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PAPERS

DISCUSSION

THE SOPHISTICATION OF EARLY STAGE DESIGN FOR COMPLEX VESSELS

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D Andrews, FREng, PhD, FRINA, RCNC (Vice President), Professor of Engineering Design, University College London

SUMMARY

Prior to the introduction of computers into Early Stage Ship Design of complex vessels, such as naval ships, the approach to synthesising a new design had been via weight equations. When it was realised that modern naval vessels (and some sophisticated service vessels) were essentially space driven initial (numerical) sizing needed to balance weight and space, together with simple checks on resistance & powering, plus sufficient intact stability (i.e. simple metacentric height assurance). All this was quickly computerised and subsequently put on a spread-sheet to iteratively achieve weight and space balance, while meeting those simple stability and R&P checks. Thus suddenly it became possible to produce very many variants, for both trade-off of certain requirements (against initial acquisition cost) as well (apparently) optimal solutions. However as this paper argues this speeding up of a very crude synthesis approach, before rapidly proceeding into feasibility investigations of the "selected design", has not led to a quicker overall design process, nor have new ship designs been brought earlier into service, in timeframes remotely comparable to most merchant ships.

It is the argument of this paper that such a speeding up of an essentially simplified approach to design synthesis is not sensible. Firstly, there is the need to conduct a more sophisticated approach in order to proceed in a less risky manner into the main design process for such complex vessels. Secondly, further advances in computer techniques, particularly those that CAD has adopted from computer graphics advances, now enable ship concept designers to synthesise more comprehensively and thereby address from the start many more of the likely design drivers.

The paper addresses the argument for a more sophisticated approach to ESSD by first expanding on the above outline, before considering important design related issues that are considered to have arisen from major R.N. warship programmes over the last half century. This has been done by highlighting those UK naval vessel designs with which the author has had a notable involvement. The next section re-iterates an assertion that the concept phase (for complex vessels) is unlike the rest of ship design with a distinctly different primary purpose. This enables the structure of a properly organised concept phase to be outlined. Following this the issue of the extent of novelty in the design of a new design option is spelt out in more detail for the seven categories already identified. The next section consists of outlining the architecturally driven approach to ship synthesis with two sets of design examples, produced by the author's team at UCL. All this then enables a generalised concept design process for complex vessels to be outlined, before more unconventional vessels than the naval combatant are briefly considered. The concluding main section addresses how a range of new techniques might further alter the way in which ESSD is addressed, in order to provide an even better output from concept to accomplish the downstream design and build process. The paper ends with a summary of the main conclusions.

1. INTRODUCTION – THE ARGUMENT THAT SHIP DESIGN IS COMPLEX

"The urge to insist that the complex is just a disguise for the simple was one of the plagues of the twentieth century" Timothy Snyder, 2012

1.1 INTRODUCTORY REMARKS

Over several decades the author has produced a large number of design related papers published in these Transactions, many of which have had extensive written discussion contributed by eminent practitioners and researchers in ship design. In addition the author has led on the production of the series of State of Art Reports presented since 1997 at several of the tri-annual International Marine Design Conferences (Andrews et al, 1997, 2006, 2009, 2012, 2015). These SoA reports on Design Methodology have addressed developments in the nature of ship design and have been re-enforced by a series of related articles in the Proceedings of the Royal Society (Andrews, 1998, 2006, 2012a) and an extensive review paper to the 2012 IMDC considering whether marine design has now reached a level of maturity (Andrews, 2012b). All these reports and papers have been motivated by a belief that the design of such Physically Large and Complex (PL&C) systems is necessarily sophisticated right from the initiation of such a design. Furthermore that inherent sophistication needs to be recognised, if the whole design process leading to a genuinely new ship is to be properly accomplished.

