and functions within PARAMARINE.

## Libraries and References

C Classification
This object defines an entry in a hierarchical classification system. These can be applied to weight or space characteristics, in equipment, spaces or tanks

Condition
This object declares a loading condition to be used in the design. (e.g. Deep, Light, Standard) Variable weights must be assigned to one of the declared loading conditions in order to be audited in the design.

Consumable Specification
ρ Density
These objects are used to explicitly declare, and give density data for, consumables to be included in the design. Variable weights representing solid items (e.g. stores) are assigned a consumable type. Variable weights representing fluids are assigned a density.

Equipment
This object allows the definition of the geometry, weight and service requirements of an item of equipment that will be used several times in the design.

Personnel Type
This object declares a type (rank) of personnel to be accommodated in the design. All personnel types must be explicitly declared this way if they are to be audited.

Service Specification
This object defines a service type to be audited in the design. (e.g. chilled water, air conditioning) Parameters such as voltage and frequency of electrical supplies are defined by this object.

User Defined Characteristics
This object allows the designer to define additional, non-dimensional properties to be audited. Typical User Defined Characteristics include cost and magazine capacity.

## Design Definition

## Guidance Objects

Layout Grid
This object generates a simple visualisation of the positions of decks and bulkheads in the early stages of the design. These do not follow the shape of the hull, but are instead finite orthogonal planes conforming to the maximum dimensions of the design. This object cannot subsequently be used for Design Building Block placement, subdivision or any other design modelling, and is for visualisation only.

Polyline
This is a line in 3D space which is defined as passing through a series of points. This object can be used to more accurately visualise the shape of the decks and bulkheads as they conform to the developed hullform.

Preliminary Sizing
This object uses a large database of merchant ships of several categories to provide initial estimates of size, based on the required payload. They manner in which the payload is specified varies for different ship types. For instance, a container ship will be sized on the number of containers it must carry, whilst a RoRo ferry has a specified lane length for vehicle stowage. The new design is estimated by simple regression from the historical data.

## Hullform Generation Objects

PARAMARINE contains two semi-automatic methods of rapidly generating hullforms from dimensions and hullform coefficients. These are the QuickHull tool for warship hulls, and the newer IntelliHull tool for merchant vessels. These tools provide a means of rapidly generating a new hull surface during the early stages of design. They do not provide a production-quality form, and editing by an experienced hullform designer would be needed to move the design to this much more detailed stage of development.

QuickHull Repository
This object is a hullform definition that can be used by the Quickhull hullform generation tool to produce a new hull. The repository object contains two forms of geometric information: 9 key points, which describe the location of specific points of the hullform, such as the top and bottom of the bow curve, and the position of the after cut up, and 7 guide curves, which describe the shape of the bow, transom, keel, deck and midships section.

QuickHull Repository Generator
This object generates the appropriate QuickHull Repository from the surface of an existing hullform. This allows the generation of a library of 'parent' hullforms for use in generating new designs.

QuickHull Generation 1
This object generates a new hull surface. The object iterates the Cross Sectional Area (CSA) curve and midships coefficient ($C_M$) of the surface to meet a specified target CSA, while ensuring that the hull passes through specified control points (so defining its dimensions) and has the general shape defined by the control curves of a parent QuickHull Repository object. The QuickHull tool is most effective at generating hullforms for warships such as frigates and destroyers, although it is also capable of generating hulls for aircraft carriers.

CSA Param
This object generates a target CSA curve for the QuickHull Generation 1 object from several input parameters: Displaced volume, waterline length (defined by end-positions), parallel mid-body extents, prismatic coefficient ($C_P$), $C_M$, entry and run coefficients (describing the slope of the ends of the curve), coefficients for the additional area of the skeg and the submerged area of the transom and any bow bulb, and the positions of the After Cut Up (ACU) and Longitudinal Centre of Buoyancy (LCB),

IntelliHull
IntelliHull Bulb Shape
IntelliHull Bulb Shape Initiator
IntelliHull Curve
IntelliHull Curve Set
IntelliHull Curve Set Initiator
IntelliHull Demand

These objects make up the InteliHull tool, which allows the rapid development of merchant ship-type hullforms which are outside the capability of the QuickHull tool. As such, this features detailed controls for bow bulb shapes. Instead of matching the CSA curve as in the QuickHull tool, IntelliHull attempts to match a set of user defined demands for dimensions and coefficients. Only the demands that are explicitly stated are met, as opposed to Quickhull, where all variables must be given a value to allow the generation of the target CSA curve.

## Basic Modelling

In addition to the hullform generation tools, the modelling of the overall envelope of the design, and the detail modelling of equipment items in the design require the use of some of the basic geometrical modelling objects within PARAMARINE. These are described below.

Solid Body

The solid body object is a three dimensional shape. These shapes can be made in a wide variety of ways. In the implementation of SURFCON within PARAMARINE, solid bodies are used to represent the envelope of the hull and superstructure. These are made using some of the objects described below. Each of the Building Block and Equipment Instance objects also has an associated solid body, representing the current spatial extents of the entity. Although referred to as a "solid body", a more accurate term would be "volume body", as these objects are actually used to represent the spaces and volumes in the ship, rather than the structures used to bound them.

Point

Points are one of the basic objects within PARAMARINE. This object is a zero-dimensional point in space, specified in Cartesian co-ordinates relative to the "world" origin – which is fixed and immovable by the designer. These are used to define extents for some of the basic solid modelling operations. For example a cuboid superstructure block could be defined by two points representing the diagonally opposite corners.

Planes

A plane is a two dimensional shape of infinite extent. It can be aligned with any of the orthogonal axes or any other angle. Planes are used to sub-divide solid bodies, and to indicate the maximum bounds for those bodies with flat sides, such as the superstructure.

Body Bounds

The body bounds object allows the designer to specify a complete set of spatial bounds for a solid body. In the case of a simple cube, this could be a set of six cubes aligned along the axes, at the appropriate offsets from the origins. There is a great deal of flexibility in the orientation and shape of these bounds, but they must form a single closed shape in order to correctly form the solid body. These are used to define the shape of the superstructure and hull envelopes.

Sheet

A sheet object is similar to a solid body in that it can take any shape, but it has zero thickness. These are normally used to form the bounds of the superstructure.

Surface

The surface object is a surface (zero thickness) described by a grid of cubic equations (B-splines). The designer does not need to edit the equations directly, but rather a grid of "control points" can be moved and the surface distorted. They can represent complex curvatures, but are less suited to modelling completely flat surfaces. Surfaces are heavily utilised in the generation of hullforms, where they are generated by the QuickHull and IntelliHull tools, or developed and edited by hand.

## Outputs

Drawing
Design Deck Sorter

The Drawing object allows the definition of 2D line drawings, based on the 3D geometry of the model of the design. These drawings are connected to the 3D model, and so are automatically updated with the latest design configuration when they are viewed. Typical drawings that would be created include Lines Plans (including Body Plans, Profiles and a Waterlines Plan) and Deck Plans. The latter can be produced directly from the Block Definition object by use of the Design Deck Sorter object, which allows the definition of the position of decks in the design. Building Blocks are automatically assigned to the appropriate deck in the resulting drawing.

Report Instance
Report Connection
Report Detail Bitmap
Report Detail Field
Report Detail Graph
Report Detail Grid
Report Detail Label
Report Detail Object Name
Report Detail Picture
Report Detail Table
Report Page
Report Template
Report Text Style

The Report Instance object is the final object in a series that allow the creation of reports describing the design. As with the Drawing object, these reports are connected to the design definition and will always show the latest configuration when viewed. Reports are defined as a Report Template that can contain drawings (Report Detail Picture), graphs (Report Detail Graph), tables (Report Detail Table) and text strings (Report Detail Label). The resulting pages can be printed directly or exported as images.

## Design Building Blocks

Design Building Block

The Design Building Block object is used to represent an entity in the Design Building Block hierarchy of the design. This object is described in the main text, in Section 3.4.2. The Design Building Block can be given several different characteristics.

Buoyant

This object identifies the Design Building Block or equipment item as being buoyant. The buoyancy can be automatically calculated from the solid body representing the item, or entered manually.

Compressibility

Used in submarine design, this allows the compressibility of a Design Building Block or equipment item to be specified.

Consumable

This object is used to specify a demand weight for a consumable. The consumable type is specified by referring to a Consumable Specification object.

Freeflood

This object identifies the building block or equipment item as being free-flooding for stability calculation purposes.

Personnel

This allows the specification of a supply or demand for a particular type of personnel, the type being specified by referring to one of the previously defined Personnel Type objects.

Service

This allows the specification of a supply or demand for a particular type of service, specified by referring to one of the previously defined Service Specification objects.

Service Conversion

This object indicates that the block converts one type of Service into another. For example, a block representing a transformer would convert a power demand at low voltage to an equivalent power demand at high voltage, with a clearly stated and controlled conversion efficiency.

Space

This object enables the specification of supply and demand values for deck area and volume. The demand can be specified manually or calculated from the current geometry of the block. The supply can be calculated from the block geometry or a different geometry specified by the Design Building Blocks' “Location” pointer. The space characteristic can be associated with a “Classification” object.

Tankage

This object declares the Design Building Block to be an uncompensated tank. The designer must specify the consumable fluid, using a density, the weight and space classifications to use, and the geometry used to define the tank. As with the space characteristic, this can be either the current geometry of the block or the target of the “Location” pointer. The latter allows the Design Building Blocks to utilise spatial data contained in a detailed model of the design that was produced using the conventional solid modelling tools.

The weight of consumable fluid in the tank is automatically calculated as the supply of that consumable, for the block, when the design is audited. For each loading condition where the tank is not completely empty, a separate “Tankage Condition” characteristics would be inserted under this object by the designer. This allows the designer to specify the relevant loading condition, and the percentage fullness of the tank.

Tankage Compensated

This object declares the Design Building Block to be a compensated tank. The controls are the same as the "Tankage" object, but with an additional setting for the compensating fluid.

User

This object defines a supply or demand of a particular "User Defined Characteristic". This allows the designer to incorporate any number of additional characteristics in the design, other than those that are currently written into the software with their own specialist objects.

Weight Absolute

Weight From Solid

These objects allow the definition of fixed or variable weights for the Building Blocks. The "Weight Absolute" has a single value, whilst the "Weight From Solid" calculates the current weight of the Design Building Block from a specified density and the geometry. These objects can be assigned to a consumable specification, in which case they provide a supply of that consumable. If they represent variable weights, then they must be assigned to the relevant vessel loading condition. These weights can be assigned to a classification object.

Tag

The Tag object allows the addition of text strings describing the design. Pointers can be added to the Tag object indicating those objects to which it refers.

Variable

The Variable object is widely used in PARAMARINE and SURFCON, both as an item added by the designer, and as an inherent property of other objects. Variables can be assigned any unit type supported by the software. They can contain fixed numbers or expressions which the software will evaluate to find the current value. These expressions can be linked to any other numerical value in the same model. This gives the designer great flexibility in constructing the model of the design. The only limitation to these connections is that they cannot lead to a "circular argument", where an object references to itself. In addition to conventional algebraic and trigonometric formulae, Variable objects can also use logical operators such as "IF", and can return text strings as an output.

Node

This object allows the definition of a node by means of an offset in Cartesian co-ordinates from the datum point of the building block. These nodes can be used to specify spatial relationships between the blocks that must be satisfied, or they can be used to link two blocks together such that their relative positions in 3D space remain fixed. The graphical representation of the resultant position of the node, relative to the world origin, is viewed by opening the "node_positions" placeholder.

Equipment Instance

This object is inserted into the Design Building Block hierarchy in the same way as the Design Building Block object. The designer sets it to refer to one of the Equipment Definition objects, and it then takes on their spatial and numerical characteristics in the design. This allows the addition of multiple, identical entities in the design. However, this object is not intended to describe functional spaces, as once an equipment instance is used within the design it cannot be edited. It is a "define once, use many times" object, as opposed to the Design Building Block, which is a "define once, use once" object.

Node Relationships

Nodal Relationship

Nodal Relationship objects are inserted under the Node Relationships object, and define a spatial relationship between two Nodes in Building Blocks or Equipment Instances. These relationships can be in the form of maximum or minimum direct distances, offsets in the primary axes, or angular relationships in bearing or elevation.

## Design Analysis Objects

Block Summary

This object gives a summary of all of the characteristics of the Design Building Block hierarchy. Totals are separated into buoyancy, complement, consumables, services, space, user defined characteristics and weight. The extreme dimensions of the spatial extents of the Design Building Block hierarchy in the X Y and Z directions are also calculated by this object.

Block Definition

The Block Definition object allows the addition of margins and properties that apply to the whole ship, such as Board and Growth Margins. Supply and demand variables for consumables, personnel, services, user-defined characteristics and space can be added here, as can absolute weights. These properties can be connected to the outputs of the Block Summary object.

Design Audit

This object audits the design. The design can be audited for buoyancy, complement, consumables, services, space, user defined characteristics and weight, which can be audited in different loading conditions. The results are presented in tabular form, which can be hierarchically arranged in one of three ways; by Design Building Block; by assigned weight or space group classification; or by subdivision. The level of detail in the resulting tabular summary of the design is controlled by setting the number of hierarchical levels to be displayed.

Clash Detection

Clash Detection Exception

These two object control how spatial clashes are assessed in the design. The 'Clash Detection' object allows the designer to specify whether spatial clashes should be assessed for the following categories; Block to Block clashes, Block to Equipment clashes, Block to Location clashes, Equipment to Equipment clashes and Equipment to Location clashes. In the case of the clashes with "location", a design problem is reported to the designer if the block or equipment item is outside the geometry defined as the "location". This allows the designer to assess whether prime movers can be accommodated in machinery rooms, aircraft in hangars etc.

The 'Clash Detection Exception' object allows objects to be excluded from the analysis. This is required because the spatial clash detection is based on a 'bounding box'. This is a cuboid simplification of the object being assessed, based on its maximum extents in the X Y and Z directions. As shown in Figure A5-2, this is an acceptable simplification for simple cuboids, but looses applicability for rotated objects, and complex shapes such as cable runs. By excluding these shapes from the clash detection, the number of false clash reports is reduced. Although a more accurate assessment of clashes using the actual object shape would be desirable, this would increase the calculation time required.

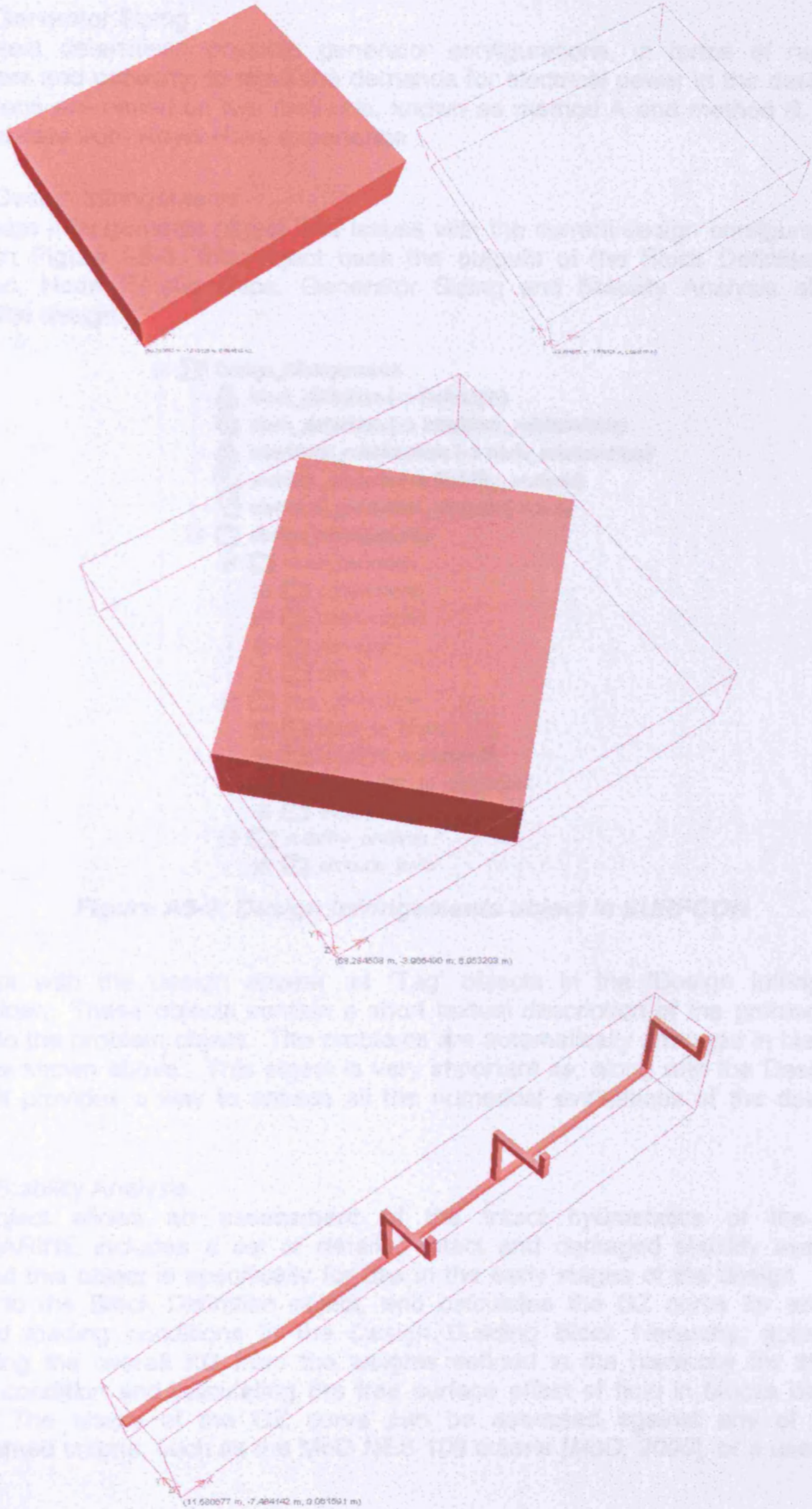

***Figure A5-2: Bounding Box simplifications for simple, rotated and complex shapes in SURFCON***

### Generator Sizing

This object determines possible generator configurations, in terms of number of generators and capacity, to meet the demands for electrical power in the design. The calculations are based on two methods, known as method A and method B, that use empirical data from Royal Navy experience.

### Design Infringements

The design infringements object lists issues with the current design configuration. As shown in Figure A5-3, this object uses the outputs of the Block Definition, Clash Detection, Node Relationships, Generator Sizing and Stability Analysis objects to assess the design.

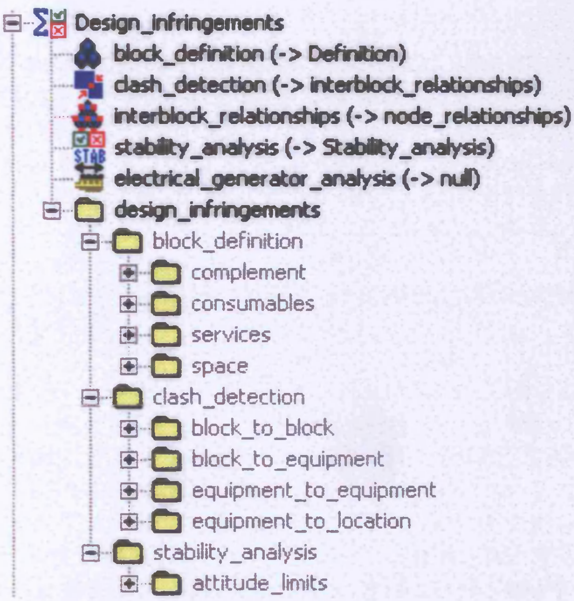


***Figure A5-3: Design Infringements object in SURFCON***

Problems with the design appear as 'Tag' objects in the 'Design Infringements' placeholder. These objects contain a short textual description of the problem, and a pointer to the problem object. The problems are automatically arranged in hierarchical order, as shown above. This object is very important as, along with the Design Audit object, it provides a way to assess all the numerical evaluations of the design at a glance.

### Stability Analysis

This object allows an assessment of the intact hydrostatics of the design. PARAMARINE includes a set of detailed intact and damaged stability assessment tools, but this object is specifically for use in the early stages of the design. It refers directly to the Block Definition object, and calculates the GZ curve for any of the specified loading conditions in the Design Building Block hierarchy, automatically calculating the overall KG from the weights defined in the hierarchy for the stated loading condition and calculating the free surface effect of fluid in blocks defined as tanks. The shape of the GZ curve can be assessed against any of the pre-programmed criteria, such as the MoD NES 109 criteria [*MoD, 2000*], or a user defined criteria.

The object provides Pass/Fail assessments, numerical reports, and a full set of hydrostatics data for the current configuration. The "stability analysis" object cannot be used for the assessment of damaged stability however, as the extent of the damage cannot be specified. That task is performed using the objects that already exist within PARAMARINE, taking advantage of the common software environment to transfer the KG from the Design Building Block hierarchy to the additional stability assessment objects.

# Appendix 6: Fast Motherships – A Design Challenge

**Originally presented to RINA International Conference "Warship 2004: Littoral Warfare & the Expeditionary Force", London, June 2004**

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## SUMMARY

It is some thirty years since the US Navy, in particular, had such a focus on high speed operations. This return of interest has been due significantly to the post-Cold War focus on littoral operations, where opposition to Coalition naval forces are more able to deploy small high speed craft. These are considered to be of sufficient threat in coastal waters for major navies to consider deploying fast craft themselves, rather than placing high value ocean going multimission warships too close inshore. However there is then a need to get these small fast coastal assets to the littoral; hence the concept of a Mothership able to transport several small fast assets to theatre in a reasonably short time.

This paper describes the design work undertaken by the Design Research Centre at UCL, as part of a team led by BMT Defence Services Limited in response to a task placed by the UK Ministry of Defence to explore the feasibility of 'mother/daughter' ship concepts as one of a number of potential solutions to the RN's Future Surface Combatant requirement. The UCL task consisted of designing a range of possible new concept Motherships, including heavy lift, docking and heavy gantry/crane options to deploy small fast assets designed in parallel by BMT-DSL. Each concept was designed using the UCL SURFCON approach as part of the Graphics Research Corporation PARAMARINE ship design system. The advantage this approach gave in designing these novel solutions to a challenging operational concept is shown through the ability of the SURFCON approach to balance both technical and configurational features in concept solutions.

## 1. INTRODUCTION

The concept of a mothership, that is a large vessel able to carry one or more smaller ships, is not new. The costs inherent in providing a significant naval capability for world wide deployment is seen by even the largest naval powers as budgetarily challenging. It is a truism in naval ship design that the essentially coastally deployable corvette can have an almost equivalent combat system capability to a frigate designed for world wide operations. The extra size, and cost, of the frigate arising from the capability to operate in deep oceans are due to the commensurate provision of endurance in fuel, stores and self support plus the considerably greater complement than the corvette, necessary for both the deployment and the independent operations in theatre. These essentially ship qualities are often hard to argue through politically charged procurement processes often obsessed with "maximising bangs for bucks" simplicities. One possible solution to this issue is to have smaller, limited endurance but highly armed vessels which are deployed by large "motherships".

The attraction of this approach has grown for the NATO naval powers since the end of the Cold War. Firstly, with no challenge to the West's command of the deep oceans there is no obvious deep ocean military threat typically requiring all naval units to be full combatants or needing the protection in depth provided by squadrons of frigates. Secondly, peace keeping operations in the littoral are more likely to be subject to asymmetric threats which high capability and expensive major combatants would wish to avoid by not going close inshore. Hence, there is seen to be a case for the Coalition navies to be able to deploy small fast and, by implication, more disposable warships. This leads directly to the concept of these small assets deployed to theatre by motherships.

The other element in this emerging concept is that of speed. Traditionally naval staffs see speed as a desirable attribute in any new concept, however the reality of the physics of ship resistance and propulsion quickly demonstrates that, in most instances, the cost implications rule out the spiralling demands of significantly enhanced speed. In a visionary paper, the retiring Chief Naval Architect and Director of Surface Ship Design for the US Navy, recently outlined the renewed interest the USN has in high-speed naval ships (1). It was over 30 years ago that the Chief of Naval Operations for the U S Navy had a vision for a 100-knot navy, which, due to the combination of the Vietnam War and the oil price hike, came to nought, despite considerable research expenditure. Keane sees the revival of this desire for high speed arising from a strategic perspective to move forces quickly to theatre, "especially in the case of a regional crisis". There are two roles envisioned for high-speed ships for the US Navy, both of which are relevant to the study this paper is in part reporting; that of small heavily armed littoral craft or "assets" and of large high-speed sealift vessels, which may produce technologies that could make the very fast mothership concept realisable in due course. However as with the earlier USN research into a high-speed navy, Keane's paper identifies a truly extensive R&D investment across a wide range of technologies necessary to make a genuine leap to achieve really fast sealift ships. Rather, the studies outlined in this paper draw only on current technology in indicating possible state-of-the-art motherships and not what might be achievable with these future technological possibilities.

This paper outlines the manner in which the UCL Design Research Centre in the Department of Mechanical Engineering became involved in the recent Mothership Study by reviewing the latter's origins in the UK Ministry of Defence's Future Surface Combatant (FSC) programme. This is followed by detailing the specific contribution made by the DRC to the Mothership Study. The major UCL contribution was a series of Mothership design studies, which are summarised in the main technical section of the paper. Finally the conclusions on the specific studies, the Mothership concept and the use of the particular ship design approach adopted are given from the perspective of the concept design team.

## 2. ORIGIN OF THE BMT/UCL MOTHERSHIP STUDY

The concept of the Fast Mothership transporting small fast assets to the littoral is a recent innovation in the long running saga of the FSC programme, which itself originated in the need to replace the remaining Type 22 and the Type 23 Frigates in the Royal Navy. While much of the internal debate and the operational and technical studies undertaken in the MoD are not in the public domain, a very good summary of what has been a chequered and extended incubation, for this intended backbone of the future fleet, was in an article written last year by the Editor of Jane's Navy International (2). Scott identifies the earliest studies on what was then the Future Escort as in 1994 coinciding with the first Trimaran frigate design produced by the Future Projects (Naval)'s Concept Design Group (3), however studies for monohull and SWATH variants had preceded even this. Despite the several delays to the FSC's Initial Gate, denoting commencement of significant expenditure and intention to proceed, outlined in last year's article, the stated intention of the MoD is to finally achieve Initial Gate in May 2004. As part of the case for releasing funds to proceed on a range of options to meet the emerging role for what is still seen as "(either) a 'one class' big-ship option, or ...broaden into a wider mixed class, or ...an adaptable and rapidly reconfigurable solution."(2), the Defence Procurement Agency's Future Business Group in late 2002 asked industry to bid for a quick but wide ranging study of the Mothership concept.

Amongst the industry invitees was the UCL Design Research Centre, a new activity established in 2000, alongside the MoD sponsored Naval Architecture and Marine Engineering Group, both components of an expanded Marine Research Group at UCL. The DRC's remit is to specifically focus on Computer Aided Design and in so doing has an alliance with the Graphics Research Corporation Limited to develop the Design Building Block approach through the SURFCON facility as part of GRC's PARAMARINE Preliminary Ship Design System (4). Through work already undertaken by the DRC related to the FSC pre Initial Gate ship studies, the utility of SURFCON in exploring novel ship concepts convinced the MoD that UCL should be invited to bid for the Mothership Study. On receipt of the study requirement the DRC decided that, while it could undertake the ship design work, the wider demands of costing and engineering investigations were best undertaken by an established consultancy rather than in academia. Accordingly UCL allied itself with BMT Defence Services Limited, with which the NAME Group at UCL has had a long standing alliance. This teaming arrangement for the Study, led by DSL, was awarded the contract in February 2003 to complete an extensive study by the end of May 2003.

Allowing for setting up the study team and the end costing and concept assessment work meant, effectively, that the design work was constrained to some nine weeks of intense effort. It was decided that a sensible division of design labour between UCL and DSL was for UCL to major on the Mothership options, described in some detail below, and for DSL to design the assets the mothership would carry as well as detailed investigations of the engineering concepts, particularly those involved in some of the handling arrangements to deploy and recover the assets posed by several of the mothership concepts. BMT DSL also decided to adopt SURFCON to design the assets which had the advantage that mothership and assets could be readily integrated, however it did require the asset designer to achieve familiarity with the unique architecturally focused methodology of SURFCON. It is indicative of the use friendly nature of the SURFCON tool that this only took a few days to achieve for a competent and PARAMARINE familiar ship designer. In the BMT/UCL proposal for the Mothership and Deployable Asset Study (5) it was proposed to consider a range of mothership solutions including heavy-lift ships, dock ships, crane ships and further innovative solutions. Following a early brain storming exercise, when a large number of innovative assets and mothership options were explored, the task was whittled down to some eight motherships, of which seven were undertaken by UCL along with two variants of the Dock Ship solution and it is these that are described further here. The brain storming exercise also strongly suggested that there were diminishing returns in 'mothershipping' relatively large surface ship single assets and so the mothership asset combinations were restricted to four medium assets (600 tonnes) or six small assets (200 tonnes).

## 3. The Specific UCL Contribution

In the joint bid to FBG, UCL provided a new SURFCON version of a mothership design previously produced by a post graduate student as part of his MSc in Naval Architecture (6). This design was for a mothership concept to deploy a 1,200 tonne conventional submarine on a dock ship with a deployment speed of 24 knots. While this was not a particularly fast mothership it was a useful demonstration of the SURFCON tool to represent an extant mothership design study using UCL design data and indicated the level of definition intended to be provided.

The UCL designs were produced using the SURFCON tool realisation of the Design Building Block approach, the logic of which has been spelt out in a recent paper in IJME (7). In essence this approach focuses on ship architecture and how it is produced as part of the evolution of a new ship design. It was precisely this aspect that was identified in 1980 (8) as being a key to a more creative approach to ship design, for the following reasons:-

- Many of the features and aspects of design which could not be properly addressed with the traditional sizing approach could now be incorporated with the better design methods and tools becoming available;
- The advent of computer aided graphic design methods, then in their infancy, but now reaching a level of maturity and being usable with personal computers (9).

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 (10). The Design Building Block approach to producing a new ship design was presented in Ref (11) at Figure 5, reproduced below at Figure 1. This diagram summarises a comprehensive set of analysis processes, most of which are unlikely to be used in the initial setting up of the design or even early iterations around the sequence of building blocks, geometric definition and size balance. In fact several of the inputs shown in Figure 1 are either specific to the naval combatant case, such as topside features, or omit aspects which could be dominant in specialist vessels, such as aircraft carriers or amphibious warfare vessels, where personnel and vehicle flow are likely to dominate the internal ship configuration.

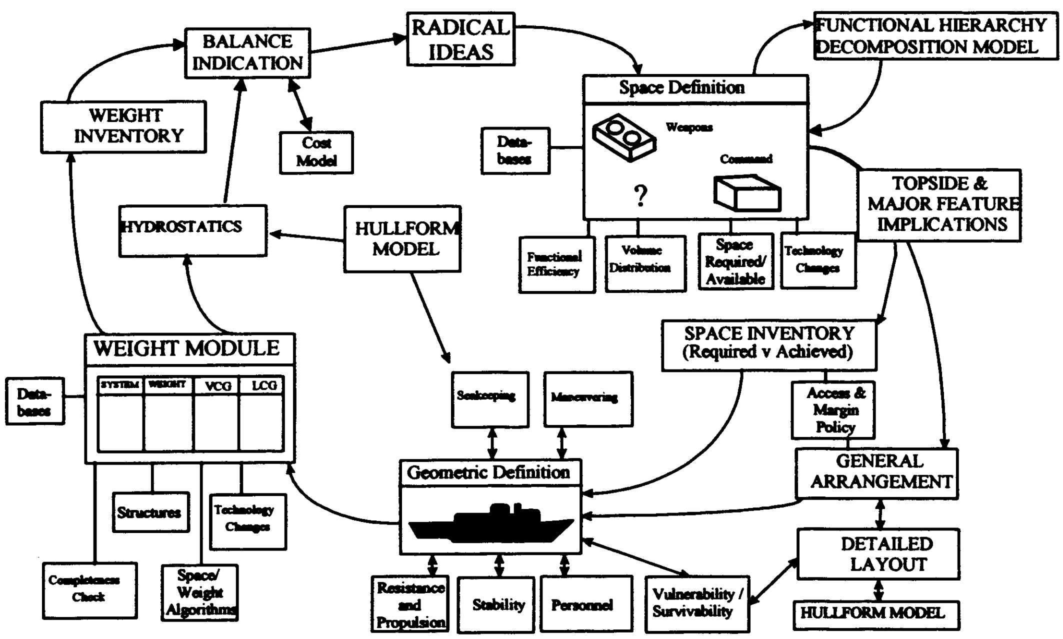


***Figure 1. Overview of the Design Building Block Methodology applied to Surface Ship (11)***

A further feature of SURFCON is the use of the term Master Building Block to denote how the overall aggregated attributes of the building blocks can be 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 (9), is that the audited building block attributes within the Master Building Block can be directly used by PARAMARINE. Thus the necessary naval architectural calculations to ascertain the balance or otherwise of the configuration, just produced by the designer, can be performed. Typical information held in the Master Building Block includes:

- Overall requirements: Ship speed, seakeeping, stability, signatures (in the case of a naval combatant);
- Ship characteristics: weight, space, centroid;
- Overall margins: weight, space and their locations for both growth and enhancement.

As the design description is built up and modified, all features of the building blocks are utilised by the system. The geometric definition (shape and location) is used to constantly update the graphical display, whilst data properties are indicated in a logical tree diagram of the design, as shown in Figure 2. Figure 2 also shows the block representation and a tabular view of typical numerical information from a specific analysis of the design.

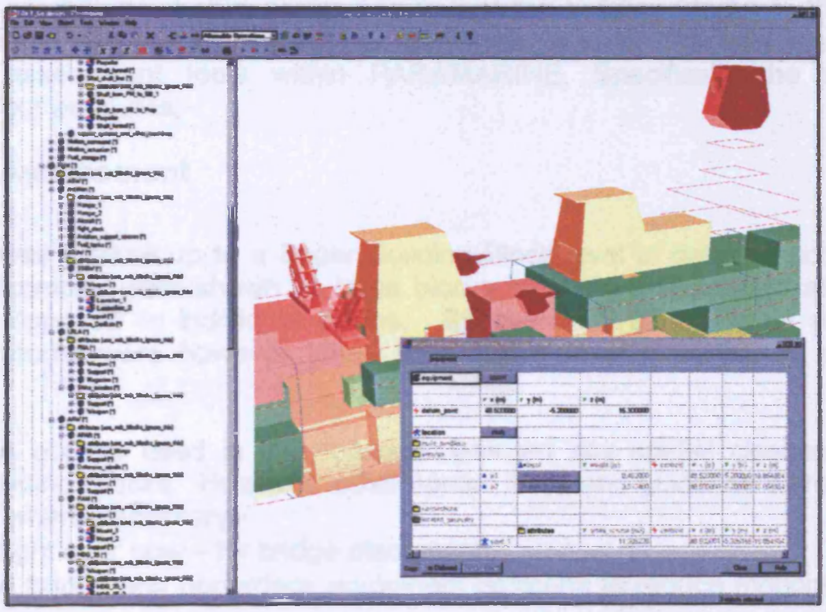

*Figure 2. Multiple views of a Design Building Block using SURFCON*

| Study | Title | Notes |
|---|---|---|
| 1 | Dock Ship | Assets offloaded by ballasting, e.g. LPD (12) |
| 1a | Command Variant of Dock Ship | Enhanced command of assets |
| 1b | Support Variant of Dock Ship | Enhanced support and maintenance of assets |
| 2 | Heavy Lift Ship | Assets offloaded by ballasting, e.g. Blue Marlin (13) |
| 3 | Crane Ship | Assets offloaded by heavy lift cranes |
| 4 | Fast Crane Ship | Enhanced speed crane ship |
| 5 | Gantry Ship | Assets offloaded by stern gantry, e.g. LASH (14) |

| | | |
|---|---|---|
| 6 | Deep Draught Ship | Assets are driven into stern well, no ballasting |
| 7 | SSK Dock Ship | Version of dock ship to carry SSK |

***Table 1. Mothership Options Produced by UCL***

Table 1 lists the seven Mothership studies and the two variants of the Dock Ship design undertaken by UCL. Each design was produced with a two digit weight definition corresponding to the MoD Naval Engineering Specification (15) to enable DSL costers Bertram Martin Consulting Limited to produce Unit Production Cost (UPC) estimates. These are both commercially and government sensitive and have been replaced in this paper with indicative values based on UCL cost data used in the MSc ship design studies. These are given for the UCL Mothership studies in Table 3 at the end of Section 4. In addition the Mothership designs produced using PARAMARINE-SURFCON are balanced ship designs such that the building blocks in the graphical representations have been used to audit the whole design. This was then assessed using the assessment tools within PARAMARINE. Specifically the assessment addressed four attributes:-

## a) Spatial Assessment

The layout was worked up to a Super Building Block level of detail. Accommodation areas, for example, were shown as large blocks by rank, with an area allowance for access, as opposed to individual cabins. Spaces such as the main and auxiliary machinery rooms were however taken to a higher level of detail, to assess their feasibility.

The auditing objects used in the software detected any spatial clashes or overlap between Building Blocks. However, other spatial limits and guidance were included in the designs where necessary:-

- Line of sight over bow – for bridge placement;
- Limits on bridge and upperdeck equipment positions to reduce motions and green sea loading;
- Machinery accommodated within spaces were assessed to ensure they fit inside the hull envelope
- Current hullform shape to visualise deck edges and bulkheads;
- Proximity of sensors and equipment.

## b) Numerical Assessment

The Design Building Block hierarchy was audited:-

- Weight, by Building Block and by weight group;
- Volume supply and demand by Building Block;
- Area supply and demand by Building Block ;
- System characteristics:
  - Sea water supply and demand (for ballast purposes) for the overall design, and by Building Block;
  - For the overall design, the supply and demand values for the following ship systems: Sewage, Dieso, fresh water, AVCAT, Lub Oil, Generator Power (Propulsion and hotel load), available liferaft seating

## c) Resistance Assessment

PARAMARINE contains objects allowing estimation of resistance using a variety of different methods. As the hullform in these studies was similar in some respects to a high speed merchantman, the Andersen/Guildhammer Series incorporated in PARAMARINE was used (16). This is suitable for single or twin screw merchant ship forms in the deep draught condition, with speeds limited to Froude Number (Fn) < 0.33. The resistance was estimated for the deep, dirty condition, with allowances for fin stabilisers, bulbous bow, rudders and pods where appropriate. This resistance was combined with the hotel load to generate a total generator power demand.

## d) Stability Assessment

The integrated spatial model allowed stability assessments to be made at the earliest stages of the design. This was important to ensure that those designs with variable draught could reach the required draught and trim conditions. In each stability run, the current weight distribution and hullform definitions were automatically used, including free surface effects in any defined tanks. The design was assessed to NES 109 criteria (17):-

- Intact, deep and light, with and without asset;
- Loading deep and light;
- Damage forward, amidships and aft for worst case of light or deep in each case;
- Damage forward, amidships and aft when loading assets.

## 4. SUMMARY OF UCL DESIGN STUDIES

Table 2 lists the combat system equipment common to all the seven designs in Table 1. This was considered to be appropriate to a warship carrying valuable assets to theatre, possibly with limited escorts, but not intended to go well into theatre in the littoral where a high threat environment would require greater self defence. The two Dock Ship variants, for Command and Support, were intended to address the implications of providing enhancements in these specific aspects. This was felt to be relevant in exploring the trade off in the relative autonomy of the assets, but was only provided for one Mothership option as the incremental impact could be readily read across to the other options, given the limited timescale for the study.

| |
|---|
| 2 x RAM launcher |
| 2 x Phalanx CIWS |
| 2 x Twin 30mm |
| Command system to control point defence weapons. |
| Basic ESM system |
| 8 x Sea Gnat decoy launcher |
| Surface Ship Torpedo Defence |
| RFA levels of communications |
| Command system to administer assets |
| 2 x Navigation radar type 1007 |
| 1 x Surveillance radar type 996 |
| 2 x flight deck spots for Lynx helicopter |
| 2 hangars for Lynx helicopter |

***Table 2. Combat System Fit to Mothership Options***

The following sub-sections summarise each of the main design options produced by the UCL Design Research Centre as its contribution to the Mothership Study. A comprehensive report was produced covering each of the designs and giving detailed weight and space breakdowns, along with justification for the significant design decisions undertaken in developing and analysing each design (18). This was summarised in the report finally submitted by BMT DSL to the MoD at the end of May 2003.

## 4.1 DOCK SHIP

### Design Summary

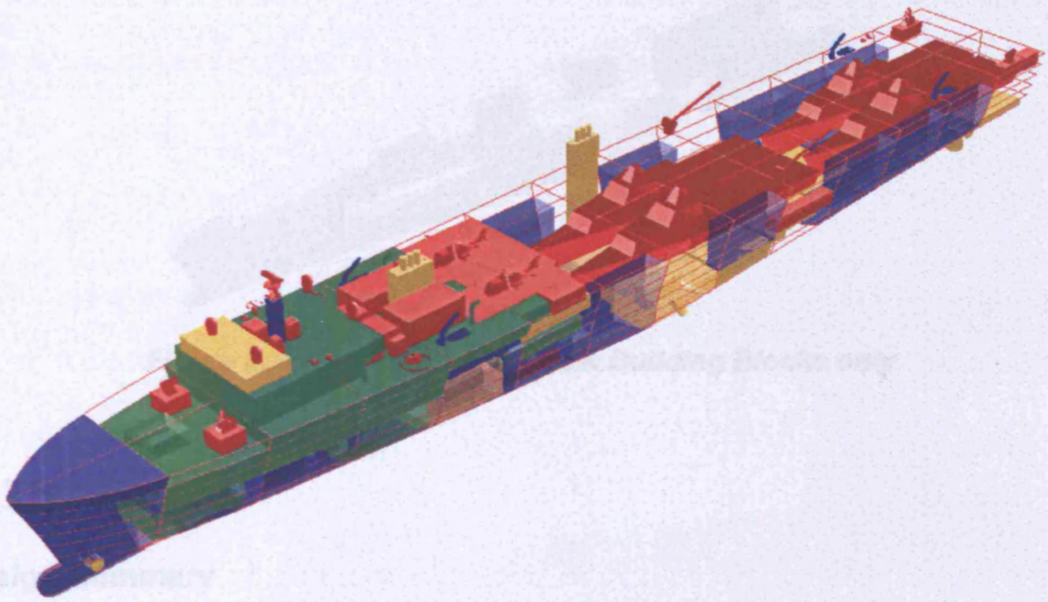

*Figure 3. Dock Ship design showing all Building Blocks*

Propulsive power for 25 knots was 46 MW. This was provided by six diesel generators driving three electric motors on conventional shafts. This vessel carried four medium or six small assets. The final design consisted of 219 Design Building Blocks plus discrete equipment items

| | |
|---|---|
| Lpp | 250m |
| Loa | 255m |
| Boa | 38m |
| Bwl | 31m |
| Draught (deep) | 7.2m |
| Deep Displacement | 32000te |
| Ballast Capacity | 25100te |
| Speed | 18/25knots |
| Range at 18knots | 10000nm |
| Accommodation | 368 |

### Specific Issues

- This design used a combination of trim and parallel sinkage to lower the assets into the water. Because the dock is more than half of the length of the vessel, a large amount of parallel sinkage is required to offload the forward assets. Large ballast tanks were thus needed, distributed along the length of the vessel, see Figure 4. This is different to the case of an LPD where most tanks are aft. The minimum beam of the vessel was fixed by the dimensions of the dock, and so the ship's length was driven by the need to minimise resistance at the high transit speeds.
- To prevent trim by the bow, one machinery space was located under the dock aft, and this limited access to this space for repair by replacement.

- The large dock was considered to introduce structural problems arising from the torsional effect which could be significant with the long dock aft. This was not assessed in detail in this study.
- Damage stability was made worse by the reduction in reserve of buoyancy when the ship is ballasted down to receive or offload assets.

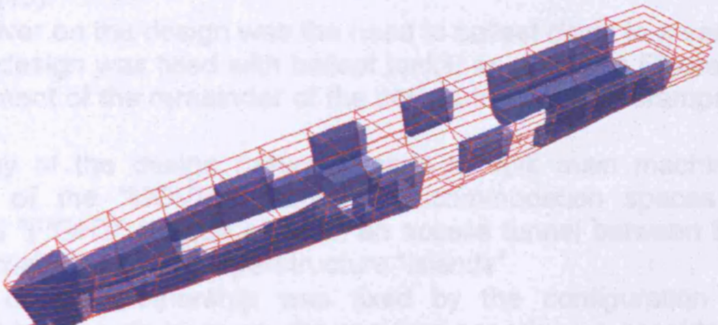

***Figure 4. Dock Ship ballast tank Building Blocks only***

## 4.2 Heavy Lift Ship

### Design Summary

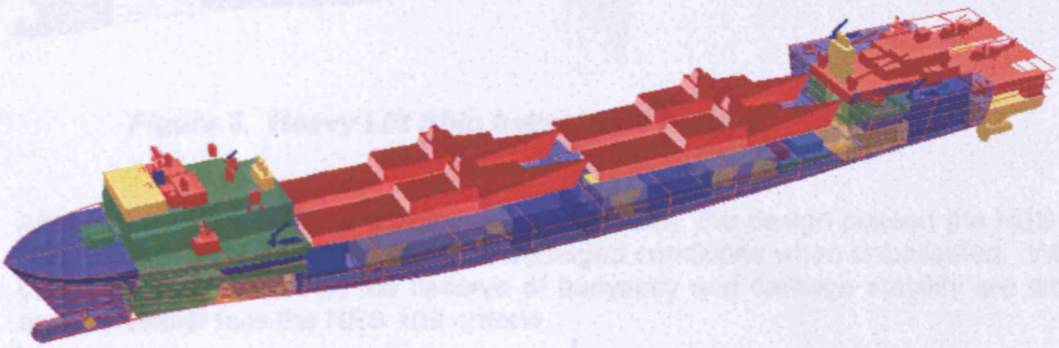

***Figure 5. Heavy Lift Ship design showing all Building Blocks***

This vessel carried two large, four medium or six small assets. Propulsive power for 25 knots was 57 MW. This was provided by six diesel generators driving three electric motors in pods. The final design consisted of 189 Design Building Blocks plus discrete equipment items

| | |
|---|---|
| **Lpp** | 250m |
| **Loa** | 259m |
| **Boa** | 43m |
| **Bwl** | 35m |
| **Draught (deep)** | 8.1m |
| **Deep Displacement** | 38000te |
| **Ballast Capacity** | 49300te |
| **Speed** | 18/25knots |
| **Range at 18knots** | 10000nm |
| **Accommodation** | 368 |

## Specific Issues

- This vessel had to ballast down to submerge the deck amidships and allow the assets to float free. This is similar to commercial heavy lift vessels such as MV Blue Marlin (13).
- The main driver on the design was the need to ballast down to a very deep draught. Most of the design was filled with ballast tanks, as shown in Figure 6. This makes the arrangement of the remainder of the compartments very cramped, see Figure 7 for example.
- The topology of the design naturally leads to split main machinery, increasing survivability of the "MOVE" function. Accommodation spaces were grouped forward, and "FIGHT" spaces aft, with an access tunnel between them. This was due to the small size of the superstructure "islands".
- The beam of the mothership was fixed by the configuration of the assets. Increases in hull length to reach the required speed were considered undesirable due to the very shallow midships structural sections, therefore the resistance was not minimised, and the installed power was considerably higher than for the Dock Ship.

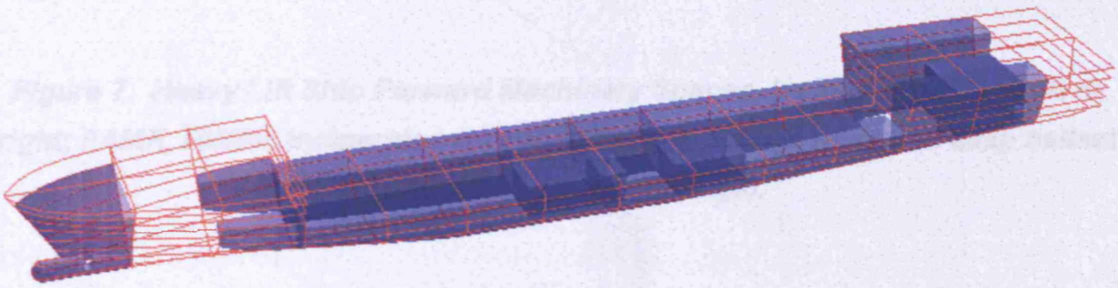

***Figure 6. Heavy Lift Ship ballast tank Building Blocks only***

- Although the freeboard amidships is very low (3m), the design passed the NES109 (17) stability criteria in the intact and damaged conditions when unballasted. When ballasted down however, the reserve of buoyancy and damage stability are small, and the vessel fails the NES 109 criteria.