This view is not widely accepted, especially by many practitioners (rather than more academically based researchers) in ship design, since the former don't necessarily read the latest debates in the IMDC or academic publications, such as the Proceedings of the Royal Society. Rather, many practitioners consider the earliest stages of ship design as relatively straight forward and so it should not be over complicated. Greater sophistication early in ship design is seen to restrict clarity. There is even the view that over philosophising can inhibit a believed ("mystical") creativity or, more prosaically, the engineering designer's scope for producing creative solutions. This view stems from a belief that the aim of early stage ship design (ESSD) should be to achieve an outline solution quickly. Thus this argument goes: the quickly produced "sketch design" can then be developed properly in the subsequent feasibility/embodiment phase, and that a technically feasible design can then be further worked up through, various, more detailed phases to a sufficient level of definition in order to be built. This paper refutes this view, at least as far as the design of complex vessels is concerned.

Recently the author also published a set of papers in a range of conference proceedings. These papers have variously addressed component elements of what can be seen to be a series of related aspects associated with ESSD. There is thus seen to be a need to bring those various aspects together in one overarching paper. This is not seen to be an attempt to produce a definitive "Theory of Ship Design". Rather, as this paper's title proposes, it is to demonstrate, as far as this is possible with such a broad and practical topic, that what is often seen as the "crude" start of a (managerially and technically) complex process downstream, is itself highly sophisticated, but in a quite different way. The use of the term "process' needs to be qualified as this can be seen to relate both to the technical steps in creating a new ship design and to the managerial process which is the overarching or strategic procedure necessary to accomplish the technical output. One problem with attempting such an exposition is that part of the complexity of the process is that these two facets are not independent processes but rather highly inter-related and hard to separate in practice, or worse it is often not clear where one stops and the other begins.

It is the author's belief that most presentations of ESSD focus on the managerial facet rather than the direct technical process; see Gale's chapter "The Ship Design Process" in Lamb's (2003) compendium and the series of papers by Keane and Tibbitts (1988, 1995 2007), on US Navy ship design practice. This managerial focus is precisely what the author addressed, from the practice of UK naval ship design, in two Transaction papers more than 20 years ago, which drew on his then recent experience, in the UK Ministry of Defence, as a warship project manager (Andrews, 1993) and then Head of Concept Design (Andrews, 1994). The 1994 written discussion, which the reader is advised to consult, provides further justification for the general argument this paper is presenting. Away from the purely naval, but still highly complex, ship design product, a similar set of papers, on the design of large cruise ships, has been produced (Levander, 2003, 2012). These sophisticated non-naval ships were the design example used by Caprace and Rigo (2012) to test an "innovative complexity metric", furthermore they propose four distinct elements of design complexity, rather than one single measure. So is there is seen to be a need to address the more technical or tactical aspects of complex ship design, while still recognising the managerial or strategic element cannot be wholly separated. Once the author's synthesis of the issues has been presented in the bulk of the paper, this question is considered further in the paper's concluding section.

1.2 SOME INITIAL REMARKS ON ESSD

A few further scene-setting remarks are considered necessary. At an early IMDC, the eminent engineering designer and theorist, Stuart Pugh remarked (to his surprise) that ship design is not like other vehicle design (e.g. he considered aircraft and automobiles to be "conceptually static"), rather "ships are conceptually dynamic, (*in*) that many differing designs (conceptually) are yet to emerge" (Pugh 1985). Thus, this could be seen to be a clue as to both the importance of concept design and its underlying subtlety. There are also many types of ship design and, in reviewing the 150 years of publications on ship design, in the RINA Transactions, the author demarcated them by the distinction between "transportation vessels" (i.e. part of a larger transportation system (Erichsen, 1985)) and "service vessels" (i.e. vessels that go to sea to do something) (Andrews, 2010a). A significant part of the latter category consists of naval vessels, where the author's experience primarily lies, but this very heterogeneous naval group is not the only significant group of services vessels. There are a growing number of vessels designed to support various offshore activities and it could be argued that the category even includes cruise ships, whose primary function is to go to sea to entertain its customers rather than, as with transportation vessels, being the cheapest way to deliver goods (or people).