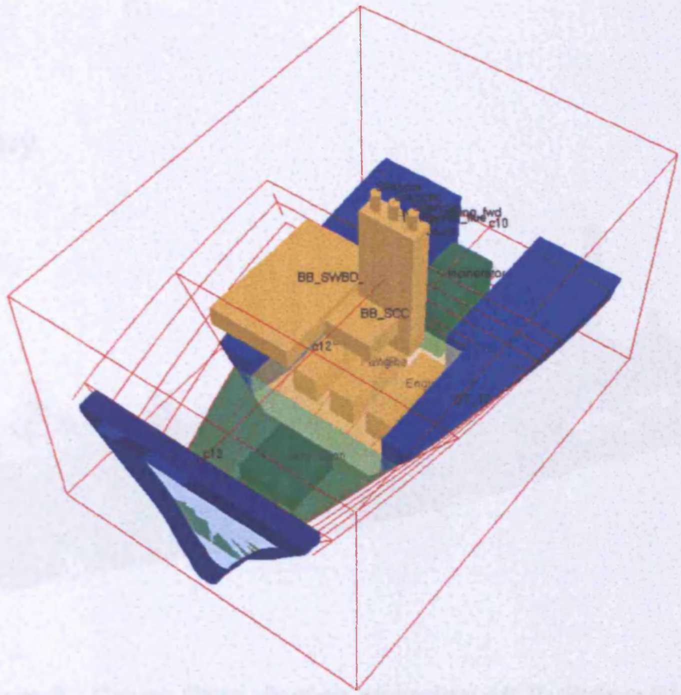


***Figure 7. Heavy Lift Ship Forward Machinery Spaces, looking aft. From left to right; FAMR, FMMR, incinerator space. Note wing ballast tanks and deep ballast tanks forward (Left of image).***

## 4.3 CRANE SHIP

### Design Summary

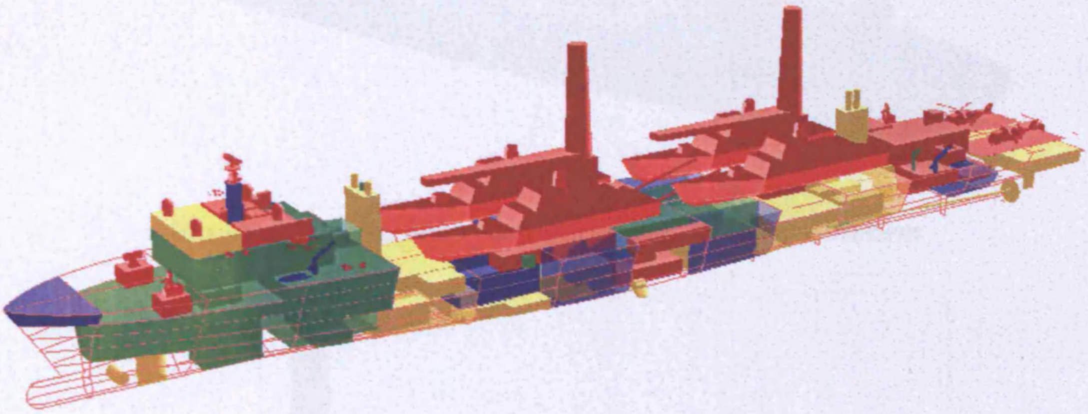

*Figure 8. Crane Ship design showing all Building Blocks*

This vessel carried four small assets. Propulsive power for 25 knots was 42 MW. This was provided by five diesel generators driving four electric motors on two shafts, with separate retractable thrusters in an Integrated Full Electric Propulsion (IFEP) arrangement. The final design consisted of 195 Design Building Blocks plus discrete equipment items

| | |
|---|---|
| **Lpp** | 220m |
| **Loa** | 227m |
| **Boa** | 38m |
| **Bwl** | 29m |
| **Draught (deep)** | 7.3m |
| **Deep Displacement** | 25500te |
| **Ballast Capacity** | 4000te |
| **Speed** | 18/25knots |
| **Range at 18knots** | 10000nm |
| **Accommodation** | 257 |

### Specific Issues

- This vessel used two heavy lift cranes to load and unload the assets. Trim and compensation tanks were required to reduce trim during the loading operation and compensate to the lost weight of the assets. This is similar in concept to commercial heavy lift vessels used for transporting spar platforms for oil exploitation (19).
- The configuration was dominated by the upperdeck arrangements. Again, the minimum upperdeck beam was defined by the asset size and layout. To reduce powering requirements the ship's length was increased from the minimum for upperdeck layout. The ship's length was limited by ensuring the length to depth ratio did not exceed 1:14 based on the hull depth aft of the forward hull.
- The reduction in ballast tankage over that for the first two designs allowed much more flexibility in the design. Thus the hull contained a large amount of void volume, not used for ballast tanks or machinery. A combination of the shallower sections aft, and trim considerations made installation of podded propulsors undesirable, so a system of tandem motors on shafts was used, with a dynamic positioning system for use when off loading the assets. (See Figure 10)

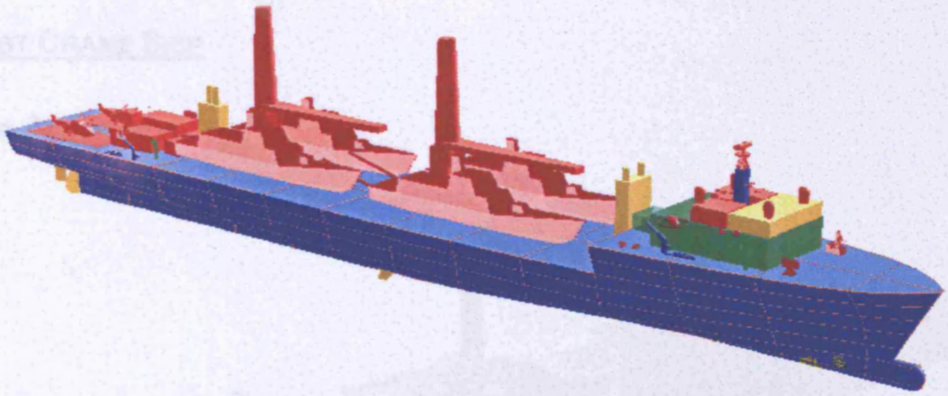

***Figure 9. Crane Ship overall design showing hullform***

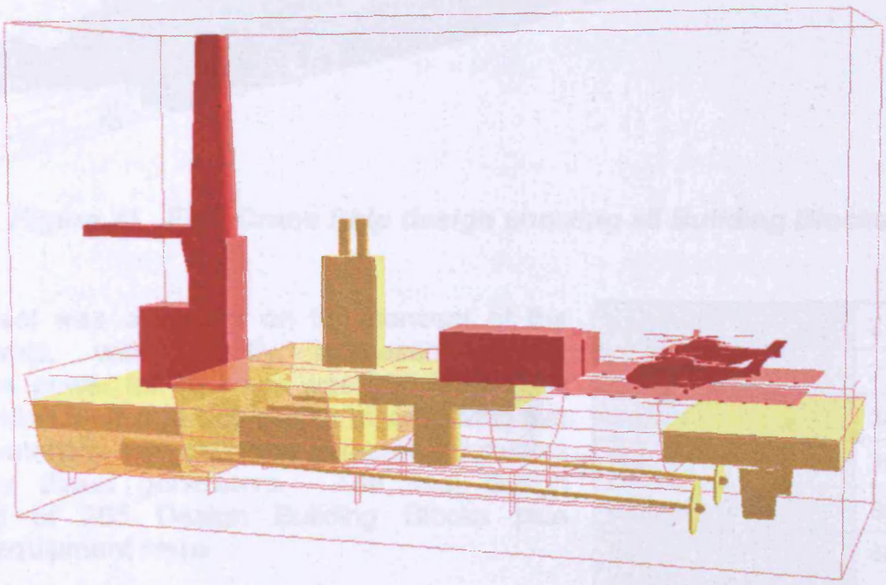

***Figure 10. Crane Ship aft arrangements. From left to right, the main compartments in the hull are the Main Motor Room, After Main Machinery Room and Retractable Thruster Machinery Room. Note the twin shafts in skegs.***

## 4.4 FAST CRANE SHIP

### Design Summary

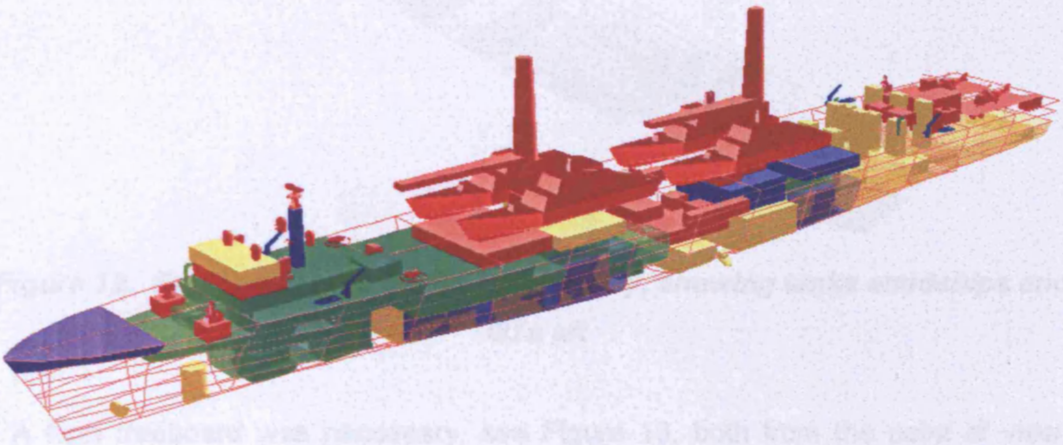

*Figure 11. Fast Crane Ship design showing all Building Blocks*

This vessel was a variant on the concept of the crane ship, with greatly increased speed. Propulsive power for 40 knots was 220 MW. This was provided by five MT-50 gas turbines driving five 50 MW waterjets, with separate retractable thrusters driven by diesel generators. The final design consisted of 205 Design Building Blocks plus discrete equipment items

| | |
|---|---|
| **Lpp** | 270m |
| **Loa** | 277m |
| **Boa** | 38m |
| **Bwl** | 30.8m |
| **Draught (deep)** | 8.8m |
| **Deep Displacement** | 46200te |
| **Ballast Capacity** | 6900te |
| **Speed** | 40knots |
| **Range at 18knots** | 10000nm |
| **Accommodation** | 257 |

### Specific Issues

- The very high transit speed dominated this design. Resistance was estimated using the Mercier (20) method for high speed, transom stern vessels. The resulting power predictions were commensurate with those stated for other large high speed vessels (21).
- Machinery choice was limited to waterjets due to the high installed power and speed. The five MT-50 gas turbines, each of 50MW, required large intakes and exhausts, and this constrained the location of the main machinery spaces. The use of mechanical transmission led to a requirement for separate service generators.
- A very large amount of fuel was required for this design amounting to some 14,000 tonnes. The fuel was not compensated for, and was therefore placed amidships to reduce the effect on trim as it was consumed. Ballast tanks were required to reduce the change in trim and draught, to ensure the waterjet intakes remained submerged.

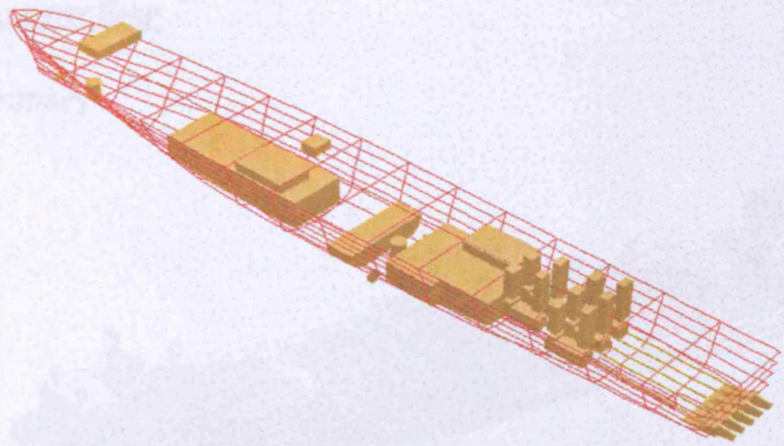

***Figure 12. Fast Crane Ship MOVE blocks only, showing tanks amidships and GTs aft***

- A high freeboard was necessary, see Figure 13, both from the point of view of seakeeping at high speed (not numerically assessed in this study) and to provide sufficient internal volume for fuel tanks. Although this could have implications for the loading of the assets, it enables the design to comfortably pass the NES109 stability criteria in intact and damaged cases.

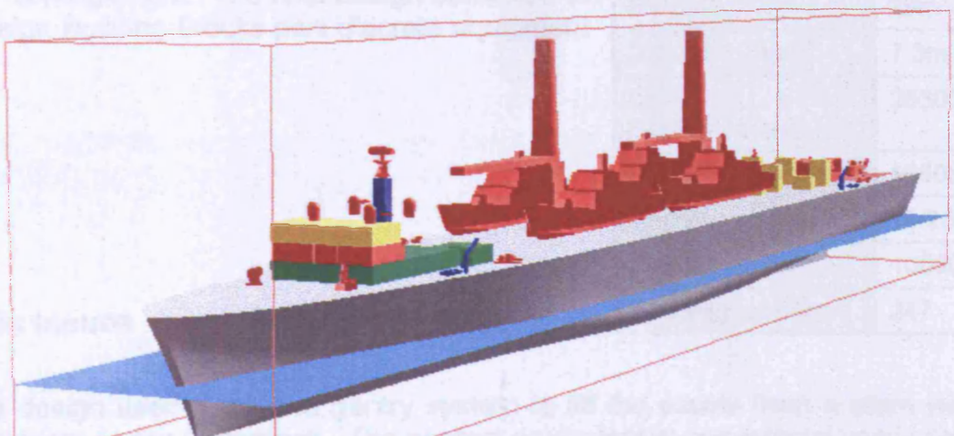

***Figure 13. Fast Crane Ship overview of design showing high freeboard along hull***

## 4.5 Stern Gantry Ship

### Design Summary

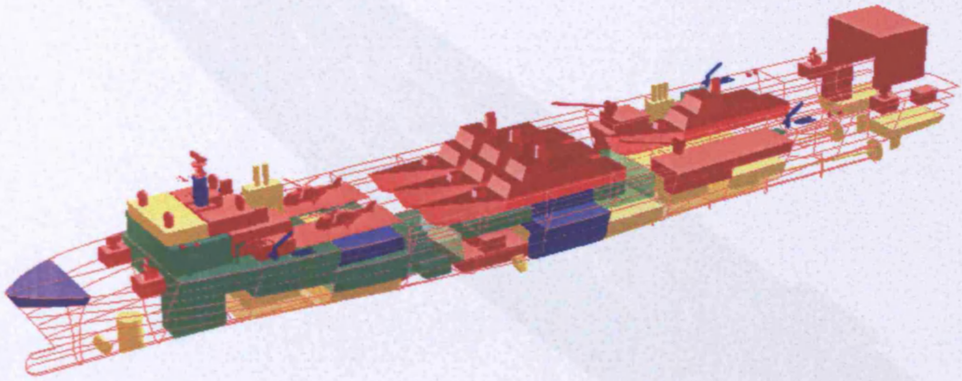

*Figure 14. Stern Gantry Ship design showing all Building Blocks*

This vessel carried four small assets. Propulsive power for 25 knots was 47 MW. This was provided by five diesel generators driving four electric motors on two shafts, with separate retractable thrusters in an IFEP arrangement. The final design consisted of 189 Design Building Blocks plus discrete equipment items

| | |
|---|---|
| **Lpp** | 220m |
| **Loa** | 227m |
| **Boa** | 38m |
| **Bwl** | 29m |
| **Draught (deep)** | 7.3m |
| **Deep Displacement** | 25500te |
| **Ballast Capacity** | 1650te |
| **Speed** | 18/25knots |
| **Range at 18knots** | 10000nm |
| **Accommodation** | 247 |

### Specific Issues

- This design used a rail and gantry system to lift the assets from a stern well and stow them on the upperdeck. The nearest equivalent in commercial use is probably the Lighter Aboard Ship, or LASH vessel (14).
- The design was driven by the upperdeck arrangements, so minimum beam and length were defined by the stowage plan of the assets. The large well in the stern precluded the use of podded propulsion and led to the choice of a tandem-motor shaft system. As with the crane ships, the lack of ballast led to a relatively large void space volume in the hull.

- Relatively small trim and compensation tanks, of 1650 tonnes capacity, were required to compensate for the weight of the assets when offloaded and reduce trim during loading operations.

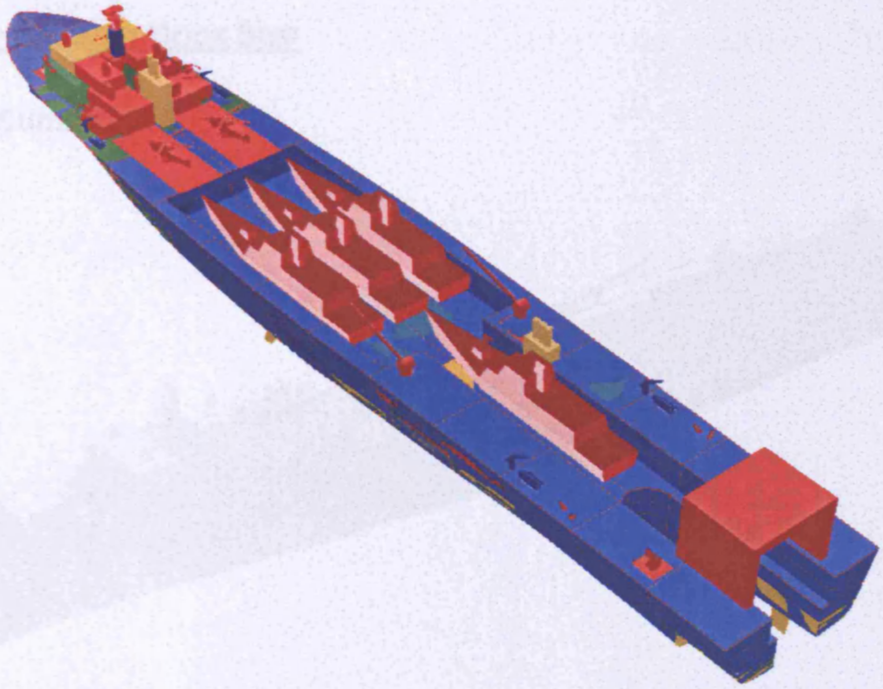

***Figure 15. Stern Gantry Ship overview of the design, showing the well deck aft. The two flight deck spots are forward of the assets, with defensive systems and ships boats distributed fore and aft on the upperdeck***

- The effects of the aft well on resistance and structures were difficult to assess. There could be an increase in resistance, and torsional effects may affect the operability of the gantry due to rail misalignment.

## 4.6 DEEP DRAUGHT DOCK SHIP

### Design Summary

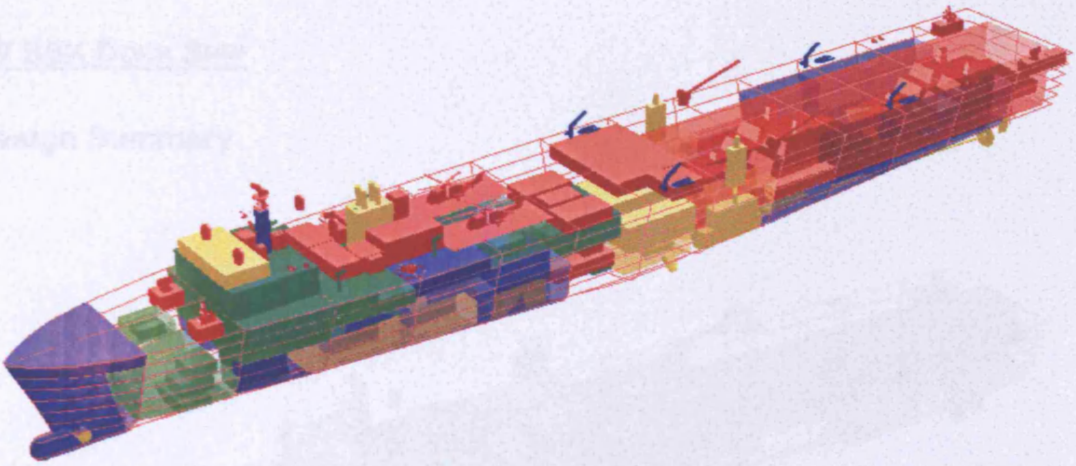

***Figure 16. Deep Draught Ship design showing all Building Blocks***

This vessel carried four small assets. Propulsive power for 25 knots was 60 MW. This was provided by six diesel generators driving four electric motors on two shafts, with separate retractable thrusters in an IFEP arrangement. The final design consisted of 210 Design Building Blocks plus discrete equipment items

| | |
|---|---|
| **Lpp** | 250m |
| **Loa** | 255m |
| **Boa** | 38m |
| **Bwl** | 31.6m |
| **Draught (deep)** | 9.4m |
| **Deep Displacement** | 45700te |
| **Ballast Capacity** | 18800te |
| **Speed** | 18/25knots |
| **Range at 18knots** | 10000nm |
| **Accommodation** | 247 |

### Specific Issues

- This design was similar to the first dock ship study, but was designed to remain at a constant draught. A stern gate was fitted, but the dock was not drained down. This was a relatively quick study to assess the impact on powering and layout of this unlikely choice of operating mode.
- There are two main ways in which this design was apparently achievable, by reducing the buoyancy of the Dock Ship baseline design or by increasing its ballast. As the size of the design was largely driven by the dimensions of the dock, it was subsequently found that reducing buoyancy was impractical.
- In this study, an increased amount of ballast was carried to produce a design with constant draught (i.e. compensated for all variables), and reduced trim. The dock space was lowered to reduce the draught required. This, and the increased ballast tankage, greatly constrained the choice for locating the main machinery spaces.

- An alternative to the use of ballast tanks would be to fit solid ballast. This would lead to more generous machinery spaces, but would not reduce the dimensions of the design significantly.
- The same concerns with torsional effects and damage aft that applied to the dock ship study also applied in this design

## 4.7 SSK Dock Ship

### Design Summary

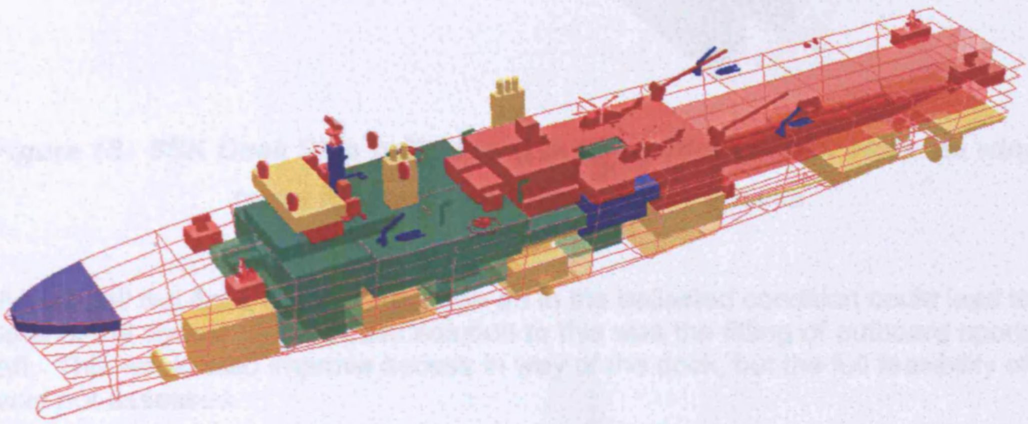

*Figure 17. SSK Dock Ship design showing all Building Blocks*

This vessel carried one large SSK. Propulsive power for 25 knots was 44 MW. This was provided by five diesel generators driving four electric motors on two shafts, with a separate retractable thruster in an IFEP arrangement. The final design consisted of 200 Design Building Blocks plus discrete equipment items

| | |
|---|---|
| **Lpp** | 190m |
| **Loa** | 197m |
| **Boa** | 32m |
| **Bwl** | 26m |
| **Draught (deep)** | 6.8m |
| **Deep Displacement** | 20650te |
| **Ballast Capacity** | 35500te |
| **Speed** | 18/25knots |
| **Range at 18knots** | 10000nm |
| **Accommodation** | 172 |

### Specific Issues

- This design was intended to carry one large SSK, of approximately 1600 tonnes submerged displacement. This required a narrower and shorter dock, but greater draught for loading and reduced trim.
- The reduced dock size allowed the dimensions of the mothership to be reduced relative to the Dock Ship. In this design, the beam was driven by stability and the required tankage for ballast. The tanks dominate the design and lead to cramped machinery spaces as shown in Figures 18 and 19.

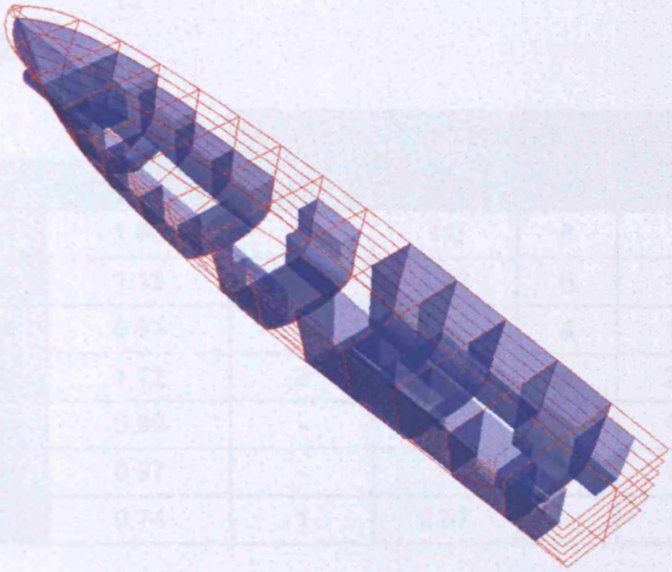

***Figure 18. SSK Dock Ship ballast tank Building Blocks only. Note the wing tanks forward, around machinery spaces***

- As with all the dock designs, damage aft in the ballasted condition could lead to the loss of the vessel. A proposed solution to this was the fitting of outboard sponsons aft. This would also improve access in way of the dock, but the full feasibility of this was not assessed.

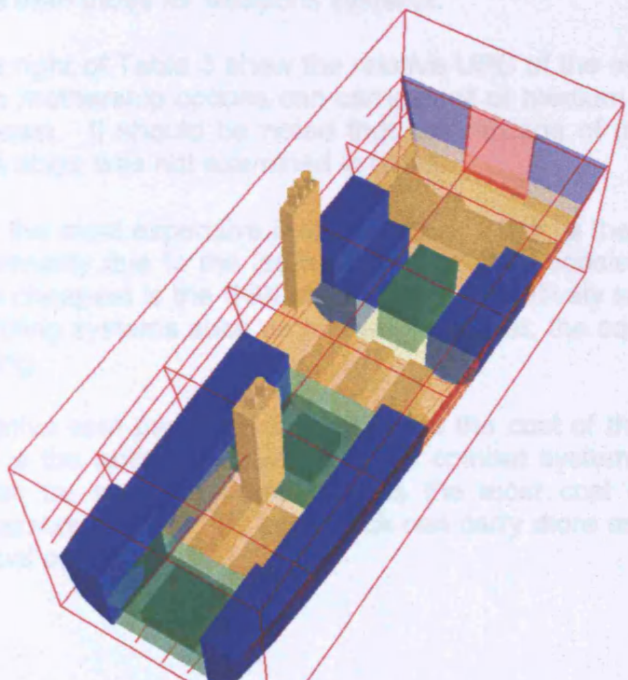

***Figure 19. SSK Dock Ship Forward Machinery Spaces, looking aft. From left to right; FAMR, FMMR, AAMR, AMMR, Incinerator Space and Motor Room. Note large wing ballast tanks.***

## COST COMPARISON

| | | UPC Per Asset | | | |
|---|---|---|---|---|---|
| **Study** | **Relative UPC** | **Medium** | **Relative** | **Small** | **Relative** |
| **Dock** | 1.00 | 4 | 1.0 | 6 | 1.0 |
| **Lift** | 1.13 | 4 | 1.13 | 6 | 1.13 |
| **Crane** | 0.91 | 2 | 1.82 | 4 | 1.36 |
| **Fast** | 1.72 | 2 | 3.43 | 4 | 2.58 |
| **Gantry** | 0.90 | - | - | 4 | 1.35 |
| **Deep** | 0.97 | - | - | 4 | 1.45 |
| **SSK** | 0.74 | 1 | 2.97 | - | |

***Table 3. Cost Comparisons Relative to the Dock Ship Design***

Table 3 shows a comparison of the Unit Production Costs of the mothership designs. These were produced using data produced for use in the UCL MSc Naval Architecture Ship Design Exercise. This data is based on advice from MoD costing experts but is not necessarily up to date and may not reflect current practices, and so only relative values have been shown in Table 3, where the values have been divided by the Dock Ship UPC. A significant area of uncertainty in the costing was the price of equipment items such as cranes and motion compensating gear. Costs for these items can be more difficult to find than those for weapons systems.

The columns to the right of Table 3 show the relative UPC of the mothership per asset carried. Five of the mothership options can carry small or medium assets and so both possibilities are shown. It should be noted that the carriage of medium (600 tonne) assets on the crane ships was not examined in detail.

Table 3 shows that the most expensive Mothership, as a unit, is the Fast Crane vessel. This high cost is primarily due to the large propulsion plant consisting of gas turbines and waterjets. The cheapest is the SSK ship. This is a relatively small vessel, with no complex asset-handling systems such as cranes. However, the cost per asset gives a quite different ranking.

The concept of relative cost per asset is to illustrate the cost of the overall capability, which in this case is the ability to deliver a given combat system into the theatre of operations. As can be seen, the dock ship is the most cost effective using this relatively simple measure of merit. Its large dock can carry more assets, thus reducing the cost per individual asset.

## 5. CONCLUSIONS

This paper has described the work undertaken by the UCL Design Research Centre in Spring 2003 as a member of the BMT DSL led study into Mothership and Deployable Asset for the MoD Future Business Group as a generic study. From a UCL DRC perspective, there seem to be three broad conclusions:-

- From a purely technical point of view, a mothership concept can be developed into a series of different balanced design solutions to carry assets to theatre at a moderately high speed. These speeds are much greater than commercial heavy lift vessels but well short of the very high speeds envisaged by recently declared US Navy preferences (1).
- Of the mothership options produced the reasonably conventional Dock Ship would appear to be the best overall, including cost, but the Stern Berth was better in terms of deploying the assets. Even the best options revealed the high cost demands made in driving a large vessel, with little capability beyond the features required to offload and recover a relatively moderate asset load, at a moderately high speed. This raises the question, more fully addressed in the BMT report to MoD, as to whether the Mothership and Deployable Asset concept is good value for the UK's highly constrained Defence Budget.
- The use of SURFCON to undertake a series of novel new concepts in a very short timescale further demonstrated the appropriateness of the UCL Design Building Block approach to preliminary ship design. It is seriously questioned whether the confidence with which the balanced designs were produced in such a short time and the design disclosure produced, for the interrogation by non ship designers, could have been achieved by conventional numerical CASD tools and separate draughting representation.

## ACKNOWLEDGEMENTS

The design work described in this paper was undertaken under sub-contract to BMT DSL whose involvement in the design evolution and assessment process is acknowledged and the permission of MoD FBG to publish this summary of the UCL contribution is also acknowledged. Responsibility for the accuracy of the UCL work resides with UCL Design Research Centre, under UCL copyright.

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# Appendix 7: Method for SURFCON / PARAMARINE in the Mothership Studies

## INTRODUCTION

This appendix contains the procedure, developed by the candidate, for producing monohull designs in PARAMARINE – SURFCON used in the mothership studies outlined in Section 5.3. A copy of this procedure was supplied to BMT DSL in February 2003.

## RICHARD PAWLING

## NOTES:

This is an overview of the method used in the generation of designs in SURFCON. The general aim of the method is that at all stages it should be possible to assess the different aspects of the designs performance, such as powering, stability and layout. In the early stages, the lower definition in the design will imply that the results of these assessments have a greater degree of uncertainty, but they can still be used to guide the designer and highlight areas that warrant more detailed study.

## PREPARATION

The first stage is to prepare the information to be used in the design, and to construct the framework of the design file. It is entirely possible that information will not be available at the start of the design, so some of the definitions etc. may have to be added later. It will probably be easier if a standard "framework" file is produced, which can then be used in the generation of individual designs.

### 1. Create Quickhull hullform definition.

- This is the set of objects that takes key points and control curves, a cross sectional area curve and generates a hullform surface, from which a solid hullform is produced.
- This will necessitate the generation of a controls folder, with the hullform characteristics and dimensions controlled by variable objects.

### 2. Add definitions.

- This is a series of folders containing definitions to be used in the Design Building Block hierarchy. These definitions include:
    - Personnel types
    - User defined specifications, such as lifeboat spaces
    - Service types, such as 440V supply
    - Loading condition types
    - Weight group classification system
    - Fluids data (densities)
    - Consumable definitions
    - Equipment definitions

### 3. Add control objects.

- A set of variables that can be used to control the placement of building blocks. These include the deck positions and related block position controls, the bulkhead positions etc. This includes the visualisations of the deck edges and bulkheads, based on the hull envelope

### 4. Add analysis objects.

- At this point in time it may be appropriate to add the resistance prediction objects to allow the assessment of powering early in the design.

## SYNTHESIS

The second stage is to commence the synthesis of the design. In these steps, we see the design develop from a relatively vague concept to a defined layout etc.

### 1. Place design generator blocks in the design space

- These are the blocks that drive the configuration of the design. For instance, in the case of a frigate, these would be the upper deck equipments and machinery. This may not be known, so a guide is that the payload blocks should be placed first, along with any large blocks that are defined in extents, such as the accommodation.

### 2. Derive minimum permissible dimensions

- These are derived from the initial layout of the design generator blocks, and any guidance as to the requirements on forecastle length etc.

### 3. Initial estimate of internal volume and displacement

- Historical data on payload volume fraction and overall density can be used to estimate the internal volume of the ship and the displacement.

### 4. Distort type hullform to current dimensions and displacement.

- Using the Quickhull objects. Dimensions and hullform factors not directly specified can be estimated from previous design data.

### 5. Initial estimate of propulsive power required.

- From the hullform and the powering prediction objects. A parametric survey should be performed at this stage to determine a range of desirable hullform parameters. The selection of more accurate coefficients at this early stage will reduce the need for re-work of the propulsion and tankage arrangements later in the design.

### 6. Choose initial machinery fit and place main machinery items, if defined.

- The machinery items may be defined individually within a encompassing building block representing the machinery spaces. Alternatively, if equipment information is unavailable, a historical scaling algorithm may be used to estimate the weight and space requirements of the machinery from the shaft power etc.

**7. Assess current layout, dimensions, hullform, equipment fit for feasibility and integrity.**

- At this point, the weight in the design is equal to the displacement, but that weight may not be fully defined in that much is a single "rest of ship" weight estimated from the payload weight. This assessment is to ensure that the dimensions, layout, machinery fit etc are commensurate both with each other and with the performance requirements of the vessel. (Powering, seakeeping, stability, personnel evolutions etc.)

**8. Increase level of definition in the design.**

- At this point, the design can be worked up to a higher level of detail, by the addition of blocks and weight groups that were assumed as part of the "rest of ship" weight previously. These will include items with a higher uncertainty and those that scale from the gross dimensions and weight of the ship and so require a numerical balance.

**9. Iterate the design to numerical balance.**

- With all scaling data added to the design, it should be brought into numerical balance so that no only does weight equal displacement, but that weight is defined and identified. Also, after this iteration, area available should be equal to or greater than area required.

**10. Increase detail in design.**

- The scaled blocks iterated previously can be placed in the design space. Many of these may be weights with no related spatial extent, such as paint.

**11. Re-assess design.**

- With the design taken to the stage of a numerical balance, it can be reassessed for performance and feasibility, as before.

**12. Parametric survey.**

- With the dimensions of the design more accurately defined, a parametric survey can be conducted to select the hullform parameters, with regards to seakeeping, resistance etc. With the layout fixed overall, the parametric survey is relatively constrained in that the only variables are the hullform parameters.

**13. Work up design.**

- If the design is required to be worked up to a high level of detail, then it will be necessary to subdivide the relatively large Super Building Blocks and Building Blocks so far added, and assess the realism of the design at a detail level. This can also include more detailed estimates of the structure then were previously undertaken.

## CONCLUDING NOTES:

This procedure has been kept relatively generic compared to those shown previously. This is because they were based on the data used in the UCL Ship Design Exercise. This is largely scaled from the overall volume of the ship, and requires a numerical balance of weight = displacement and area required = area available, which is reached through numerical iteration.

This procedure is still not a completely rigid method. It would be expected that some algorithmically based data will be added to the design at an early stage, such as the structural weight etc. The general reason for leaving this data until later in the procedure is to avoid rework: When the design is iterated to numerical balance, the area of the scaled spaces will change, and if these have been added to the arrangement then they will have to be re-assessed.

The other area where procedures may be "pulled forwards" is the parametric survey. If hullform parameters are particularly important to the design, then it may be desirable to perform the parametric survey earlier in the design, when the layout is less well defined and thus more flexible to change. Importantly, this also allows a more accurate estimate of powering.

# Appendix 8: Innovative Ship Design for High Speed Adaptable Littoral Warfare

**Originally presented to RINA International Conference "Warship 2006 Future Surface Warships", London, June 2006**

**David Andrews and Richard Pawling**

**Design Research Centre, University College London**

## SUMMARY

At the 2004 Warship Conference the authors presented a paper on the use of SURFCON in the preliminary design of a fast Mothership concept to transport small combatants from the UK to a littoral combat zone. The study reported in the proposed paper was driven by a general interest in fast naval vessels to operate in littoral operations. Another option for naval operations in littoral waters is a fast but ocean going littoral combatant. Given the operational needs for such vessels is expected to be multi-mission, a solution is seen to be to build adaptability into the design so several roles could be accomplished. One way in which this adaptability can be provided is through a large enclosed deck area able to take containerised equipment and deploy containers or even small craft, including drones, out of the stern of the vessel. The combination of high speed, adaptability and survivability readily suggested a trimaran configuration.

The exploration of this demanding novel high speed concept was part of a demonstration to the US Navy Office of Naval Research that the UCL Design Building Block approach could be used to undertake concept design studies of novel ship types. The requirements of the US Navy's Littoral Combatant Ship were accessed from open information and the fast (40 knot) trimaran configuration option was adopted. The combination of the propulsive powers required and the need to stow and deploy from the vessel's stern the modularised assets made the design configurationally demanding. Without recourse to a full SURFCON representation in combination with the naval architectural analysis, using the PARAMARINE analysis modules, it is doubted if a believable concept could have been readily produced to this advanced concept.

## 1. INTRODUCTION

At the 2004 Warship Conference the authors presented a paper on the use of SURFCON in the preliminary design of a fast Mothership concept to transport small combatants from the UK to a litoral combat zone (1). The same budgetary pressures that led to that concept for world wide deployment of naval power has led the US Navy to devise the concept of a fast but larger and ocean going Littoral Combatant Ship, the LCS. The US Navy concept is characterised by a need for high top speed, to operate in the potentially high threat littoral environment, coupled with a rapidly deployable multi-mission payload to cope with a range of possible missions, from Mine Countermeasures to deploying Special Forces assault craft. Separately the US Navy Office of Naval Research (ONR) showed an interest in the UCL preliminary ship design approach implemented in the GRC SURFCON design tool (2). This capability is summarised in the next section and it was decided that the capabilities of this design approach would be best demonstrated by the UCL Design Research Centre taking the LCS requirements and producing a preliminary design solution that could be compared with studies produced by the US Navy ship design organisation.

The attraction of a littoral focused naval combatant has arisen for major navies since the end of the Cold War. Firstly, with no challenge to the West's command of the deep oceans there is no obvious deep ocean military threat typically requiring all naval units to be full ocean combatants together with the protection in depth provided by squadrons of escorts. Secondly, peace keeping operations in the littoral are more likely to be subject to asymmetric threats which high capability and expensive major combatants would wish to avoid by not going close inshore. Hence, there is seen to be a case for the Coalition navies to be able to deploy small assets from vessels which can operate in the littoral using high speed. This was seen by both ONR and the UCL DRC as ideal case study of a radically new combatant concept to test the UCL Design Building Block approach and the specific SURFCON implementation. It was further decided to select the Trimaran option of the range of hull types then being considered for the LCS as this would further demonstrate the capability of this approach to support innovative ship design.

The next section briefly summarises the Design Building Block approach to preliminary ship design, this is followed by a summary of the LCS requirement issued by the US Navy. The main body of the paper shows how this relatively short study proceeded through the various design stages typically undertaken using the graphically driven DBB design method. The final design produced is then analysed, its design drivers highlighted and comparisons drawn with an earlier US/UK comparative design exercise and a more convention frigate design produced using the DBB approach. The concluding section looks not only at the issues raised by this design study with regard to the LCS concept but also what such an innovative concept revealed with respect to the use of the Design Building Block approach to preliminary ship design. This is done from both a general point of view and in comparison with the other ship studies that the DRC has undertaken recently demonstrating the scope and capability of this approach to innovative ship design.

## 2. Outline of the Design Building Block Approach

The UCL Design Research Centre was established in 2000, alongside the MoD sponsored Naval Architecture and Marine Engineering Group, as part of an expanded Marine Research Group at UCL. The DRC's remit is to specifically focus on Computer Aided Design and in so doing has an alliance with the Graphics Research Corporation Limited in developing the Design Building Block approach through the SURFCON facility as part of GRC's PARAMARINE Preliminary Ship Design System (2).

The logic behind the SURFCON tool realisation of the Design Building Block approach, has been recently spelt out by the first author in a paper to IJME (3). In essence this approach gives a great focus to ship architecture and ensures this is produced alongside the traditional numerical sizing and naval architectural balance in the initial design synthesis. The Design Building Block approach to producing a new ship design was presented in Ref (2) at Figure 5, reproduced below at Figure 1. This diagram summarises a comprehensive set of analysis processes most of which are unlikely to be used in the initial setting up of the design or even early iterations around the sequence of selecting and placing Design Building Blocks, hull geometric definition and size balance. In fact several of the inputs shown in Figure 1 are either specific to the naval combatant case, such as topside features, or omit aspects which could be dominant in specialist vessels, such as aircraft carriers or amphibious warfare vessels, where personnel and vehicle flow are likely to dominate the internal ship configuration.

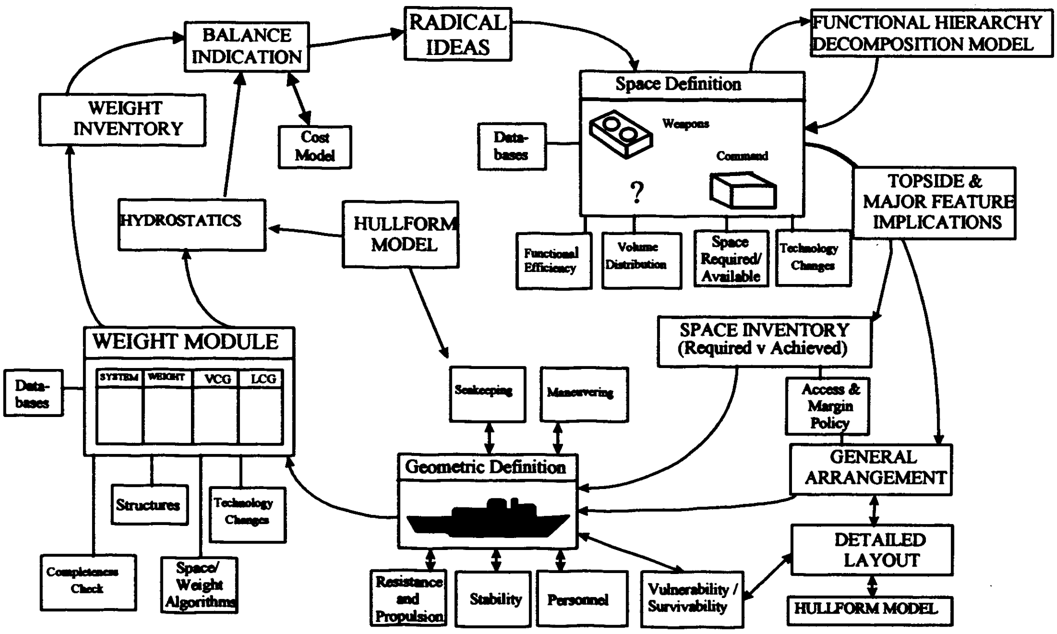


***Figure 1 Overview of the Design Building Block Methodology applied to Surface Ship (2)***

A further feature of SURFCON is the use of the term Master Building Block to denote how the overall aggregated attributes of the Design Building Blocks can be 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 (4) is that the audited building block attributes within the Master Building Block can be directly used by PARAMARINE, so the necessary naval architectural calculations to ascertain the balance or otherwise of the configuration just produced by the designer can be performed. Typical information held in the Master Building Block includes:

- Overall requirements: Ship speed, seakeeping, stability, signatures (in the case of a naval combatant);
- Ship characteristics: weight, space, centroid;
- Overall margins: weight, space and their locations for both growth and enhancement.

As the design description is built up and modified, all features of the building blocks are utilised by the system. The geometric definition (shape and location) is used to constantly update the graphical display, whilst data properties are indicated in a logical tree diagram of the design, as shown in Figure 2. Figure 2 also shows the block representation and a tabular view of typical numerical information from a specific analysis of the design.

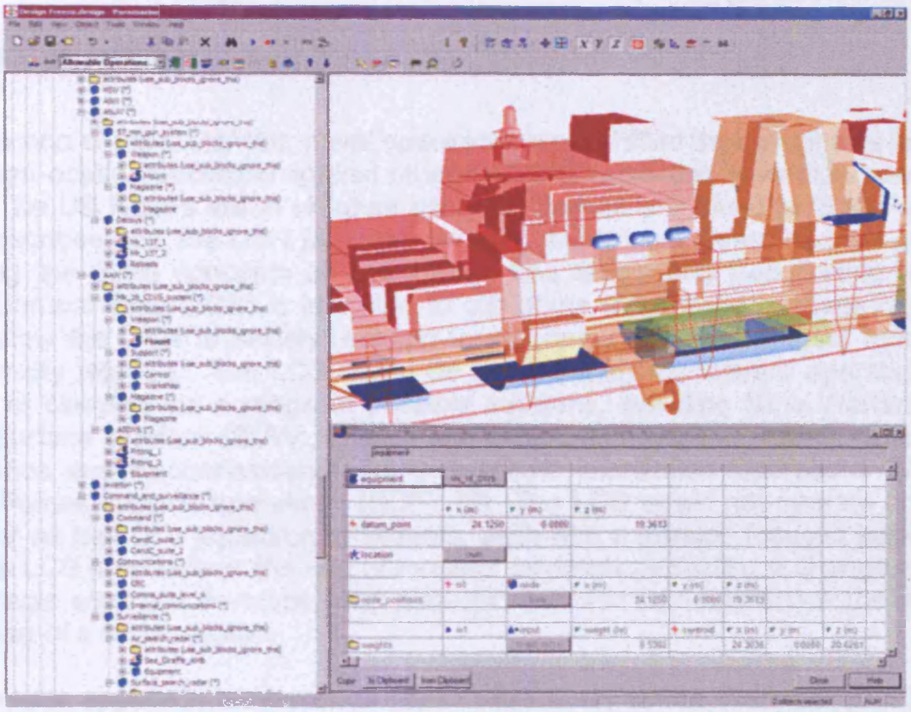

***Figure 2: SURFCON showing the three panes for tree structure, graphics (Building Blocks) and analysis (weight balance in example)***

## 3. ORIGIN OF THE STUDY

### 3.1 The ONR Project

From an interest in the SURFCON tool the Assistant Director for Naval Architecture in the ONR Europe Office in London suggested that the authors visited ONR Headquarters, the Naval Sea Systems Command (NAVSEA) and the Naval Surface Warfare Centre Carderock (NSWCCD) all in Washington D.C. From this visit in July 2002 a draft statement of work for a task entitled "Evaluation of Object-Oriented Ship Design Technology" was produced. About a year later a second set of meetings took place after the placing of a contract with UCL. The design work undertaken by the DRC under the contract lasted from this July 2003 meeting to early April 2004 and was largely undertaken at UCL.

The primary objective of the project was to demonstrate the SURFCON – PARAMARINE toolset and the DBB approach's ability to enable comparative evaluation of advanced hullforms in support of the US Navy's Future Naval Capability for littoral combat and power projection and in particular enable assessment of the tool's ability to handle US Navy ship design practice and processes. This led to not just the LCS but also the trimaran option being selected as the first example to be produced. It was subsequently decided by ONR / NSWCCD that it was not necessary to extend the evaluation of the tool set and method to the wider range of unconventional hull forms first envisaged.

## 3.2 LCS Operational Concept

Since the end of the Cold War, naval operations have shifted their emphasis from blue-water open-ocean operations against other navies to projecting sovereign power in the littoral. The US Navy's vision of future naval operations is outlined in "Sea Power 21", which describes how the USN faces an evolving anti-access threat and will overcome this using the three concepts of Sea Strike, Sea Shield and Sea Basing. (5) The Littoral Combat Ship (LCS) is intended to contribute to all three of these capabilities and to allow the USN to flexibly respond to a variety of different threats from low- to high-intensity warfare. The LCS would be a self-deploying, forward operating vessel capable of carrying out a range of possible missions, including Mine Warfare (MIW), Littoral Surface Warfare (SUW), Littoral Anti-Submarine Warfare (ASW), Intelligence, Surveillance and Reconnaissance (ISR), Maritime Interdiction Operations (MIO) and Special Forces support operations (SOF). (6) The LCS would not operate on its own but rather as part of a squadron of vessels, each with a mission focused payload. As such, the LCS emphasises the use of modular payloads permitting a change of role as the strategic scenario develops, and network – centric warfare, where the individual ship is part of a larger system.

This modular approach is described as a "seaframe", where the core LCS fit has a limited payload of defensive weapons, sensors, command and communications equipment and the main warfighting payload is modular, deployable and removable. This is similar to the aerospace concept of an "airframe", where the mission is defined by payload carried under the aircrafts wings or in a bomb-bay. Another significant feature of the LCS is a capability to both deploy trans-ocean at conventional speeds and once in the littoral ramp up to much higher speeds. The latter is envisaged to reduce exposure and vulnerability to threats, while allowing a rapid reaction to an emerging tactical situation. (7)

### 3.3 Design Requirements

The requirements for the design were those laid out in the LCS requirements document as issued by the US Navy. (6) This design was to satisfy the Threshold Level requirements as shown in Table 1.

| LCS Flight 0 Critical Design Parameters | | |
|---|---|---|
| **Category** | **Threshold Level** | **Objective Level** |
| Total Price Per Ship | Meet Cost As an Independent Variable (CAIV) target in the REP | Exceed CAIV target in the REP |
| Hull Service Life | 20 Years | 30 Years |
| Draft at Full Load Displacement | 20 feet | 10 feet |
| Sprint Speed at Full Load Displacement in Sea State # | 40 knots in Sea State 3 | 50 knots in Sea State 3 |
| Range at Sprint Speed | 1000 nautical miles | 1500 nautical miles |
| Range at Economical Speed | 3500 nautical miles (>18 knots) with payload | 4300 nautical miles (20 knots) with payload |
| Aviation Support | Embark and hangar; one MH-60R/S and VTUAVs, and a flight deck capable of operating, fueling, reconfiguring, and supporting MH-60R/S/UAVs/VTUAVs | Embark and hangar; one MH-60R/S and VTUAVs, and a flight deck capable of operating, fueling, reconfiguring, and supporting MH-60R/S/UAVs/VTUAVs |
| Aircraft Launch / Recover | Sea State 4 best heading | Sea State 5 best heading |
| Watercraft launch / Recover | Sea State 3 best heading within 45 mins. | Sea State 4 best heading within 15 mins. |
| Mission Package Boat type | 11 metre RHIB | 40ft High Speed Boat |
| Time for Mission Package Change-Out to full operational capability including system OPTEST | 4 days | 1 day |
| Provisions | 336 hours (14 days) | 504 hours (21 days) |
| Underway Replenishment Modes (UNREP) | CONREP, VERTREP and RAS | CONREP, VERTREP and RAS |
| Mission Module Payload | 180te (105te mission package / 75te mission package fuel) | 210te (130te mission package / 80te mission package fuel) |
| Core crew Size | 50 Core Crew Members | 15 Core Crew Members |
| Crew Accommodations (Both core crew and mission package detachments) | 75 personnel | 75 personnel |
| Operational Availability (Ao) | 0.85 | 0.95 |

***Table 1: LCS threshold and objective requirements (6)***

The two most demanding of these requirements were seen to be the high speed requirement for an ocean going ship and the use of modular payloads. A numerical description of the threshold mission payload, including core ship weapons and sensors, mission modules and hangar and payload bay sizes was provided to the DRC by NSWCCD.