Trying to categorise ships in order to understand how different ships are or should be designed, further exposes the complexity of many ships. A recent use of the general analytical tool of Network Analysis to look at a very complex example of the naval vessel, the nuclear submarine, revealed to some extent the nature of the complexity of the design problem that we ship designers are addressing. Collins et al (2015) at Figure 1 looked at the interactions between the various major subsystems and top-level component elements in such a vessel, when considering the effect of incorporating a radically new propulsive device. Given such complexity, albeit this example is at the very top end of design complexity and product cost, one should not be surprised that producing a new ship design *ab initio* is likely to be of commensurate complexity. The largely accepted simple representation of the ship design process by the Design Spiral has been seen by many in the field as "describing the ship design process". However, this has been challenged, first by Brown in several of his seminal papers on post-WWII naval ship design (Brown, 1986, 1995) and more recently by UCL authors (Pawling et al, 2017a) in a paper considered in Section 2. Furthermore it would be naïve to believe that such a range of complex ship types: from (for naval vessels) nuclear submarines to naval combatants (typically destroyers and frigates) to aircraft carriers and amphibious warfare ships and even naval auxiliaries, like fleet tankers (which are quite unlike commercial oil tankers), would follow the same design process, such that "one size fits all". This misapprehension was specifically addressed in a recent conference paper, the argument of which is highlighted in Section 3 (Andrews, 2013a).

The danger of a belief that all ship design follows the same process (either strategically and/or tactically) is not because that wouldn't indeed be highly attractive but because it is profoundly wrong. This is because such a tempting simplification then unreasonably limits the opportunity to properly explore the potential options for a new ship project. Furthermore and most importantly, this would inhibit investigating the full solution space, which it is necessary to do in order to explore the design coherence and balance (including the affordability and risk) of a comprehensive set of potential solutions. This can only be done by properly and concurrently investigating both the robustness of the initial thoughts on the requirements and exploring an extensive set of new design options. This conjoint approach, that of Requirement Elucidation, has been put forward by the author in several Transaction (Andrews, 2011) and RINA conference papers on systems engineering themes (Andrews, 2010b, 2012c).

A final scene setting point is the fact that a series of new techniques are being applied in advanced research into ship design. This means that a wider general debate, beyond those currently engaged research teams, is seen to be necessary with regard to tackling the inherent complexity of the design of such ships. Research into applying new techniques to a range of ship design problems is being conducted in several research centres, namely, Universities of Michigan, Trondheim, Delft and at UCL (the latter led by the author, see various key papers above). Thus a further justification for the current paper is to integrate together the separate elements of ESSD for complex vessels, addressed in many of the author's publications on ship design, to provide a broad understanding of the ship design process. This can then be used to address how such emerging techniques could best assist future ship designers in tackling the genuinely sophisticated and demanding nature of ESSD.

The paper tackles this task by firstly considering most of the major RN programmes in which the author was significantly involve over three decades in the UK Ministry of Defence. This then leads onto addressing a range of issues that are primarily of concern in early stage ship design, when most of the big decisions are made. The concept phase for a major ship programme is then outlined followed by categorising ship designs by the design novelty of any given option. The approach of "designing inside out", pioneered by the author, is then outlined with example studies undertaken since the author focussed on ship design research at UCL over the last two decades. From all this it is possible to outline a generic process for ESSD of complex vessels. The remaining sections cover complex ships, other than the ubiquitous naval combatant, followed by outlining recent developments in advanced approaches to ship design, before concluding that indeed the modern practice of the concept design of complex vessels is inherently sophisticated.