## 4. DEVELOPMENT OF THE DESIGN

### 4.1 Overall Procedure used in the Design Study

Previous ship design studies using SURFCON led to the development of a broad general approach to using the tool in early stage ship design. (8) This consists of general descriptions of the overall approach, rather than detailed procedures, ensuring the application of the approach to a wide variety of ship design types. The first task within the project was for the UCL DRC to produce a more detailed procedure for the US Navy users which took the designer through the four stages of design used in the Design Building Block approach, as implemented in the PARAMARINE software.

As outlined in Reference 9, the approach consists of four main stages, each representing an increasing level of definition of the ship design. At each stage an appropriately holistic definition for the ship design is produced, with assessments of as wide a range of performance aspects as is sensible at that stage in the design evolution. Table 2 illustrates typical design decisions taken at each stage.

| **Design Preparation** |
|---|
| Selection of Design Style |
| **Topside and Major Feature Design Phase** |
| Design Space Creation |
| Weapons and Sensor Placement |
| Engine and Machinery Compartment Placement |
| Aircraft Systems Sizing and Placement |
| Superstructure Sizing and Placement |
| **Super Building Block Based Design Phase** |
| 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. |
| **Building Block Based Design Phase** |
| 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. |
| **General Arrangement Phase** |
| Drawing Preparation |

***Table 2: Building Block design stages showing major design choices (9)***

### 4.2 Preparation Stage

The aim of this stage was to identify the capabilities required. These capabilities are translated into metrics appropriate to the Design Building Block hierarchy:-

- Speed,
- Range,
- Endurance,
- Payload equipments and space demands
- 'ilities' eg: producability, accessibility, maintainability, adaptability,
- Accommodation requirements.

At this stage of the design major stylistic aspects should be selected, for example;

- Hullform topology,
- Technical design standards.

This allowed the assembly of a "design framework" containing sufficient data to start the design process, but with no explicit definition of the design. Examples of the data that would be contained by this framework include;

- Early stage design algorithms,
- Weight and space grouping systems (e.g. UK NES 163 (10), US Ship Work Breakdown Structure (SWBS) (11)),
- Data on equipment, particularly major machinery features.

From the metrics and stylistic aspects some of the design generators were identified. These allowed the definition of the initial layout of the design.

For this study several decisions were taken in the Preparation Stage that strongly influenced the design, namely:

- The topology of the vessel was specified as a trimaran, and a Series 64 hullform (12) was provided by NSWCCD as the basis for the main hull.
- The LCS requirements indicated that the design would be high speed (in the region of 40 knots) and shallow draught (20 feet, 6.1m). The high maximum speed indicated that waterjets were the most likely propulsor, although this was not finalised at this stage.

### 4.3 Major Feature Design Stage (MFDS)

The main aim of the MFDS is to develop the overall layout and spatial style of the design, using primarily those Super Building Blocks directly specified by the requirements, such as payload items (FIGHT) and main machinery spaces (MOVE). The initial configuration for the LCS study is shown in Figure 3, and consists of the following Design Building Blocks:

- Estimated mooring space forward
- Bridge
- 2 Main Machinery Rooms (MMRs), each containing one generic MT-30 size gas turbine with intake and exhaust
- 2 shafts
- 2 waterjets
- 57mm gun
- 57mm magazine
- Combat Information Centre (CIC)
- Payload bay, containing 10 payload items
- Hangar bay, containing 8 payload items
- Deployment ramp for payload items out of stern
- 20mm Close - In Weapons System and workshop

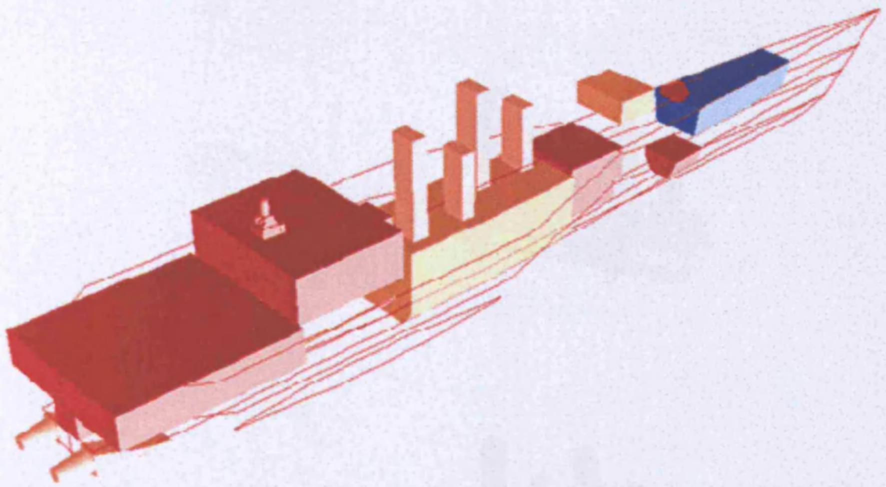

*Figure 3: Initial configuration generated in the Major Feature Design Stage*

This set of initial DBB includes the largest FIGHT items, and specifically those required for the main mission. It also includes the basic MOVE group blocks, as high mobility was specified as part of the requirements document. The hullform was roughly sized using the UCL Ship Design Exercise method outlined in Figure 2 of Reference 13. This enables the designer to get a first estimate of propulsive power required. Initial estimates of intact stability and required GM were used to generate an approximate side hull configuration by specifying a required waterplane inertia (area and transverse position). Table 3 provides a summary of the initial ship characteristics.

| | |
|---|---|
| **Number of DBB** | 18 (in 11 discrete SBBs and grouped BBs) |
| **Displacement** | 2830te |
| **Enclosed Volume** | 14100m3 (Required) 15300m3 (Available – includes voids) |
| **Length, main hull, waterline** | 126.2m |
| **Major Decisions** | |
| 18 basic SBB placed to generate the design.<br>Overall configuration established<br>Strong interaction between FIGHT and MOVE groups identified<br>CIC initially placed forward<br>Split GT Main Machinery Rooms amidships<br>Decks placed<br>Hull length corresponding to estimated displacement greater than required for layout alone<br>Approximate side hull configuration defined | |

*Table 3: Summary of the initial LCS design*

The ship design at this stage was very rough, but allowed the main drivers in the design to be revealed and examined, and an early evaluation of the overall topology of the likely solution space was possible. In each stage of the initial design process the design was iterated to a "balanced" condition, as could be seen with the machinery configuration. During the MFDS the option of waterjets, machinery spaces, shafts and slow-speed propulsors was examined and a number of alternatives assessed, as can be seen in Figure 4 for two cases.

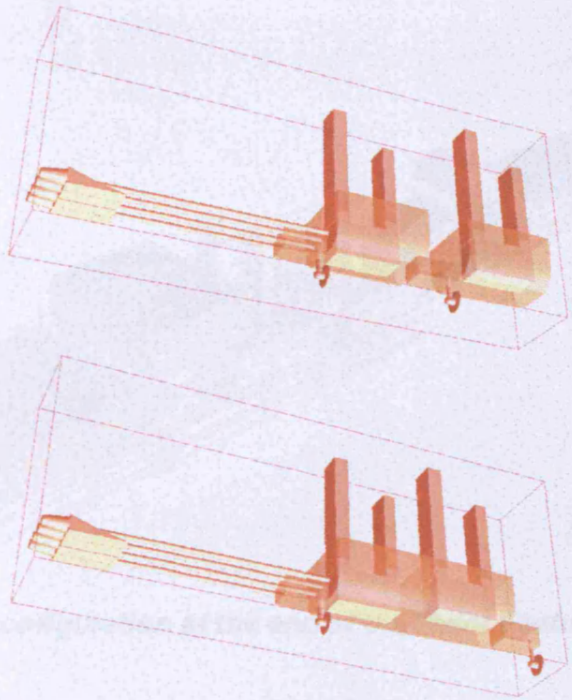

***Figure 4: Machinery configuration options considered in the MFDS***

The MFDS also incorporated the first estimate of structural weight, using typical values for overall structural density and the volumes of the three hulls, box and superstructure blocks. Structural weight densities were drawn from open-source data and previous UCL research (14, 15, 16) Figure 5 and Table 4 show the definition of the design at the end of this stage.

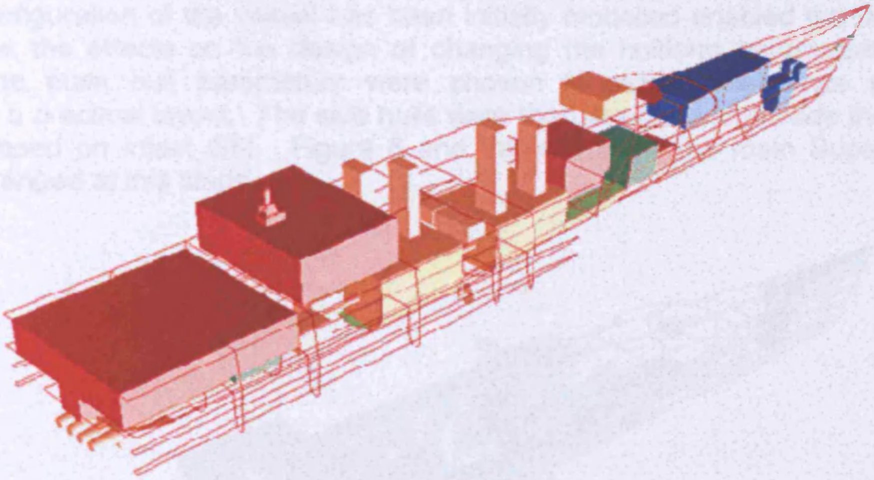

*Figure 5: LCS configuration at the end of the Major Feature Design Stage*

| **Number of DBB** | 47 (in 15 discrete SBBs and grouped BBs) |
|---|---|
| **Displacement** | 2900te |
| **Enclosed Volume** | 21000m3 (R) 24000 m3 (A) |
| **Length, main hull, waterline** | 135m |
| **Major Decisions** | |
| 46 SBB placed to be confident in the design<br>Fuel tanks placed<br>Initial Auxiliary Machinery Rooms placed forward and aft<br>Hull lengthened due to increased displacement<br>Cruise pods placed amidships<br>Waterjet configuration changed to a row of 4 smaller jets<br>Bulkheads placed based on configuration | |

*Table 4: Summary of the LCS design at the end of the Major Feature Design Stage*

## 4.4 Super Building Block Design Stage (SBBDS)

This stage of the process is intended for refining the definition of the design by incorporating the secondary drivers on the configuration, and assessing the impact of the primary design drivers identified earlier. Super Building Blocks (SBB) representing all the main features of the design are placed in the configuration, and the hullform can be defined in more detail. SBBs placed at this stage for the LCS study included:

- Main access routes
- Deep magazines
- Command spaces
- Communications spaces (as a large flat)
- Accommodation spaces (as three large flats)
- Auxiliary machinery spaces

At this stage a hullform parametric survey was undertaken to determine the impact of hullform shape options on the overall design. Performing this procedure after the overall configuration of the vessel has been initially modelled enabled the designer to incorporate the effects on the design of changing the hullform parameters. In this design, the main hull parameters were chosen to reduce resistance whilst still permitting a practical layout. The side hulls were then designed to provide the required stability based on intact GM. Figure 6 and Table 5 show the main Super Building Blocks arranged at this stage.

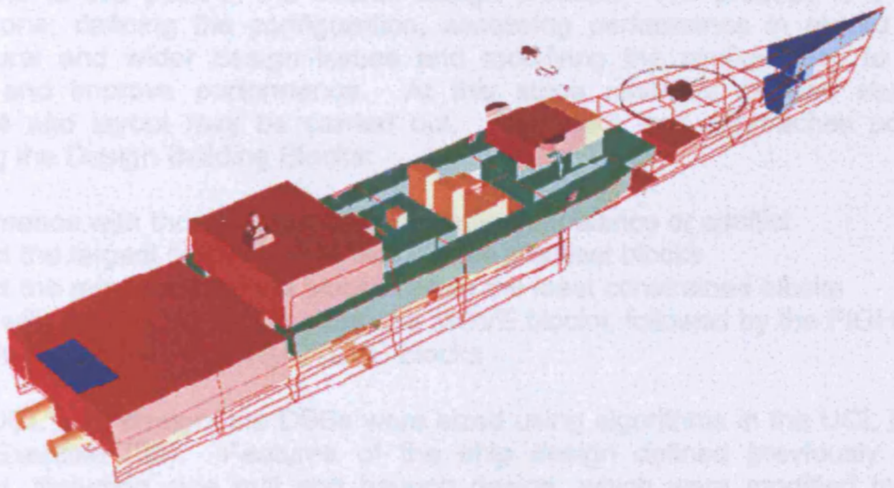

***Figure 6: Super Building Blocks placed in the LCS design***

| | |
|---|---|
| **Number of DBB** | 110 (in 33 discrete SBBs and grouped BBs) |
| **Displacement** | 3100te |
| **Enclosed Volume** | 18913m3 (R) 22700m3 (A) |
| **Length, main hull, waterline** | 135m |
| **Major Decisions** | |
| Both main GTs moved to a single MMR<br>Defined cruise GTA machinery spaces<br>Moved cruise pods aft of midships<br>Waterjets changed to final staggered configuration<br>Position of main items in all SBB defined<br>Accommodation placed as 6 large blocks<br>Possible conflict between cruise GTA ducting and superstructure identified<br>Side hull dimensions defined | |

***Table 5: Summary of the design at the end of the Super Building Block Design Stage***

Several major features of the layout were then examined by generating and comparing alternate configurations, such as locations for the CIC, which was ultimately placed under the hangar.

With the positions of bulkheads, decks etc determined, the SBBDS included the second estimate of structural weight, using equivalent thicknesses, material densities and areas of main structural elements. This was deemed necessary because of the unconventional nature of the trimaran and its relative novelty leading to a relatively high structural weight fraction (See Hampshire et al (17) and Andrews (18)). The equivalent thicknesses were calculated using a spreadsheet based tool used in teaching at UCL. (19) At this stage alternative structural and material configurations were also considered leading to the choice of aluminium main hull and box, and composite superstructure and side hulls, as a steel option was prohibitively heavy for such as high speed vessel.

## 4.5 Design Building Block Stages

In the DBB Stages, a design is worked up to a sufficient level of detail to satisfy the designer that he or she has sufficiently addressed the levels of risk and uncertainty appropriate to this point in the overall design process. The process is a generally iterative one; defining the configuration, assessing performance in regard to naval architectural and wider design issues and modifying the configuration to maintain balance and improve performance. At this stage relatively detailed studies into structures and layout may be carried out. There are four approaches possible in modifying the Design Building Blocks:

1. Commence with those blocks causing design unbalance or conflict
2. Select the largest blocks before tackling the smallest blocks
3. Select the most constrained blocks before the least constrained blocks
4. Start with the FLOAT blocks, then the MOVE blocks, followed by the FIGHT blocks, and finally the INFRASTRUCTURE blocks

For the UCL LCS design, the DBBs were sized using algorithms in the UCL MSc Ship Design Exercise (20). Features of the ship design defined previously were re-examined, including side hull and haunch design, which were modified to improve damage stability. This was done largely by an iterative process of synthesis, analysis and improvement. For the case of the haunch design in a trimaran, it is usually possible to produce a design that gives the required waterplane area at any given angle of roll (for simple damage cases), but the development of such a method was beyond the scope of this study given that it was not seen to be a critical design driver at the initial design phase.

Detailed areas of design such as the layout of auxiliary machinery spaces and distributed systems were also considered at this stage. Figure 7 shows the SURFCON model of the final initial design, with all blocks and equipment items visible, and Table 7 gives details of the model. Table 6 gives the principal particulars of the final design.

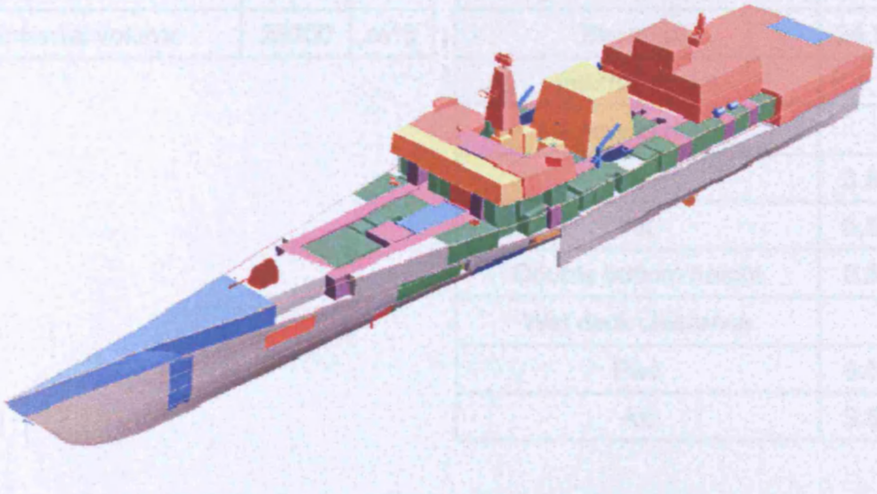

***Figure 7: The final LCS design SURFCON model***

| | |
|---|---|
| **Number of DBB** | 343 (in c. 25 SBBs and 11 grouped BBs) |
| **Displacement** | 3212te |
| **Enclosed Volume** | 19500 m3 (R) 26000m3 (A) |
| **Length, main hull, waterline** | 136.3m |

***Table 6: Summary of the final LCS design balance***

| **Main Hull** | | |
|---|---|---|
| Length, wl | 136.3 | m |
| Length, oa | 141.3 | m |
| Beam, wl | 10.5 | m |
| Beam, oa | 11.4 | m |
| Depth | 13.4 | m |
| Draught | 4.4 | m |
| Displacement | 3050 | te |
| Cp | 0.575 | |
| Cw | 0.73 | |
| Cm | 0.826 | |
| Cb | 0.475 | |
| Circular m | 9.5 | |

| **Side Hull** | | |
|---|---|---|
| Length, wl | 68.2 | m |
| Length, oa | 68.2 | m |
| Beam, wl | 2 | m |
| Draught | 1.9 | m |
| Displacement | 81 | te |
| Cp | 0.425 | |
| Cw | 0.596 | |
| Cm | 0.706 | |
| Cb | 0.3 | |
| Circular m | 15.9 | |

| **Overall** | | |
|---|---|---|
| Displacement, oa | 3212 | te |
| Internal volume | 26000 | m^3 |

| **Box** | | |
|---|---|---|
| Length of parallel section | 68.2 | m |
| Beam, oa | 24.5 | m |
| Internal decks | 1 | |
| Deckhead height | | |
| Fwd | 3.5 | m |
| Aft | 5.5 | m |
| Double bottom height | 0.5 | m |
| Wet deck clearance | | |
| Fwd | 5.5 | m |
| Aft | 3.5 | m |

***Table 7: Principal particulars of the final LCS design***

## 5. THE FINAL UCL LCS DESIGN

### 5.1 Specific Issues by Functional Groups

### a) FLOAT

The largest space demand in the FLOAT functional group was the volume of void spaces in the main and side hulls. Figure 8 shows the extent void spaces, whilst Figure 9 shows the next largest demand in space, the area of access routes. Figure 10 shows the rest of the FLOAT group (mooring equipment, ballast tanks, ships' boats and damage control equipment. Structure is hidden, for clarity).

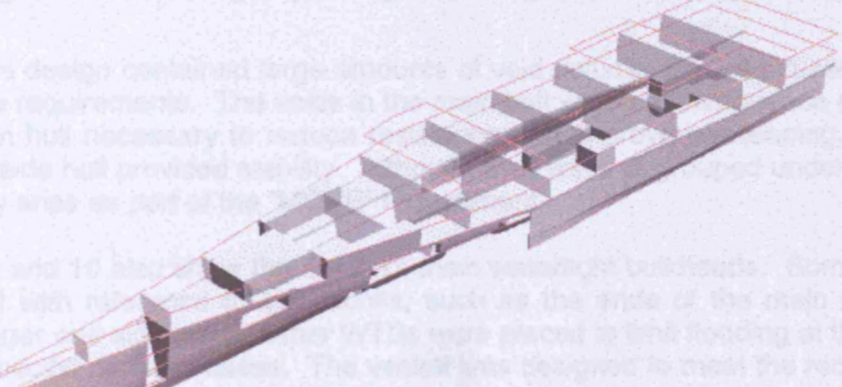

***Figure 8: Void volumes in the LCS FLOAT group***

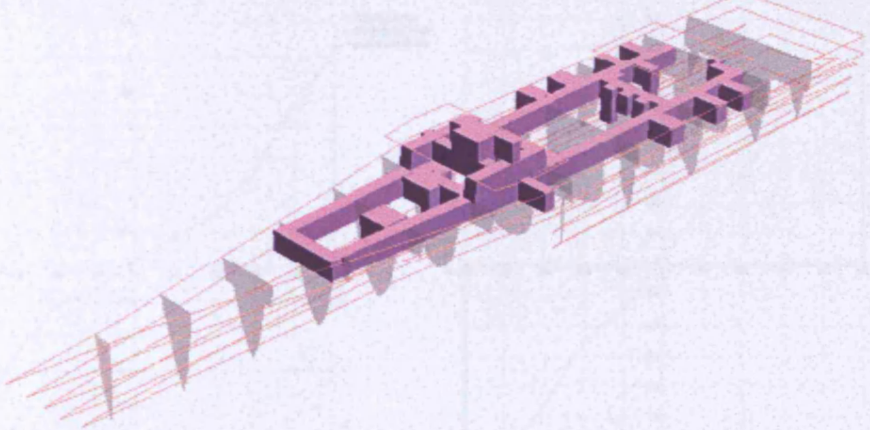

***Figure 9: LCS access areas***

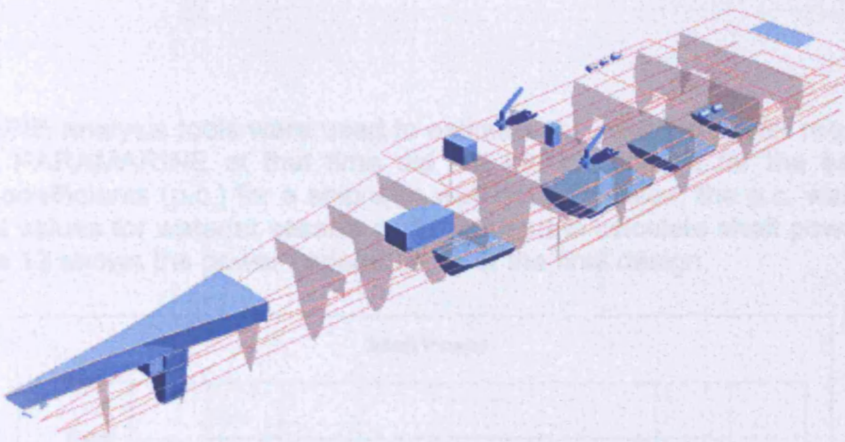

*Figure 10: FLOAT group Design Building Blocks for LCS study*

Although this design contained large amounts of void volume, this was "used" to meet performance requirements. The voids in the main hull were a consequence of the long slender main hull necessary to reduce resistance and improve seakeeping, while the voids in the side hull provided stability. Although they were all grouped under "FLOAT", some clearly arise as part of the "MOVE" requirement.

Figures 8, 9 and 10 also show the design's main watertight bulkheads. Some of these were placed with reference to key blocks, such as the ends of the main machinery spaces, hangar and side hulls. Other WTBs were placed to limit flooding at the ends of the hull in specific damage cases. The vessel was designed to meet the requirements of the NES 109 damage stability criteria, with symmetric (main hull) and asymmetric (side hull) damage considered. (21) Examples of stability curves (GZ curves) produced by PARAMARINE for the intact and damage conditions are shown in Figure 11.

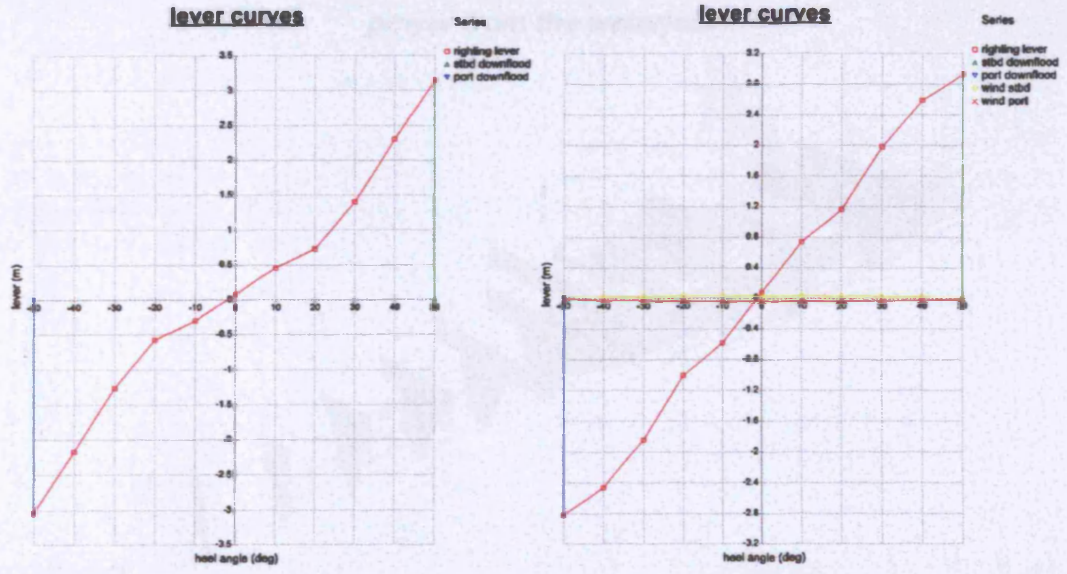


*Figure 11: GZ curves for the deep load intact (left) and deep load damaged (right) conditions for the LCS final design*

## b) MOVE

PARAMARINE analysis tools were used to estimate the effective power required for 40 knots. As PARAMARINE at that time did not include objects for the estimation of propulsive coefficients (p.c.) for a ship with waterjet propulsion, the p.c. was estimated from typical values for waterjet vessels and that used to calculate shaft power required. (22) Figure 12 shows the power / speed curve of the final design.

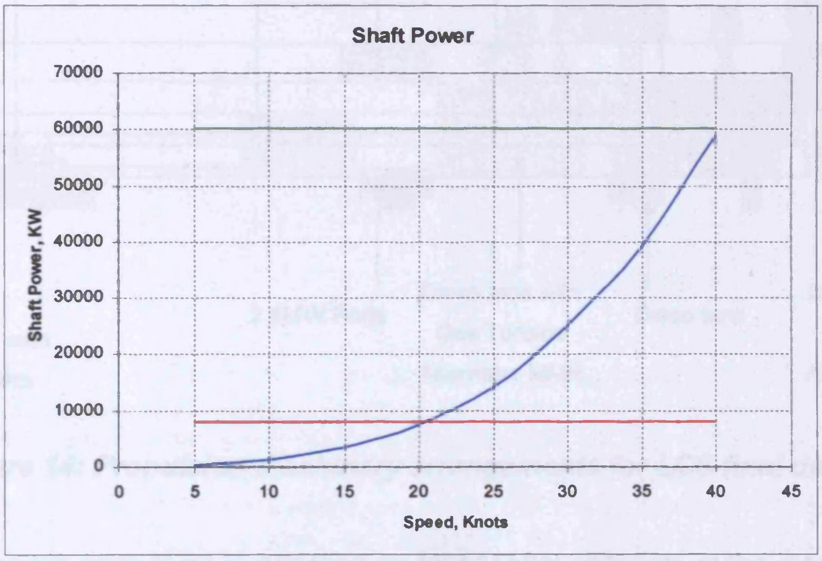


***Figure 12: LCS final design Shaft Power / Speed Curve. The RED line is the maximum power from the cruise pods and the GREEN line is the maximum power from the waterjets***

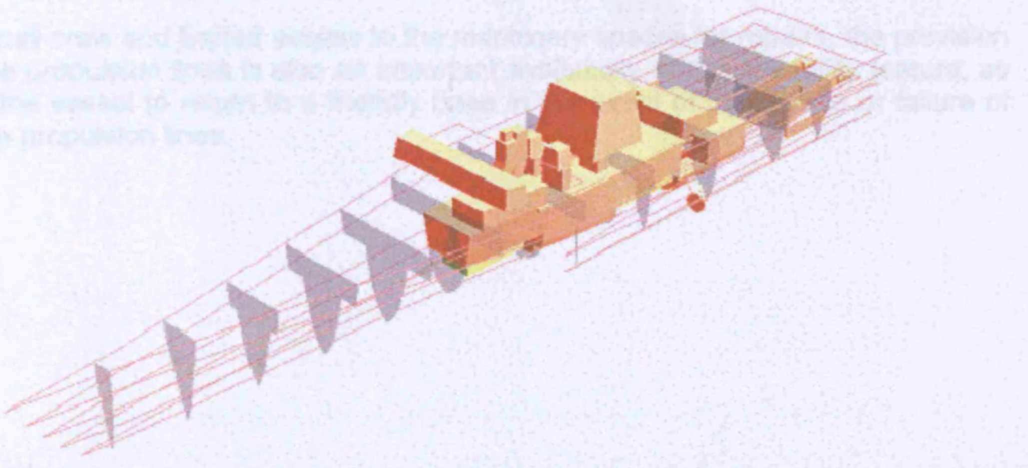

***Figure 13: LCS final Design Building Blocks for the MOVE Functional Group***

Figure 13 shows the MOVE blocks as configured in the final design, whilst Figure 14 provides more detail on the arrangements of the main machinery. The requirement both for medium speed cruise and high speed sprint drove the design to a two-mode propulsion machinery solution. At cruise speeds (20 knots) propulsion is via two 4MW Permanent Magnet Motors in pods just aft of amidships. Power for these is provided by two notational 6.6MW advanced cycle gas turbine alternators in split machinery rooms above the waterline.

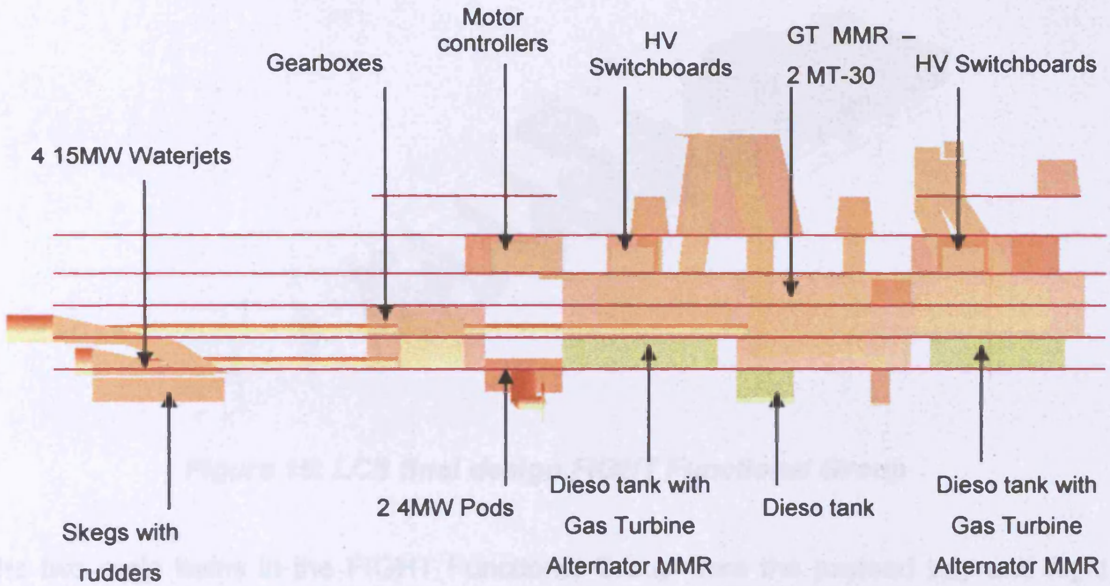


***Figure 14: Propulsion machinery arrangements for LCS final design***

At higher speeds propulsion is provided by four 15MW waterjets at the stern, driven by two Rolls-Royce MT-30 has turbines in a single main machinery room. Multiple waterjets were chosen rather than the original 2 large waterjets (Figure 3) for the following reasons:

- Increased efficiency at part load;
- More flexible configuration at the stern;
- Smaller cut-outs in the stern structure.

With a small crew and limited access to the machinery spaces for repairs, the provision of multiple propulsion lines is also an important availability and survivability feature, as it allows the vessel to return to a friendly base in the event of damage to or failure of one of the propulsion lines.

## c) FIGHT

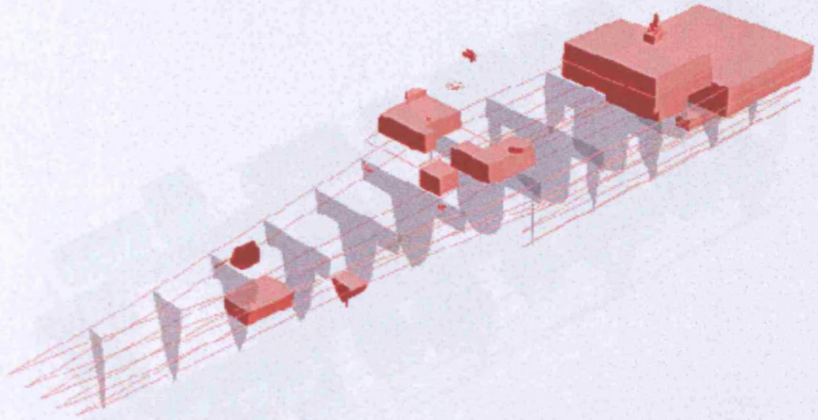

***Figure 15: LCS final design FIGHT Functional Group***

The two main items in the FIGHT Functional Group were the payload bay and flight deck. Figure 15 shows all FIGHT blocks in the design. The payload bay contained a ramp for watercraft deployment that required access to the stern, this dictating its location at the stern. The width of the payload bay determined the minimum width of the box structure. Although a midships position for the flight deck would have been preferable to reduce local motions, the large intake and exhaust ducts for the gas turbines amidships led to the aft location of the hangar and flight deck. An additional interaction between the FIGHT and MOVE Functional Groups occurred at the stern, where the payload ramp and waterjets competed for transom space. Figure 16 shows the hangar and payload bay with the payload modules within. The other FIGHT items of equipment were small and had little effect on the overall design.

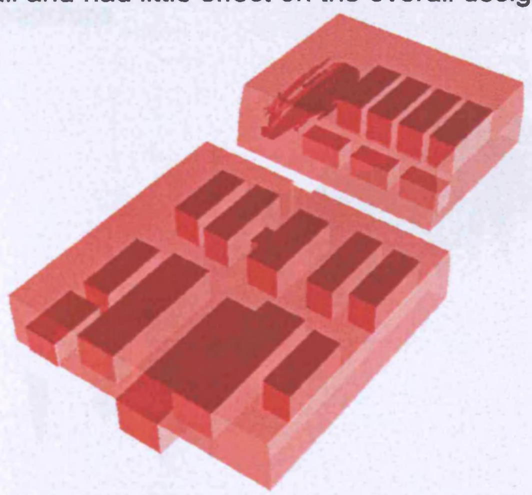

***Figure 16: Hangar and payload bay showing payload modules and deployment ramp for LCS final design***

## d) INFRASTRUCTURE

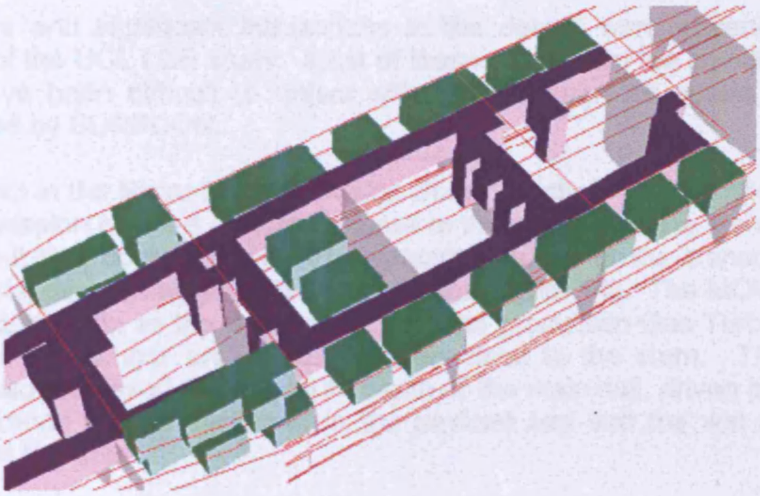

***Figure 17: Accommodation blocks and access routes for LCS final design***

The largest area in the INFRASTRUCTURE Functional Group was that for accommodation (see Figure 17). Although the vessel was intended to have a small crew of 75, the use of cabin-based accommodation increased the total area required relative to traditional mess decks. The cabins were fixed in size and had to be arranged so that bunks were longitudinal, this increased the access area required. The box structure on No 2 deck was vital in achieving a satisfactory layout, with the accommodation on each beam and the various support spaces over the machinery rooms on the centreline. This allowed the same area to be arranged in a shorter length of the ship, just aft of amidships.

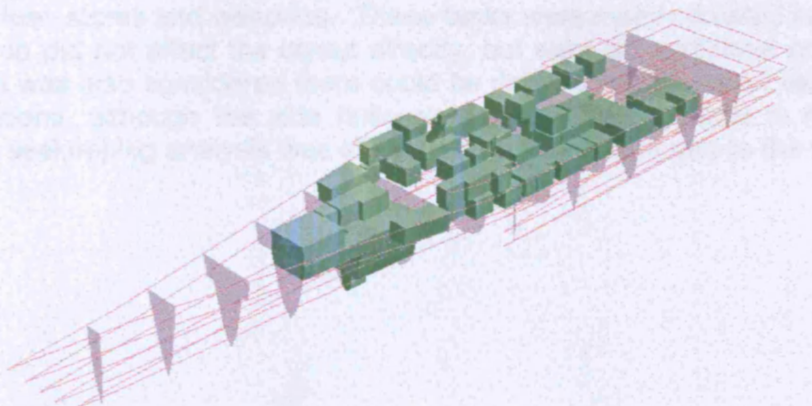

***Figure 18: LCS final design INFRASTRUCTURE Functional Group***

The final design contained three Auxiliary Machinery Rooms, with systems split between them to provide redundancy in the event of damage. Unfortunately the four shaft lines aft resulted in a cramped after machinery space. The vessel was divided into two damage - control zones; forward and aft, any further zoning was considered unnecessary given the concentration of assets onboard.

## 5.2 Design Drivers

Several drivers and significant interactions in the design were observed during the development of the UCL LCS study. Most of these arose from the layout of the vessel, and would have been difficult to detect without the integrated spatial model of the design provided by SURFCON.

The initial layout in the Major Feature Design Stage (Section 4.3) identified several key drivers. The mission payload required access to the water over the stern of the vessel via a ramp, but this conflicted with the waterjet position at the transom and led to selecting the staggered waterjet arrangement (See Figure 14). The MOVE and FIGHT groups interacted again as the large ducting for the propulsion Gas Turbines restricted the position of the hangar and drove the flight deck to the stern. The size of the payload bay also increased the minimum depth of the main hull, driven by the need for sufficient clearance for the deckhead in the payload bay and the wet deck from the waterline under the box.

Although the payload requirements played a key role in generating the initial design, the high speed requirement had more influence over the configuration and selection of ship equipment. In addition to the interaction with the FIGHT group, the long and narrow hull required for high speed had large voids forward, and the shaftlines aft occupied most of the hull in this region, which could otherwise have been used for stores, tanks or support spaces. The need to minimise resistance also led to the adoption of many advanced light weight technologies, such as composite structures and shafts and notational advanced cycle gas turbines for low speed propulsion. Design and growth margins were reduced relative to current combatants because of the propulsion power demands this would have entailed. This increased the uncertainty and risk in the design.

The shallow draught selected for the side hulls (to reduce wetted surface area and interference with the main hull) required that the vessel would operate within a limited range of draughts, and so a ballasting system would be neccessary to compensate for the usage of fuel, stores and weapons. These tanks were mainly created in the double bottom, and so did not affect the layout directly, but were an additional complexity in the design. It was also considered there could be detrimental effects on seakeeping in certain conditions, although the side hulls were lengthened in order to reduce this. However, no seakeeping analysis was attempted on this design due to the limited time available.

### 5.3 Comparison with Other Designs

Figure 19 shows a breakdown of the total weight of the UCL LCS using the USN SWBS, compared with two frigate designs prepared using UK and US design standards for a comparative exercise. (11) Figure 20 shows a similar comparison with a UCL SURFCON design broadly equivalent to a Type 23 frigate (2), but in this case the weights are shown for the SURFCON Functional Groups.

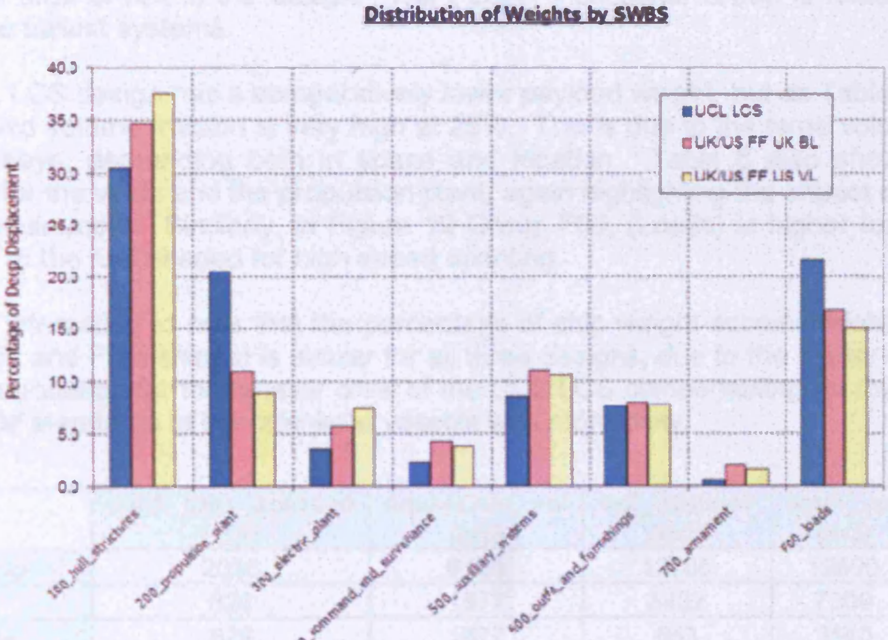


*Figure 19: Comparison of UCL LCS design with UK/US frigate designs*

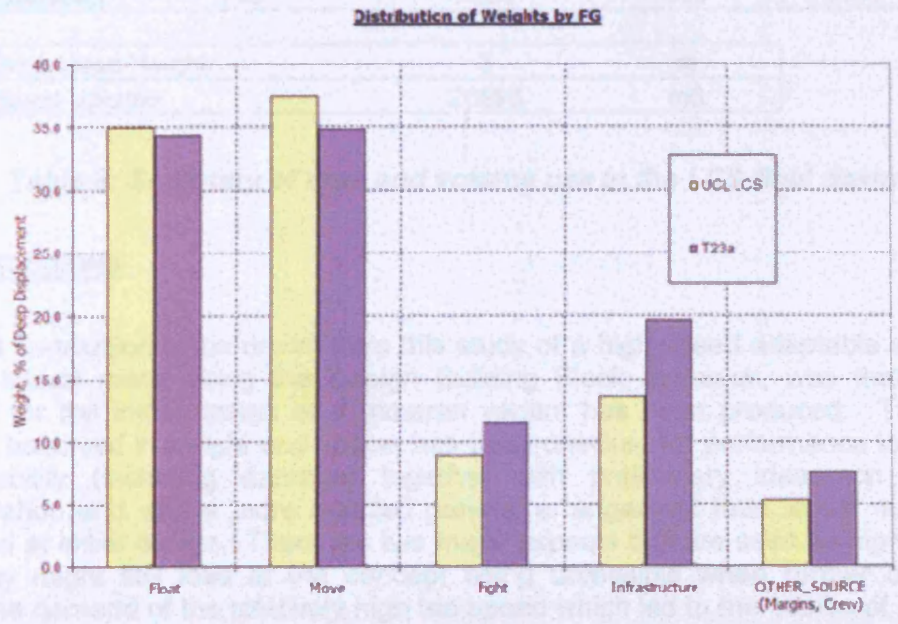


*Figure 20: Comparison of UCL LCS design with UCL Type 23 –analogue design*

These figures show that the UCL LCS devotes a larger percentage of the ship to propulsion, as would be expected from its high speed requirement. The weight of machinery seats is included under the MOVE Functional Group and the US SWBS Group 100 (Hull Structures) weight group, thus in Figure 20 FLOAT and MOVE are closer than are the SWBS groups 100 and 200 (Propulsion Plant). This assists by associating the weight with the function it serves, while the breakdown shown in Figure 19 is useful for examining the detail breakdown of the ship. Figure 19 shows that the UCL LCS has a lower structural weight fraction. It has been noted elsewhere that trimaran designs usually have higher structural weight fractions than monohulls (23) so this is an area of risk in the design. The FLOAT Functional Group is relatively large due to the ballast systems.

The UCL LCS design has a comparatively lower payload weight, but as Table 8 shows, the payload volume fraction is very high at 25%. This is due to the large volume of the payload bays, demanding both in space and location. Table 8 also shows similar volumes for the voids and the propulsion plant, again highlighting the impact of the high speed requirement. Similarly, in Figure 19 Group F00, (Loads) is higher for the UCL LCS due to the fuel needed for high speed sprinting.

It is also interesting to note that the percentage of ship weight accommodation (Group 600, Outfit and Furnishings) is similar for all three designs, due to the higher standards of accommodation for the smaller crew of the UCL LCS compensating for lower 1980s and 1990s standards of the reference vessels with more crew.

| | deck_area_demand (m2) | equivalent_vol (m3) | vol_demand (m3) | total_vol (m3) | Percent |
|---|---|---|---|---|---|
| **Whole_Ship** | 2035 | 6105 | 13785 | 19890 | |
| **Float** | 626 | 1877 | 5432 | 7309 | 37 |
| **Excl. Voids** | 626 | 1877 | 663 | 2540 | 13 |
| **Voids** | - | - | 4769 | 4769 | 24 |
| **Move** | 251 | 752 | 3590 | 4342 | 22 |
| **Fight** | 416 | 1247 | 3824 | 5071 | 25 |
| **Infrastructure** | 743 | 2229 | 939 | 3168 | 16 |

| | | |
|---|---|---|
| Nominal Deck Head Height: | 3 | m |
| Total Enclosed Volume: | 25993 | m3 |

***Table 8: Summary of area and volume use in the LCS final design***

## 6. CONCLUSIONS

The first conclusion to be drawn from this study of a high speed adaptable combatant for the littoral made using the Design Building Block approach, was that a viable solution for the initial design of a trimaran variant has been produced. The design study is balanced in weight and space, has been checked for performance in powering and stability (including damage) together with preliminary ideas on structural configuration and with a more detailed general arrangement than would normally be expected at initial design. There are two major aspects that are seen as high risk such that they might still lead to the concept being unfeasible when further developed. Firstly the demand of the relatively high top speed which led to the choice of a trimaran configuration also meant an advanced technology structural arrangement of an aluminium main hull and composite side hulls and superstructure. This enabled the structural weight fraction to be kept sufficiently low (30%) to avoid ship size rising and compromising the chosen propulsion fit which is the second area of high technological risk. The choice of four waterjets and the propulsive power they will generate is likely to require considerable design development should this design proceed. The modelling of the inlet and outlet flows to the waterjet and the structural implications of such geometry together with the resultant thrust load distribution, into a complex and narrow stern arrangement, is of concern and may need extensive analytical and even physical prototyping to resolve. Thus while the initial design could be said to be balanced and conceivable, whether it is truly feasible and achievable is less clear. However a major objective of any initial innovative concept is to identify the focus of downstream design development and this certainly has been revealed by the Design Building Block approach adopted.

Some specific insights were learnt from the application of the Design Building Block approach to such an innovative ship design. Despite the novelty of the design it was possible to rapidly develop the design through the four stages of development outlined in Section 4. This was in large measure due to the interaction between the three descriptive modes of SURFCON shown in Figure 2. The key design drivers of high speed and the modular payload's stowage and deployment were readily identified through the graphical representation. This also meant the potential conflict of the substantial machinery, after end architecture and modular payload stowage could be addressed from the earliest considerations of configuration. The extent of void spaces, driven by the need to drive up the length of the main hull was readily assessable from the Design Building Block description. As with any multi-hull, it really is not sensible to undertake sizing the vessel without consideration together of dimensions, form and arrangement, which virtually dictates a graphical representation to inform the initial sizing. The production of a balanced design (in not just weight and overall space but also architecture) is what distinguishes a proper initial ship design from mere artists' impressions. This again has been fully realised by a numeric, performance and architectural balance emerging from a designer driven interaction of all three descriptions – with the graphical aspect being particularly information rich.