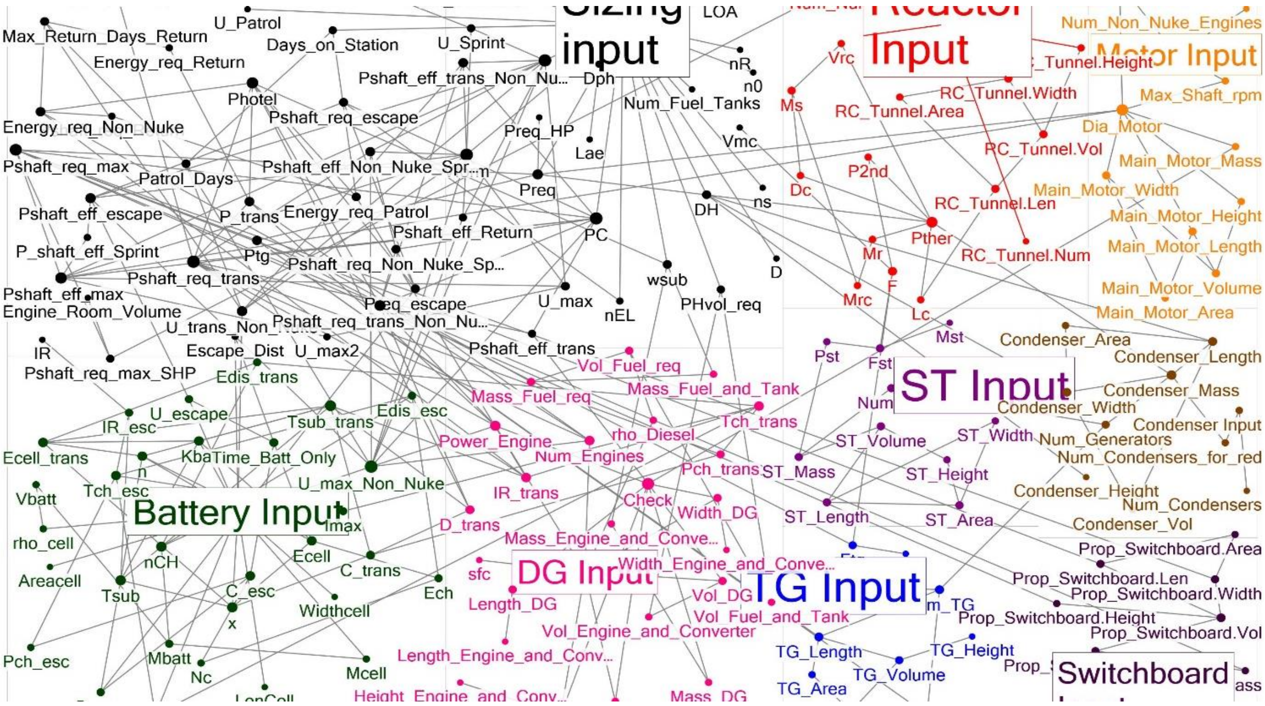


Figure 1: A representation of naval vessel complexity – a partial network model of a nuclear submarine's system structure (Collins et al, 2015)

2. KEY DESIGN ISSUES ARISING FROM MAJOR RN WARSHIP PROGRAMMES

In order to balance the generic nature of most of the argument to be presented, this section provides a brief review of a wide range of actual designs produced for the Royal Navy, which highlights the key design issue of style choice. These designs for the Royal Navy are those in which the author had considerable design involvement in his career (1965-2000) in the Royal Corps of Naval Constructors (with the exception of the last of the eleven examples). The objective is not to provide a detailed analysis of each design or even less their (often dominating) project management concerns but rather to highlight what appears to be unique about each programme and its overall design intent. This is done to reinforce the argument of this paper that what is needed, in a highly complex design environment, from the chosen design approaches and methods applied to such complex designs is pragmatism, given each design is unique as this section concludes.

2.1 RECENT R.N. NAVAL DESIGN PROGRAMMES

i) INVINCIBLE Class CVS

This was an entirely new genus of aircraft carrying ships, which were initially designed to carry ASW helicopters but with “provision” for STOVL aircraft. The major decision explored in the concept phase was to fit gas turbine main engines, which reduced the complement by 500 down to just below 1000. It was a novel ship, driven by architecture /configuration and designed to full naval standards, able (at the last moment) to fit and operate the Sea Harrier, which itself was under development as the first vessel was being built. This latter task was the current author’s principal role in the project (1975-78) (Honnor & Andrews, 1982).