When the study on the LCS is compared with the various other studies, undertaken by the DRC and which have been summarised in the authors' paper to the 2006 IMDC (8), it can be seen that such an innovative concept has further demonstrated the utility of the Design Building Block approach and the practical example of it that constitutes SURFCON within PARAMARINE. Thus the early monohull combatant studies showed the impact of different functional elements (in FIGHT) and that a detailed system evolution of electric propulsion could be investigated. The Mothership studies (1) were less highly tuned than the LCS, not just due to their size but also the immaturity of the operational concept, so were a different demonstration of innovative initial design than that described in this paper. The aviation ship studies were different again in looking at major aviation carrying ships rather than the more limited aviation features of LCS, which appear to be less critical than the two main drivers for this design. However it is worth saying this, to a degree, is because a trimaran configuration has inherent advantages for small combatants carrying aviation assets. The other studies that the DRC has undertaken recently were more to do with the ability given to the initial ship designer, by the Design Building Block approach, to explore aspects that were not previously easily addressed in initial design – namely Design for Production and Personnel Simulation. Both these increasingly important topics can now be addressed ab initio due to the Design Building Block approach, providing the designer from the start with an internal configuration description so these issues can directly influence the designer's judgement on the major sizing, form and configurational choices from the start.

To finally conclude, the LCS design study, as a current real example meeting a demanding requirement for an innovative high speed and adaptable littoral warfare combatant, has added to the UCL DRC's growing portfolio of Design Building Block based design studies. Such studies provide increased confidence in the design approach and in the practicality of the toolset employed enabling designers to produce innovative and creative ship designs.

## 7. ACKNOWLEDGEMENT

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# Appendix 9: Method for SURFCON / PARAMARINE in the Trimaran LCS Study

## INTRODUCTION

This appendix contains the detailed procedure developed by the candidate for the design of Trimarans in PARAMARINE – SURFCON. This procedure was developed from that used in the motherships study (Appendix 6), andwas sent to NSWCCD in October 2003. The procedure is divided into four main sections:

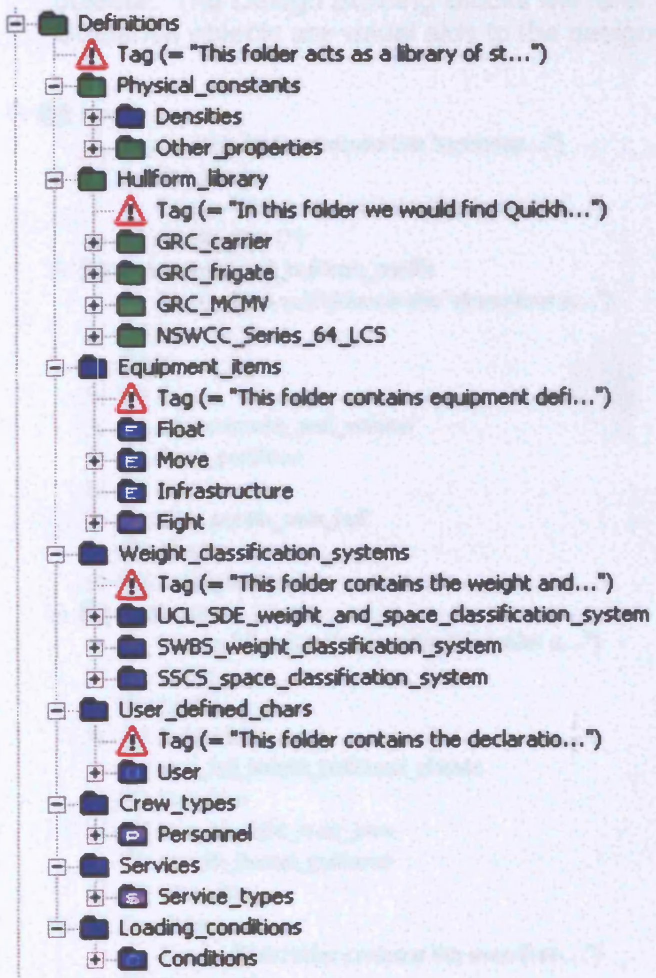
- Preparation Stage
- Major Feature Design Stage
- Super Building Block Design Stage
- Building Block Design Stages

## PREPARATION STAGE

- Identify capabilities (functions) required. These capabilities and functions must be translated into terms that can be expressed in the Design Building Block Hierarchy:
    - Speed
    - Range
    - Endurance
    - Payload equipments and spaces
    - 'ilities' eg: Producability, accessibility, maintainability, adaptability
    - Accommodation requirements
- The 'style' of the design to meet these requirements must be decided upon. Style in this case refers to the overall architecture of the vessel:
    - Hullform type: High speed monohull, low speed SWATH, trimaran?
    - Propulsion: IFEP, Mechanical
    - Damage control:
    - Zoning: For FLOAT only (DC) or MOVE, FIGHT and INFRASTRUCTURE?
    - HVAC: Centralised / distributed systems?
    - Access: Specified requirements? (Evacuation time?)
    - Adaptability: DBBs to represent future technology insertion?
    - Accommodation: Mess or cabin based?
    - Margins: Weight, space, propulsive and electrical power, KG
    - Design standards: Lloyds NSR, NES 109 etc.
- These will not necessarily be detailed descriptions, but will allow the selection of the appropriate library files to generate the basic framework of the design file:
- The structure of this framework is described below.

## Definitions

- This folder acts as a library of standard definitions and specifications for the design to refer to. Paramarine - Surfcon requires several of the variable types to be explicitly declared at one point in the design file.
- An example of this is in the 'crew_types' folder, which contains declarations of the crew types to be found in the design. These declarations or definitions are then referred to in the Design Building Block Hierarchy (the design proper) when that particular variable is needed.
- An alternative way of looking at this arrangement is that the declarations of crew types, user defined specifications and loading conditions provide the column headings in the auditing tables.

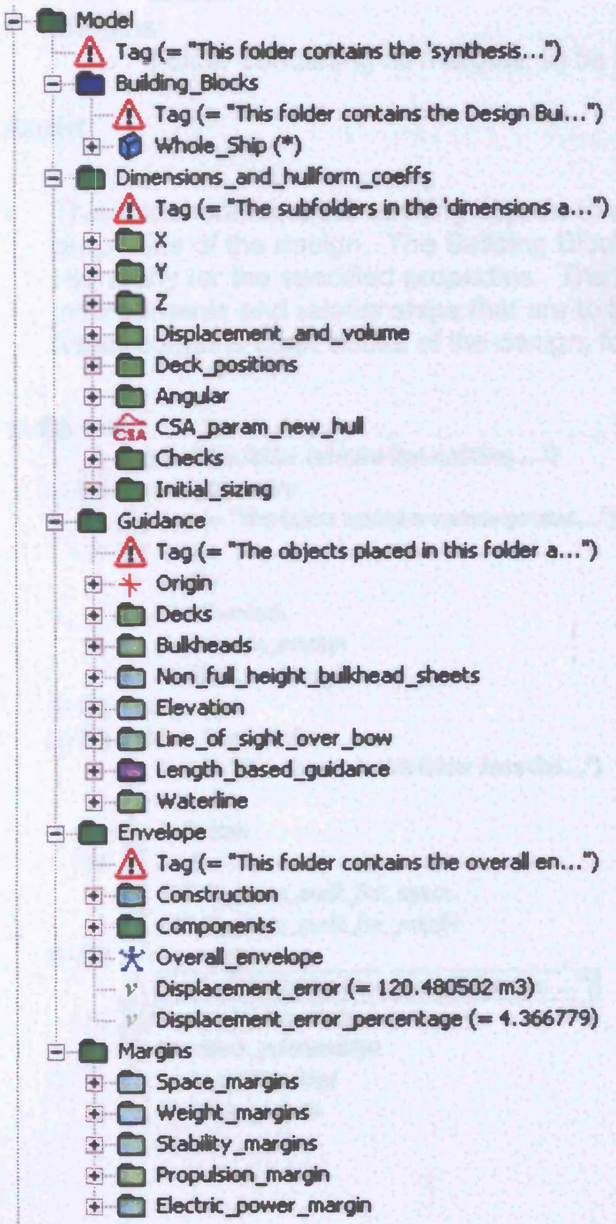



- Physical constants
  - Densities, “g” etc
- Type ship hullforms
  - Quickhull Repository objects for ‘type’ ship hullforms.
- Equipment items
  - FLOAT: Ships boats, liferafts, anchors.
  - MOVE: Prime movers, shaft lines, propulsors.
  - FIGHT: Weapons, aircraft.
  - INFRASTRUCTURE: STP, RO plants, pumps, RAS rigs.
- Weight classification systems

  - NES 163, SWBS, SSCS
- User defined characteristics
  - Propulsion power, liferaft spaces
- Crew types
  - By rank, e.g. Officer / CPO / PO / JR for RN use
- Services
  - 440V, 6.6Kv, air conditioning, chilled water
- Loading conditions
  - Deep, light, basic, light sea-going

## Model

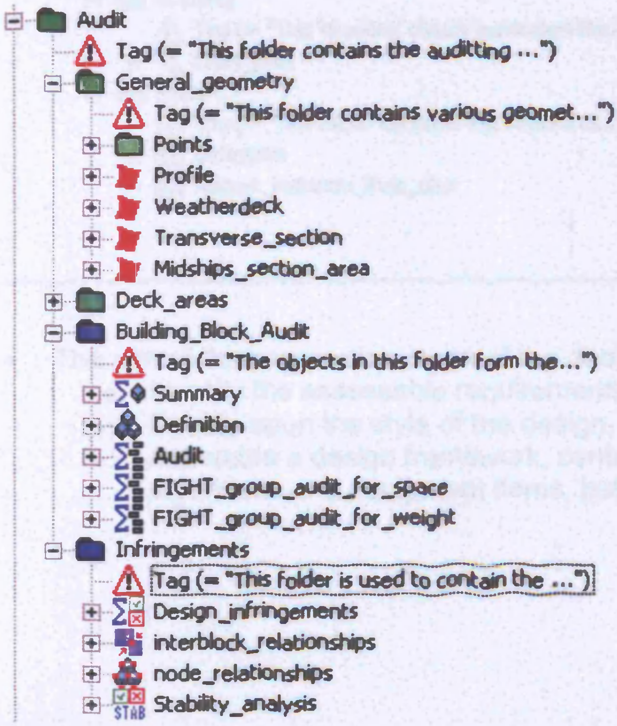
- This folder contains the 'synthesis' aspects of the design - the Design Building Block Hierarchy, overall dimensional controls for the hull, margins and guidance objects. The Design Building Blocks will refer to the dimensions and margins. The Guidance objects are visual aids to the designer.



- Building Blocks
  - Design Building Block Heirarchy (DBBH) made up of imported files:
  - Standard FLOAT blocks Damage control, ships boats etc
  - Standard MOVE blocks: Prime mover, tankage etc
  - Standard FIGHT blocks: AAW-RAM, AAW-AEGIS, ASW-LAMPS etc
  - Standard INFRASTRUCTRE blocks: Accommodation by rank, SW systems, FW systems etc
- Dimensions and Hullform Coefficients:
  - Controls over the size of the ship, shape of the hullform and the positions of decks and Design Building Blocks on those decks.
- Initial sizing folder contains historical gross ship density and PVF relationships to allow initial estimates of ship size.
- Guidance:
  - Visual guidance aids to the designer.
- Envelope:
  - Solid model of hull and superstructure used in stability analysis and to provide envelope for spaces such as Main Machinery Rooms and fuel tanks.
- Margins:
  - Folder containing all margins, to be referenced by all block properties.

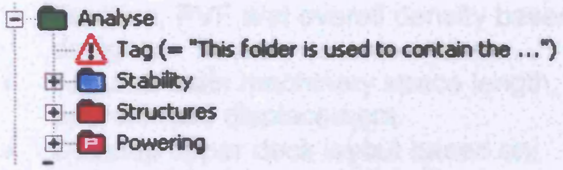
## Audit

- This folder contains the auditing objects to allow an assessment of the overall properties of the design. The Building Block Audit audits the Design Building Block Hierarchy for the specified properties. The Infringements objects control the infringements and relationships that are to be assessed. The General Geometry folder contains other audits of the design, for example deck area.



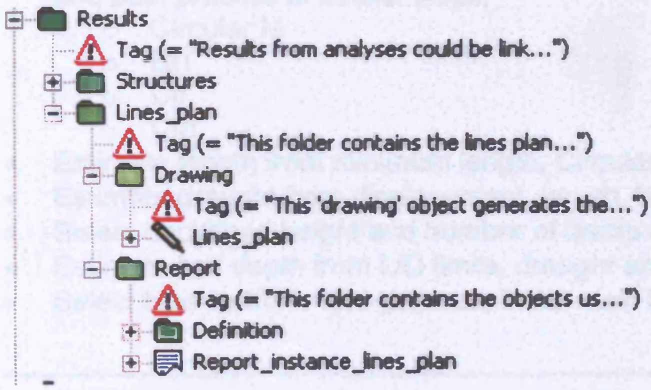
## Analysis

- This folder is used to contain the objects associated with more detailed analysis of the design. Damaged stability analysis, detailed structural analysis and powering calculations would be placed here.




## Results

- This folder contains the output objects for the design. Lines plans and general arrangement drawings would be placed here, as would tabular weight and space breakdowns, stability analyses etc. The Report objects can be used to generate a standard ship description that can be output at any point in the design process for use in design reviews.

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- The aim of the preparation stage of the design is to:
  - Identify the assessable requirements of the design (Metrics).
  - Decide upon the style of the design.
  - Assemble a design framework, containing data in the form of design algorithms and equipment items, but with no design definition as yet.

## MAJOR FEATURE DESIGN STAGE:

### 1. Initial Sizing

- Audit design for total FIGHT Functional Group weight and volume.
- Estimate volume and displacement from payload volume using Payload Volume Fraction, PVF and overall density based on past practice or functionally similar designs.
- Assume main machinery space length, based on machinery philosophy and approximate displacement.
- Develop upper deck layout based on:
    - Main functional FIGHT blocks,
    - Main functional MOVE blocks; bridge, main machinery spaces
    - Upperdeck arrangement limitations, e.g: Minimum length of forecastle
- Derive minimum upperdeck length and beam from layout considerations

---

### 2. Initial Main Hull Hullform Generation

- Select initial form parameters, based on minimum length, displacement and speed and past practice or similar ships;
    - Circular M
    - B/T
    - Cp
    - Cm
- Estimate length from minimum length, Circular M and displacement
- Estimate draught from displacement, length, beam, form parameters
- Select deckhead height and number of decks in hull
- Estimate hull depth from L/D limits, draught and freeboard limitations
- Select type hullform and generate initial main hull

---

### 3. Resistance Estimation for Main Hull

- Estimate main hull resistance based on hullform, displacement, length, draught and ship type
- Assume initial propulsive coefficient based on machinery philosophy and type hullform, and estimate shaft power
- Make first estimate of electrical power requirement based on dimensions, equipment and complement
- Make initial selection / sizing of prime movers and other SDBB / high-level MOVE DBBs
    - Bridge
    - Main system blocks such as GTAs, switchboards, converters and controllers

---

## 4. Service Load and Tankage

- Size ships service generators (Unless IFEP, then included under the above)
- Estimate and place auxiliary machinery spaces based on generators and past practice
- Place prime movers and generators in main and auxiliary machinery spaces
- Estimate required tankage for propulsion and generation and place fuel tankage in large blocks

---

## 5. Initial Bulkhead Placing

- Place initial watertight bulkheads based on:
    - Structural continuity and main block positions
    - crude length-based damage and compartment standard (e.g. 15% length, 3 compartment standard)
- Select reasonable initial frame spacing on;
    - Bulkhead spacing
    - Length
    - Displacement

---

## 6. Assessment

- Re-assess layout for feasibility

---

## 7. Side Hull Design

- Select side hull length and position based on;
    - Damaged stability
    - Resistance
    - Layout
    - Structural continuity
    - Seakeeping
- Select style of side hull and initial side hull parameters
- Use Quickhull to produce side hull envelope
- Develop box layout based on;
    - Upperdeck layout
    - Bulkhead spacing
    - Side hull position and dimensions
    - Damaged stability

---

## 8. Superstructure Design

- Define initial superstructure extent

- Make initial estimate of structural weight value and centroid, based on;
  - Similar sized designs and structural weight fraction
  - Area density of the main hull, box, side hulls and superstructure
  - Length of the main hull
  - Volume of the main hull, box, side hulls and superstructure

---

## 9. Numerical Balance

- Check inclusion of all weight groups. A consistency check is needed, using the selected weight breakdown system, to ensure that all weight and space groups have been included as fixed blocks or algorithmically scaled blocks. Most of these blocks will only consist of demand data, and will have no spatial extents. If a standard DBBH containing data has been used to generate the design, then this step will be simplified.
- Iterate design to numerical balance of weight / displacement and space available / space required. All DBB will now have a space demand and weight value.

---

## 10. Assessment

- Estimate the CoG of unplaced weight groups based on;
  - Past practice and centres of volume of main hull, side hull, box and superstructure
  - This can be added as a single "Rest-of-ship" weight at an assumed LCG and VCG
- ASSESS design for performance;
  - Intact stability and trim
  - Resistance, propulsion and endurance
  - Layout effectiveness
  - Basic damage stability
- Feedback results of assessment into configuration at Major Feature level.

---

- This concludes the Major Feature Design Stage. The major spatial drivers in the design should be clear, and the style and overall layout of the design has been verified as feasible.
- An initial assessment of the design has been made with respect to the S5 properties: Speed, Seakeeping, Stability, Strength and Style.
- The ship should be balanced in the following respects;
  - Resistance = propulsive power
  - Fuel required = fuel supplied
  - Generator demand = generator supply
  - Internal volume required = internal volume supplied
  - Weight = displacement
  - Upperdeck dimensions = required dimensions
  - Intact stability required = intact stability achieved

**<u>SUPER BUILDING BLOCK DESIGN STAGE:</u>**

## 11. Design Refinement

- Define and place main FLOAT elements;
  - Mooring forward and aft
  - Ships boats
- Main ACCESS elements
- Place main non-upper deck FIGHT elements;
  - Sonar
  - Magazines
  - Aviation fuel tanks
  - C4I spaces
- Define and place main INFRASTRUCTURE elements;
  - Accommodation as large blocks with area allowance for access

---

## 12. Parametric Survey

- Parametric Survey on main hull. Refine main hull dimensions and form parameters on;
  - Stability
  - Resistance
  - Refine side hull definition to meet;
  - Damaged stability
  - Resistance
  - Layout
  - Structural continuity
  - Seakeeping

---

## 13. Assessment

- Estimate the rest-of-ship CoG based on;
  - Past practice and centres of volume of main hull, side hull, box and superstructure
  - Individual locations for key weights such as systems and structures
- ASSESS design for performance:
  - Intact and damaged stability and trim
  - Resistance, propulsion and endurance
  - Layout effectiveness (Suitability for ship mission, aviation, adaptability, producability, accessibility, topside arrangement etc)
  - Seakeeping
- Feedback results of assessment into configuration at Super Building Block level.

---

- This concludes the Super Building Block Design Stage. This stage of the process refines the definition of the design by incorporating the secondary drivers on the configuration, and assessing the impact of the primary design drivers identified earlier

- At the end of this stage, the layout has been worked up to a useful level of detail, with the Super Building Blocks in all of the Functional Groups placed. The assumptions used in the Major Feature Stage can be re-assessed for their validity.
- The parametric survey conducted on the main and side hulls has been conducted, so the hullform parameters have been fixed.
- A more detailed assessment of the design has been made with respect to the S5 properties: Speed, Seakeeping, Stability, Strength and Style.
- The ship should be balanced in the following respects;
  - Resistance = propulsive power
  - Fuel required = fuel supplied
  - Generator demand = generator supply
  - Internal volume required = internal volume supplied
  - Weight = displacement
  - Upperdeck dimensions = required dimensions
  - Intact stability required = intact stability achieved

**<u>BUILDING BLOCK DESIGN STAGES:</u>**

## 14. Design Refinement

- Subdivide FLOAT SBBs to define FLOAT support spaces;
  - Access
  - Damage control
  - Liferafts
  - Damage control spaces (Zoning)
- Subdivide MOVE SBBs to define MOVE support spaces;
  - Assess main machinery spaces for internal arrangement as auxiliary systems such as pump blocks are added
- Subdivide FIGHT SBBs to define FIGHT support spaces;
  - Mast equipments
  - Cable trunks
  - Ready-use lockers
- Subdivide INFRASTRUCTURE SBBs to define INFRASTRUCTURE support spaces;
  - Auxiliary machinery spaces detail arrangement
  - Accommodation spaces detail arrangement
  - ATUs and ventilation spaces
  - Electrical distribution spaces

---

## 15. Assessment

- ASSESS design for performance:
  - Intact and damaged stability and trim
  - Resistance, propulsion and endurance
  - Layout effectiveness
  - Seakeeping
- Feedback results of assessment into configuration at Building Block level.
- Refine design as to required level of detail.

---

- This stage represents the development of the design.

- The level of detail to be worked to will depend upon the nature of the study. A typical level of detail would be that seen in the MsC Ship Design Exercise at UCL. The layout would show all internal spaces and hatches, however, no equipment would be defined in these other than in the main and auxiliary machinery spaces. This equipment would be at a level of detail equivalent to a 'block' on an overall system diagram.
- At each stage, when the design is assessed, the results should be fed back as requirements or recommendations into the design.
- There are three main methods that can be used to structure each stage of the refinement:

  - Largest blocks to smallest blocks
  - Most constrained blocks to least constrained blocks
  - FLOAT blocks, MOVE blocks, FIGHT blocks, then INFRASTRUCTURE blocks

# Appendix 10: The Implications of an All Electric Ship Approach on the Configuration of a Warship

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## SYNOPSIS

It has been stated that one of the advantages of an all electric approach to prime power generation and distribution on a frigate is that it 'frees the ship designer from the tyranny of the shaft'. While there has been considerable effort devoted to the Marine engineering system concerns in producing the All Electric Ship, there has not been a commensurate level of investigation into the ship design implications. The paper presents a series of studies using the SURFCON graphically centred preliminary computer aided ship design tool, based on the Design Building Block approach which originated in the Ship Design Research team at UCL. This tool is incorporated in the Graphics Research Corporation Ltd PARAMARINE CASD suite and thus enables graphically descriptive and naval architecturally balanced ship designs to be produced. Explorations have been undertaken, for a monohull frigate concept design on how an advanced electric machinery fit could be configured to provide a more effective and survivable overall ship design.

## INTRODUCTION

This paper addresses the implication of the adoption of an All Electric machinery fit, on the configuration of a modern warship. This is done with particular reference to a generic frigate design case, as the most ubiquitous example of warship design practice.

The Electric Ship has been the subject of considerable effort and many expositions in recent years (1,2), particularly describing the substantial developments by the US Navy (3) and through the Anglo-French programme (4). The descriptions produced of both these latter activities have commented on the wider ship design advantages of adopting such a form of machinery plant for both ship propulsion and power generation but have primarily focused on the marine engineering issues rather than the overall ship design consequences. One clear message of general ship design applicability from the proponents of the All Electric Ship (AES) is that an all electric installation "releases the ship designer from the tyranny of the shaft line". Just how valid this might be is explored later in the specific range of frigate studies.

From a ship design point of view it is recognized that in warship preliminary design the choice of the propulsion system is a major determinant of the overall size, style and cost of the eventual design solution. Thus in the three linked phases of the first stage of the design of a major new naval ship programme, those of Concept Exploration, Concept Studies and Concept Design (5), the choice of the propulsion system figures alongside the material features of the combat system or major payload (in the case of an aircraft carrier or amphibious vessel) as a principal design determinant.

In such preliminary ship design work, traditionally the demands of the prospective main propulsion fit are seen by the naval architect as significant in terms of overall ship space and weight drivers. Thus the main and auxiliary machinery spaces have been seen as "inevitably" located deep and centrally in the ship as a single block, at least initially. In weight terms the propulsion and power generation fit is second only to the structural weight in contribution to ship lightweight. Thus at least as far as machinery spaces' overall length is concerned there is a need for the marine engineer to produce an outline layout of the machinery spaces relatively early in preliminary design, especially in the case of the corvette/frigate/destroyer range of combatants. This is seen as leaving little scope on the part of the naval architect and marine engineer, jointly or independently, to explore much in the way of interaction between the major machinery spaces architecture and that of the rest of the evolving ship architecture. This was probably largely justifiable with the pre-All Electric "tyranny of the shaft line", but is no longer sensible. There is therefore an urgent need to explore the choices and interactions between the domain of the marine engineer and that of the naval architect, as the custodian of the overall ship architecture. This has become possible through recent advances in computer aided preliminary ship design, built on the ship design methodology pioneered by the first author, and which are briefly outlined in the following section of the paper.

## SHIP CONFIGURATION AND THE DESIGN BUILDING BLOCK METHODOLOGY

Ship architecture and how it is produced as part of the evolution of a new ship design is a major aspect of ship design which has, in general, been somewhat neglected by the profession of naval architecture. It was precisely this aspect that was identified in 1980 (6) as being a key to a more creative approach to naval architecture, for the following reasons:-

- Many of the features and aspects of design could not be properly addressed with the traditional sizing approach but could be incorporated with the better design methods and tools becoming available;
- The advent of computer aided graphic design methods, then in their infancy, but now reaching a level of maturity and being usable with personal computers (7).