ii) DUKE Class Type 23

This frigate evolved from the 105m “towed array tug” in steps (112m, 118m) to 123m general-purpose frigate post-Falklands (and after the official Concept Phase). It was the first flared RN hull form (for RCS reasons) and pioneered a CODLAG propulsion fit (for ultra-quiet acoustic signature to operate the towed array passive sonar). Both these features were incorporated from the Concept Design and belied the (post Concept) Design Manager’s comment to author, who had been concept design leader (1978-80), that “the work done at concept was irrelevant”, since these were the two most fundamental ship design decisions. Both CODLAG and the hull form were retained despite the significant growth in size post-concept. The class was politically mandated to be short life and “margin less”, when everyone in the concept team “knew”, despite the Navy Minister’s edict, this decision would not be held. (Many ships in the class will be in R.N. service for at least 28 years, rather than the mandated 18 years ship life.)

iii) FORT Class AOR

The first naval auxiliary designed with an “equal” mix of solid and liquid cargoes, so there was no obvious type ship to draw on. Designed to carry and operate several large ASW helicopters and to be self-protected against a high level of air threat, with RCS reduced upper works and PDMS weapon fit, yet it also had to comply with RFA merchant navy rules. (Luckily the vessels’ Cold War role in GRIUK gap was no longer required when the two remaining ships entered service post 1989, so this major conflict in the design intent was not tested (given the PDMS system was not fitted in service).) (The author was concept design leader 1979-80.)

iv) SANDOWN Class SRMH

The original concept was for a utility modular build (of prime movers and combat management) in a less sophisticated hull design than that of the HUNT Class MCMs, but in the end the modular fit was not pursued. (Author was concept ship design leader 1979-80.)

v) VANGUARD Class SSBN

Essentially the concept combined the large diameter (US) middle portion with new machinery (PWR2) in aft section and the previous SSN design adapted for the front portion. It was the last major in-house MoD design produced to highest standards and completed to time and within cost budget. (Design commenced early in the 1980s, the author was the structural and hydrodynamic design lead 1984-86.)

vi) ALBION & BULWARK LPDs

The concept was to provide amphibious force command with major up lift and novel Ro-Ro Landing Craft, which drove the design. It was a fraught acquisition with threat of SLEP of old ships as a “planning” option. The worked up SLEP option was rejected by the Admiralty Board, despite pressure from HM Treasury. As Project Manager (1986-1990) the author insisted on the SLEP option being forced to meet same requirement as new build (“otherwise I can design a cheaper new build to meet any reduced (SLEP) standards”). All this was done post concept and demonstrated the dangers of advancing beyond the concept phase with insufficient concept option exploration. This can be seen as poor Requirements Elucidation (see Section 3.5).

vii) OCEAN LPH

Commercial standards were mandated due to lack of any concept and feasibility studies, together with a very simplistic costing based on a possible conversion option. The Project Manager (the author 1986-1990) fought the naval staff over the significant level of non-naval standards imposed on an essentially high value unit (given its “cargo” of hundreds of troops plus vehicles and 12 Commando helicopters). The PM managed to raise the purchase budget but not sufficiently to significantly amend the extent of the very limited naval standards. The design was subsequently criticised by the MoD chief marine engineer as this recourse to COTS practice significantly increased the engine support requirement for the whole fleet (due to this one ship’s unique engine fit). Needless to say these costs were not shown in original procurement cost allocation, which was obsessed with direct initial procurement cost, rather than the “true cost” of the design solution. Interestingly, many have subsequently argued that HMS OCEAN has been “good value for money”, however it has not been used in naval warfare (rather than being very usefully deployed in peace keeping missions), so the jury should be out regarding the viability of such a commercially based solution to produce a major warship so cheaply.

viii) RFA ARGUS

How not to procure a major conversion of a Ro-Ro containership to helicopter training ship. The Project Manager (author 1986-1990) had to defend to the Parliamentary Select Committee the payment to the shipbuilder of huge cost overruns on a Fixed Price contract (see HCDC minutes in Hansard (H.M.S.O., 1989)). This case proved naval ship acquisition is a lot more than just engineering design and even conversion to a support (training) role can be demanding. Much of the procurement problems can be considered to have arisen largely due to several unwise acquisition edicts imposed on this project early in the programme, before the author inherited the end of the conversion and the task of getting the ship into service.

ix) DARING Class Destroyers

This project was originally a light cruiser style concept, which subsequently drew on considerable post-concept design work for NFR90 and then CNGF, but also had to accommodate the complement impact resulting from Type 23s’ lack of complementing margins. (An excellent example of how one major design choice on one class of ships then has a later significant cost on another. Again a proper Concept Phase exploration should have revealed this apparently hidden downstream cost implication.) The author led on early “Type 43” ship concept studies (1978-79) and was a member of the six man Anglo-French steering team (1991-92) setting up the Type 45’s precursor, the CNGF.

x) FSC /Type 26 Frigates

Original concept of an adaptable long range “colonial cruiser” became modular payload based (similar to the USN LCS class but without the latter’s (unnecessarily?) high speed). The author was the original Project Director and then IPT Leader (1998-2000) before two further delays were made to proceeding beyond Initial Gate. These delays could be said to be due to the difficulty in arguing through MoD acquisition system the need for a highly adaptable ship. This is because justifying a new class to fit a new weapon (e.g. Type 45) or sensor (e.g. Type 23) is much easier to demonstrate using classical Operational Analysis (OA), that the concept of “adaptability”. This says more about the limits of OA than the sense in the need for adaptability in a post-Cold War future. This project’s history strengthens the argument for a Requirements Elucidation based concept process, instead of the then prevalent (solution independent) Requirements Engineering basis to derive the requirements case, and the former would have led to better design-aided decision-making (Andrews, 2003a).

xi) ASTUTE Class SSNs

Initial concept by GEC of a modular build reverted to follow on of Trafalgar Class but with 10,000 “solution independent” functional requirements reflecting, as with FSC, the false dogma of Requirements Engineering adopted by the UK DPA as part of the SMART Procurement initiative (UK MoD SPIT, 1999). (This is the only example of the programmes outlined here in which the author was not closely involved, but was merely an interested observer.)

As a clear (often leading) participant in all but one of these eleven major UK naval programmes over some 25 years to 2000, the author considers they show that for such complex designs:

a) All designs are different in their design drivers;
b) All design environments are different as the constraints on a given programme and the design environment, in which it takes place, will be different even from time adjacent programmes. This is because the design environment is always changing, together with pressures from those other (often parallel) programmes;
c) It is important to recognise as early as possible the unique mix of strategic and technical drivers that apply to each new programme;
d) There is a need for the design team to exercise control over the process. Thus, as the concept phase is about requirement elucidation, the concept needs to remain technically coherent and balanced (for a ship/submarine design team that can only mean it must be naval architecturally led). While there may be new sub-systems (e.g. machinery, sensors or weapons) there remains the need to ensure the whole ship aspects chosen for that design are coherent and appropriate to being sustained through life (not just on build).

2.2 THE CRUCIAL CONCEPT ISSUE OF STYLE

One major aspect in the complexity of the overall design process and especially at the very front end of the concept phase is that of Style. This is the crucial first step in commencing any design option and even after that has been synthesised (preferably through an architectural synthesis) the issue is more than just developing the sub-systems. It is also a (hopefully) conscious adoption of a specific overall 9or macro) design style in commencing each distinct solution option. For the taxonomy of ship sub-systems these have traditionally been defined for commercial ships using the shipbuilding basis of steelwork, machinery, outfit and payload or, for a naval vessel, a more nuanced work breakdown (NES163, 2000). The UCL developed architectural approach to ship synthesis has preferred a more functional break down of Float, Move, Fight (or operations for non-combatant ships) and Infrastructure (i.e. F, M, F, I), which was originally adopted for the UK MoD submarine concept tool, SUBCON (Andrews et al, 1996). Although this breakdown is more design than construction oriented, it still does not take into account the cross cutting "ilities" and design integration aspects, nor the sustainability issues (see Table 1). Most of these issues are properties that affect all the subsystems, yet largely arise from the aggregated properties of the whole ship. They have been summarised for a complex ship in Brown and Andrews' term of S^5 (1980). The first four of these categories can be considered "traditional naval architecture" (i.e. Speed, Stability, Strength and Seakeeping), while the fifth is that of Style (see Table 1) and that term also refers back to the primary design decision to be made in commencing any ship design option (see Andrews (2017a) and in Figure 4 which is discussed in Section 3.3).