The manner in which exploration of ship internal configuration and layout helps to open up many of the more protracted and less readily analysable aspects of ship design has been taken further by the first author, firstly in considering the integration of configuration in initial ship design (8) and more recently placing this approach to the design of ships (and other complex systems) in a wider context (9). The current section draws on proposals which have been presented on ship layout or the architecture of ships, and how such an approach enables ship designers to explore alternative ship arrangements (10).

### The Example of Frigate Architecture

In 1987 Brown presented a paper entitled "The Architecture of Frigates" (11), which drew on his experience of preliminary warship design and on research undertaken at University College London (8, 12, 13). Brown's paper was largely a comprehensive survey of many of the aspects and constraints impinging on frigate layout design. He emphasised how, for a frigate and similar combatant vessels, the key to the internal layout is the design of the upper or weather deck 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 1 below shows an updated version of Brown's frigate configuration from Ref 14.

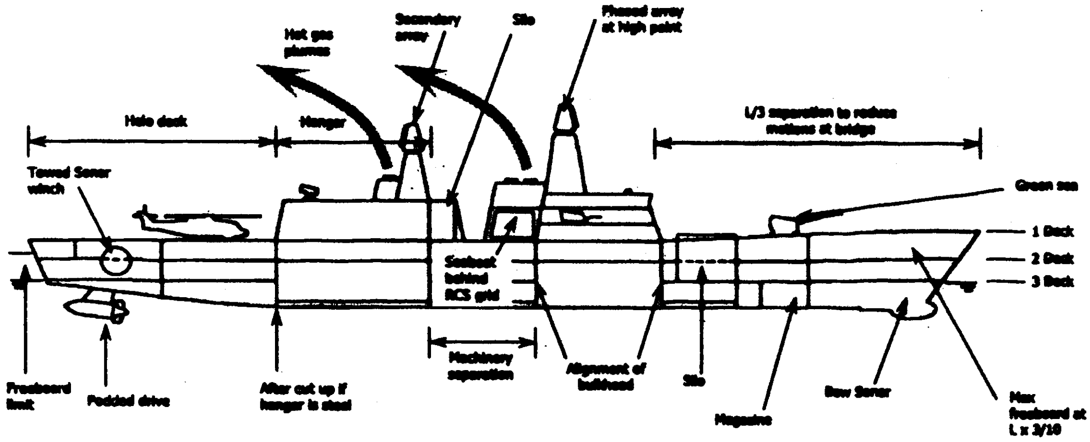

*Fig 1 Frigate Layout Considerations (14)*

## Integrated Ship Synthesis

Production of a warship's general arrangement 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. Competing with these requirements are the needs of the marine engineer who has minimum lengths for machinery and locations fixed by shafts, intakes, exhausts etc. 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 presented in the first paper proposing the architecturally driven design synthesis (6). In 1986 an example of a sequence for allocating the various compartments in a frigate design was published (8). 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 hull form parameters. It was also argued that with integration of the ship architecture, weight, space and form parameters, alternative layouts could be explored while the hull form and dimensions were still fluid. The ability to readily alter the layout was also held to justify the initial adoption of a conventional layout sequence, but only provided that ability and to re-sizing the design could then be exploited (rather than this layout being adopted and closing down the option of configuration exploration). The 1986 paper also proposed 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 2 taken from Figure 11 of Ref.8). However in all these cases the traditional machinery configuration meant that the layout synthesis assumed that the propulsion and power generation spaces were largely excluded from this exploration and only impacted on the main operational and infrastructure spaces through the presence of intakes, uptakes and removal route considerations.

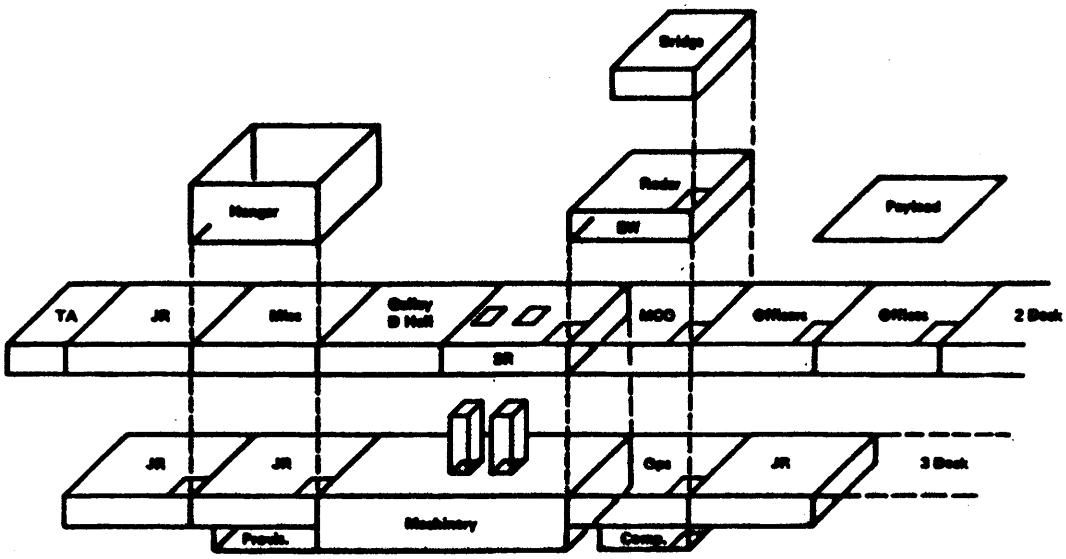


*Fig 2 Ab initio Frigate Compartment Block Synthesis (8)*

## Design Building Block Methodology

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 (15). The Design Building Block approach to producing a new ship design was presented in Ref 16 at Figure 5, reproduced below at Fig 3. This diagram summarises a comprehensive set of analysis processes most of which are unlikely to be used in the initial setting up of the design or even early iterations around the sequence of building blocks, geometric definition and size balance. In fact several of the inputs shown in Fig 3 are either specific to the naval combatant case, such as topside features, or omit aspects which could be dominant in specialist vessels, such as aircraft carriers or cruise liners, where personnel and vehicle flow are likely to dominate the internal ship configuration.

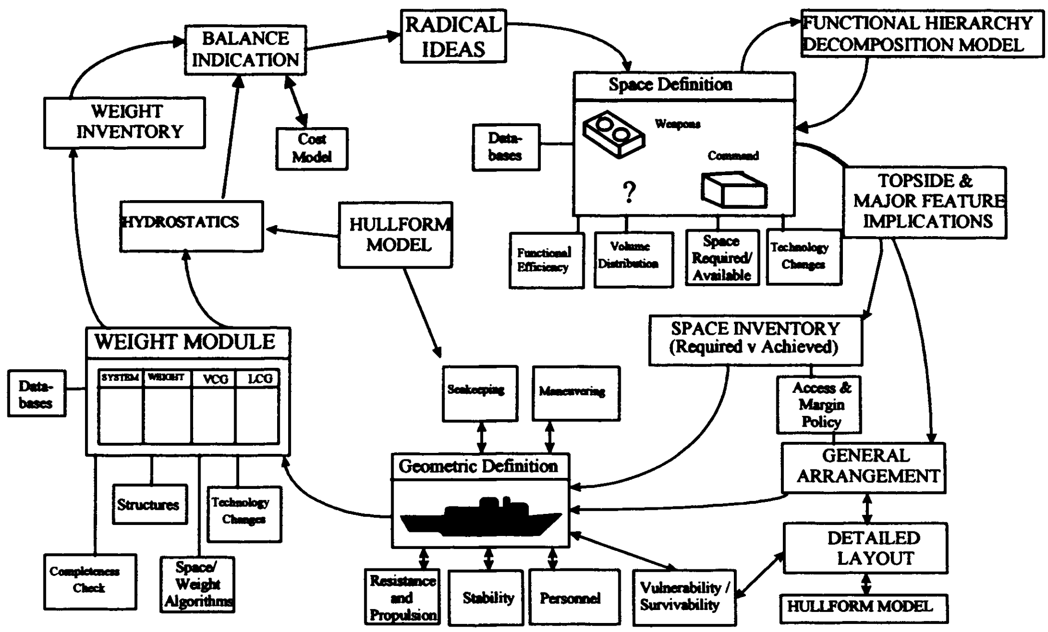


*Fig 3 Overview of the Design Building Block Methodology applied to Surface Ship (16)*

A further feature of the Design Building Block approach that was outlined in some detail for the 1997 UCL prototype system and which has recently been fully incorporated in the SURFCON element of PARAMARINE, is that of the "Functional" breakdown (15). This was adopted in preference to the usual weight breakdown essentially based on the shipbuilding trades (i.e. steel, machinery, electrics and outfit, plus the combat system in the case of naval vessels). This more functional breakdown (i.e. float, move, fight or operations and infrastructure) has advantages. The more traditional breakdown can inhibit the designer from considering radical solutions, not just to the layout but also to the engineering choices, in contrast to the UCL approach with the early introduction of the architectural element which is seen as a means of exploring more innovative configurations.

A further feature is the use of the term Master Building Block to denote how the overall aggregated attributes of the building blocks can be 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 (7) was that the audited building block attributes within the Master Building Block could be directly used by PARAMARINE to perform the necessary naval architectural calculations to ascertain the balance or otherwise of the configuration just produced by the designer. Typical information held in the Master Building Block includes:

- Overall requirements: Ship speed, seakeeping, stability, signatures (in the case of a naval combatant);
- Ship characteristics: weight, space, centroid;
- Overall margins: weight, space and their locations for both growth and enhancement.

The 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. Data that can be contained within a building block is of several categories, as follows:

- Numerical Data (e.g. Weight, power, manning);
- Constraint Data (e.g. Mast spacing, proximity of antennae and processors);
- Parametric Data (e.g. Structural mass of hull – dependent upon, say, hull length);

- Geometric Data (e.g. Volume, area, shape, location);
- Descriptive Data (e.g. Name, explanatory notes on function and performance).

As the design description is built up and modified, all features of the building blocks are utilised by the system. The geometric definition (shape and location) is used to constantly update the graphical display, whilst data properties are indicated in a logical tree diagram of the design, as shown in Fig 4 along with the block representation and a tabular view of the numerical information. Some characteristics that do not have a specific spatial extent are still represented in the graphical display; for example, weight centroids are shown with the traditional "centroid" icon. This parallel graphical and numerical display permits the user the "drag and drop" blocks in the design space.

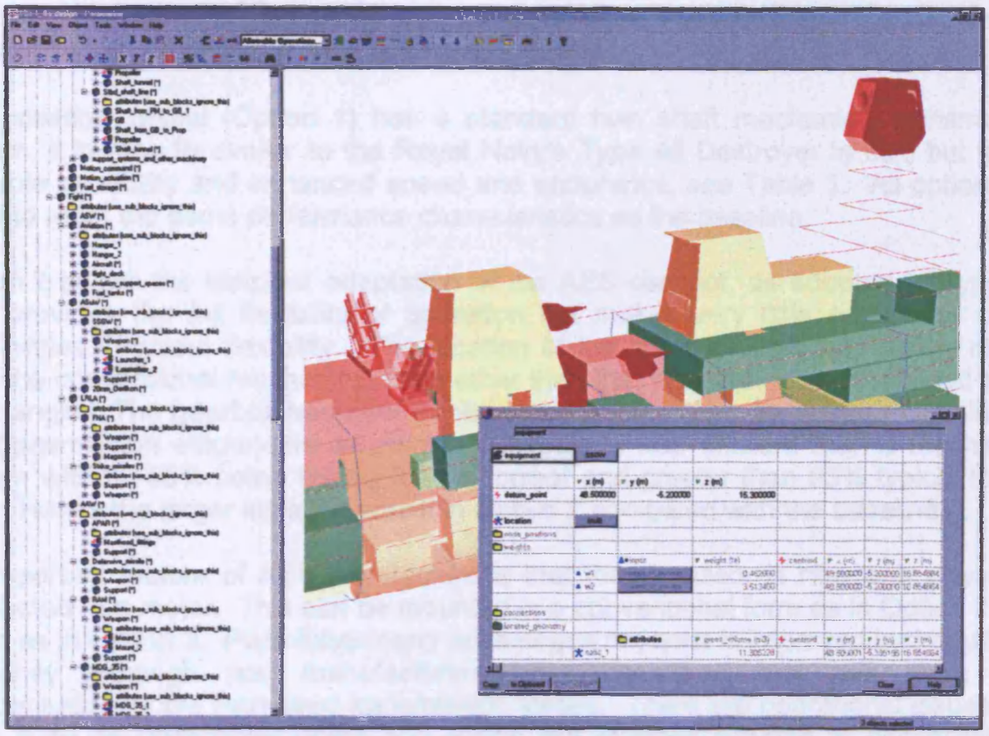

***Fig 4 Multiple views of a Design Building Block***

The Design Building Blocks are particularly useful when comparing different machinery fits as it is possible to assess the impact of, say, pods versus traditional shafts. Each component of machinery associated with the propulsion system can be identified with a design block and the total ship impact readily assessed. For example, it is not sufficient to just compare the mass of each alternative system but also how the weight of each system impacts on the ship in terms of trim, stability, power demands and additional structural weight.

SURFCON has been used by the UCL Design Research Centre for design investigations for both the UK MoD and the US Navy Office of Naval Research, with the "Mothership" studies undertaken in conjunction with BMT (17) being recently outlined in the public domain. The tool has also been recently employed to explore design for production in initial design for a range of ship types as part of the UK Shipbuilders and Ship repairers Association shipbuilding initiative (18). The examples in the next section, from recent investigations considering the impact of an All Electric machinery fit, demonstrate that ship architecture can be investigated in reasonable depth at the initial design stage of a ship concept design investigation. This facility widens the scope for early exploration of a greater range of ship design drivers and fosters the approach to creative ship design that has been advocated by the UCL Design Research Centre.

## EXAMPLE OF MONOHULL – CONVENTIONAL vs ALL-ELECTRIC PROPULSION

The following is an example of the use of the Design Building Block methodology and the SURFCON system, applied to the design of a large multi role frigate. The comparison of the overall ship designs is given in Table 2 and the subsequent diagrams show the machinery spaces arrangements with the major equipment highlighted and the adjacent tabular listings highlight the machinery and design implications of each design study. A standard mechanical fit is used as the baseline with the AES variants becoming progressively more extensive in exploiting the all electric potential culminating in a speculative design.

The baseline vessel (Option 1) has a standard twin shaft mechanical transmission system, it is broadly similar to the Royal Navy's Type 45 Destroyer in size but with a multirole capability and enhanced speed and endurance, see Table 1. All options are sized to meet the same performance characteristics as the baseline.

Option 2 shows the simplest adaptation of the AES concept, as adopted in Type 45. This provides the full flexibility of operation but makes very little advantage of the possibilities in layout flexibility. The location of the prime movers has hardly moved from the conventional mechanical case other than that they are now not inclined at the shaft angle. The gearbox has been replaced by a motor and generator. Considering just transmission efficiencies an electrical system is less efficient than a mechanical system with 80-85% being typical for the former and greater than 95% typical for the later. Hence the larger installed power in Option 2 compared with the baseline.

An important feature of AES architecture is that the propulsor is now only physically connected to a motor. This can be mounted in a conventional form as in Option 2 or in a pod as in Option 3. Pods have many advantages not least is improved hydrodynamic efficiency although pod manufacturers have countered that this more than compensates for the increased transmission losses. There are operational issues with pods such as underwater noise and shock, but of more concern in configurational terms is that they concentrate the weight of the motor and propeller further aft. This is exacerbated by the loss of buoyancy aft as the hull form is optimised for water flow into the pods. Additionally the ship no longer has thrust blocks and instead the force is transmitted to the hull at the pod/hull interface, again much further aft than before.

Propulsion plant can now be distributed through out the ship both longitudinally and vertically to improve survivability as shown in Option 4. Although flexibility in operation is not being considered in this paper there is one aspect where it impinges on layout design. Engine running hours can be varied much more readily when they are connected to an electrical distribution system. Engines that are more accessible and easier to maintain can be run in preference to those more difficult to access. This also opens the way for locating an engine where previously it would not be considered because access and/or removal is difficult, it need only be run on the rare (for a warship) occasions that the ship is at full speed.

As there is no longer a requirement to match the engines to the propeller characteristic the size and number of engines is also fully flexible and Option 5 takes advantage of this and demonstrates a main machinery fit of 4 smaller 13MW engines. A top speed of 19.5 knots (compared to a probably over generous 24.5 knots for Option 3) can be achieved on single engine operation which is sufficient for most operations. There is also a case for making two of the main engines simple cycle.

The survivability of a ship can be improved by increasing its watertight subdivision and providing separation of the main machinery. As can be seen in Options 1, 2 and 3 the main machinery rooms are the longest and largest compartments below the waterline. Longitudinal subdivision is possible but not acceptable from a stability point of view. In an AES ship the engines could be mounted transversely, which could provide a greater number of much shorter machinery spaces. The bearings of the generators and gas turbine would have to be strengthened since they would see greater gyroscopic forces. Their axis of rotation would now be normal to the ship's roll and yaw axes instead of its pitch and yaw axes. Option 6 takes this a stage further and considers the hypothetical case of mounting the gas turbines vertically with intake upper most. This has a number of advantages, see Figure 11. No installation like this yet exists but the basic technology does. Vertical mounting of large generators is common in hydroelectric plants and aero gas turbines regularly operate at large angles of inclination. Option 6 is speculative but it demonstrates that the flexibility AES provides still has many opportunities to explore.

## The Designs

The example designs developed for this paper represent a multi-role vessel intended to fulfil the key user requirements specified for the Future Surface Combatant, see Table 1. Complement and accommodation demands were estimated from the payload, using the system detailed in the UCL SDE Data Book. (19) The accommodation provision for all variants was identical, 28 officers, 16 chief petty officers, 33 petty officers, 65 rates and 50 special forces personnel. Maximum Activity Load for the hotel load was estimated at 2.7MW, based on the payload and accommodation. The flight deck and hangar positions were kept fixed.

***Table 1 Payload and Requirements***

| Function | Equipment | Function | Equipment |
|---|---|---|---|
| ASW | - Bow sonar 2050<br>- Towed Array 2087<br>- Magazine Torpedo Launch System<br>- Surface Ship Torpedo Defence<br>- Anti Submarine Warfare Merlin helicopter | C4I | - 2 x Navigation radar 1008<br>- BAE SSCS Combat Management System<br>- Integrated Communications System inc. SCOTT SATCOM<br>- Link 16/22<br>- Co-operative Engagement Capability |
| ASuW | - 8 Surface to Surface Guided Weapons<br>- Anti Surface Warfare Merlin/Lynx helicopter<br>- 2 x 20mm Oerlikon<br>- 2 x General Purpose Electro Optical Device | ECM/EW | - Jammer 675<br>- Cutlass ESM<br>- 4 x 2 DLB floating decoy<br>- 8 x Sea Gnat decoy projectors |
| LRLA | - 1 x 155mm Future Naval Artillery system<br>- 4 x MK41 strike length Vertical Launch System | Special Forces | - Accommodation for 50<br>- Second hangar used to store boats or helicopter<br>- Large boat crane by hangar |
| AAW | - Advanced Phased Array Radar<br>- 2 x Infra Red Search and Track systems<br>- IFF system<br>- 4 x MK41 strike length Vertical Launch System<br>- 2 x RAM Inner Layer Missile System<br>- 2 x 35mm Close In Weapon System | Early Entry | - 30 knt threshold maximum speed, Sea State 3, 10% margin<br>- 7000 nm at 20 knots cruise speed, Sea State 3, 10% margin<br>- 45 days stores |

In total, six designs were developed, including the baseline and five different electrical machinery fits. The use of the SURFCON tool allowed the designs to be assessed and balanced:

- Total ship weight = total displacement
- Total volume and area required ≤ area and volume supplied
- Propulsive power required ≤ propulsive power supplied
- Electrical generating power required ≤ Generating power supplied
- Chilled water demand ≤ Chilled water supplied
- Variables (Dieso, fresh water) demand ≤ Variable supply

- Stability = compliance with NES 109 for intact and damaged cases

Weights, spaces and auxiliaries requirements were estimated using the UCL Ship Design Exercise Data Book so no sensitive information is contained in the model. Other information was sourced from previous UCL MSC ship designs which featured IFEP propulsion architectures. (20), (21), (22)

***Table 2 Summary of the designs***

| | Option 1: Baseline | Option 2: Baseline + IFEP | Option 3. IFEP + Pods | Option 4. Distributed Prime Movers | Option 5. Small Prime Movers | Option 6. Vertical GTAs. |
|---|---|---|---|---|---|---|
| Waterline length | 141.0 m | 149.0 m | 147 m | 147 m | 148 m | 147 m |
| Overall length | 147.0 m | 155.0 m | 153.0 m | 153.0 m | 154.0 m | 153.0 m |
| Waterline beam | 17.1 m | 18.3 m | 17.95 m | 18.0 m | 18.1 m | 17.9 m |
| Overall beam | 18.81 m | 20.13 m | 19.75 m | 19.8 m | 19.91 m | 19.7 m |
| Draught | 5.1 m | 5.49 m | 5.36 m | 5.39 m | 5.4 m | 5.34 m |
| Depth, midships | 12.3 m | 12.69 m | 12.56 m | 12.59 m | 12.6 m | 12.54 m |
| Depth, bow | 14.3 m | 14.69 m | 14.56 m | 14.59 m | 14.6 m | 14.54 m |
| Displacement, deep | 6035 te | 7287 te | 6915 te | 7022 te | 7073 te | 6863 te |
| Enclosed volume | 21019 m3 | 22631 m3 | 22090 m3 | 21626 m3 | 23132 m3 | 22159 m3 |
| GMtf intact, deep | 1.78 m | 2.7 m | 2.9 m | 2.5 m | 2.7 m | 2.6 m |
| Trim by stern, deep | 0.14m | 0.53m | 0.48m | 1.00 m | 0.77 m | 0.92m |
| Total installed generator power | 50 MW | 66.42 MW | 66.42 MW | 56.4 MW | 56.2 MW | 56.4 MW |
| Propulsive coeff. | 0.65 | 0.56 | 0.67/0.64 | 0.67/0.64 | 0.67/0.64 | 0.67/0.64 |
| Power for 30 knots | 50.6 MW | 64.4 MW | 52.4 MW | 52.9 MW | 52.9 MW | 52 MW |
| Power for 20 knots | 9.9 MW | 12.9 MW | 11.2 MW | 11.2 MW | 11.4 MW | 11.1 MW |
| Prime Movers | 2 x WR21 ICR GT (4 x 1.5MW ICR GTA) hotel only | 2 x WR21 ICR GTA 3 x 4.9MW GTA 1.2MW Battery | 2x WR21 ICR GTA 4.9MW GTA 1.5MW ICR GTA 1.2MW Battery | 2x WR21 ICR GTA 4.9MW GTA 1.5MW ICR 1.2MW Battery | 4x 13.3MW ICR GTA 2 x 1.5MW ICR GTA 1.2MW Battery | 2 x WR21 ICR GTA 4.9MW GTA 1.5MW ICR GTA 1.2MW Battery |
| Transmission | Mechanical | Electrical, 6.6Kv | Electrical, 6.6Kv | Electrical, 6.6Kv | Electrical, 6.6Kv | Electrical, 6.6Kv |
| Motors | (Gearbox) | 2 x 30MW AIM | 2 x 30MW PMM | 2 x 30MW PMM | 2 x 30MW PMM | 2 x 30MW PMM |
| Propulsors | Conventional 2 x 4.5m Props | Conventional 2 x 4.5m Props | 2 pods, scaled on Shottel SSP | 2 pods, scaled on Shottel SSP | 2 pods, scaled on Shottel SSP | 2 pods, scaled on Shottel SSP |
| MMRs | 2 | 2 | 2 | 2, 1 on upperdeck | 3, 1 on upperdeck | 4, 2 vertical and 1 on upperdeck |
| AMRs | 2 | 2 | 2 | 2 | 2 | 4 |

## CONCLUSIONS

This paper has looked at how ship configuration can be brought more centrally into the initial ship design process, how the Design Building Block approach, pioneered by the UCL naval architecture and ship design research effort, and can be used to explore one of the claimed ship design consequences of the current moves to exploit electric propulsion developments in naval combatants.

Through a specific large surface combatant design study a range of AES arrangements have been introduced into the design and balanced design studies presented showing both the overall ship design impact and the arrangements for each study's machinery spaces. Given the investigation has been limited to a specific ship type with overall combat and ship performance characteristics, any conclusions are likely to be provisional; however the following initial conclusions from this investigation are seen to be :-

- Large GTAs limit the scope for their placement beyond the usual midships deep location;
- Shafting elimination gives ship layout advantages but pods and their adjacent conversion machinery introduce further local layout and structural constraints;
- The need to maximise survivability is a major determinant in selecting layout options;
- Arranging GTAs vertically has some advantages in machinery space demands but raises other design impacts that require further investigation.
- High voltage cable runs have a significant ship impact mainly due the constraints on which compartments they can be adjacent too but also their weight;
- Electric ship options are likely to be heavier than non electric equivalents, resulting in impact on overall initial ship cost, however the through life cost advantages are likely to more than balance this.

Overall the advantage of being able to explore different machinery configurations has further justified the design utility of the UCL Design Building Block approach in its current form provided by the SURFCON addition to GRC Limited's PARAMARINE preliminary ship design system.

It is further considered that the studies of the monohull combatant presented should be extended to multihull forms particularly the Trimaran variants where it is considered the configurational advantages suggested by AES machinery fits could show greater advantages in the overall ship impact.

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