The apparently "functional design" approach by Nordin (2014) to conventional submarine concept design (discussed further in Section 9.4) actually requires the "style" selection to achieve a matching of "functions with form". This is acknowledged in Nordin (2014) in his Fig. 21 where he presents his "generic submarine model" with the second step ("Set Design Parameters and Philosophy") having "Style" inserted at the end of this step. This recognition that there are philosophical issues in such complex vessel design, by acknowledging the designer's fundamental choice of the overall (or macro) style in any new design concept, is seen as justifying the author's continued emphasis on a philosophical vision to future developments in marine design (Andrews 2012b). (Should there be any doubt as to the veracity of thinking philosophically about such issues, this is discussed further in Section 9.5.)

Table 1: Listing of style topics relevant to a naval combatant design

Stealth	**Protection**	**Human Factors**	**Sustainability**	**Margins**	**Design Style**
Acoustic signature	Collision	Accommodation	Mission duration	Space	Robustness
Radar cross section	Fire	Access	Watches	Weight	Commercial
Infra-red	Above water weapon effect	Maintenance levels	Stores	Vertical centre of gravity	Modularity
Magnetic	Underwater weapon effect	Operation automation	Maintenance cycles	Power	Operational serviceability
Visual	NBC contamination	Ergonomics	Refit philosophy	Services	Producability
	Shock		Upkeep by exchange	Design point (growth)	Adaptability
	Corrosion			Board Margin (future upgrades)	
	Damage control				

For a naval combatant in particular, it is not just the ship design process that is complex but also that most major new naval designs also incorporate the concurrent design of a combat system. This can also be compounded when the density of complexity is extreme and that could be said to reach a limit in the design of a nuclear submarine (SSN), with a physical density approaching three times that of a surface vessel. Alongside the lack of prototypes, the high degree of autonomy at sea and creating an artificial and mobile environment for large numbers of people, there is Pugh's (1985) recognition that, unlike aircraft or cars, the choices of form for ships are highly "dynamic". About the only thing going for almost all surface ships (unlike submarines which are as safety critical as aircraft), despite the continued intractability of the physics of operating at the interface of two media, is that in safety terms ships are relatively benign compared to submarines and aircraft. This is because most ships have an excess of reserve of buoyancy, even after they have suffered a significant degree of flooding damage.

Given there are so many different types of ship, this implies there is a need for different approaches to ship design. This is due in part to the different measures of merit (MoM) or performance (MoP) appropriate in helping the designer make design decisions (see Figure 4 in Section 3). Thus those commercial vessels, which are part of a transport system, have a direct MoM (i.e. Required Freight Rate (RFR)). This is more complex in the case of cruise ships, as the architectural choice in placing different cabins types in different locations affects whole ship design choices (Levander, 2012). In the case of mega-yachts, almost uniquely, the measure of merit does not seem to be related to achieving an economically efficient design – almost the opposite! For commercial service vessels the design approach has become more complex in recent years, with the recognition of the need for (hard to define) through life adaptability (see Gaspar's (2013) approach applied to offshore support vessels and discussed in Section 9.4).

It might be thought, despite the wicked requirement problem (see Section 3.5), in an era of austerity that, at least for typical mono-hulled naval combatants, there is so much history that designing such vessels must be highly evolutionary, thus easing the designer's task? However the lengthening gaps between building new naval designs seem to be such that loss of collective knowledge and experience could be seen to be risking an already (politically) fraught design environment (Andrews, 2013a). Even the option of multi-hulled solutions, 'though less risky than advanced technologies (see items 5.6 and 5.7 in Section 5), is rarely advanced. This is because such options need better under pinning research, even in the concept phase, to propose reasonably de-risked alternatives to the mono-hull. It is also worth pointing out that many programmes for naval vessels are not for the classic combatants (i.e. frigates, destroyers and cruisers) but rather for specialist ships, such as aircraft carrying vessels and amphibious warfare ships, as well as naval auxiliaries, all of whose designs can be considered to be essentially configuration driven (Andrews, 2003b and addressed in Section 8).

It has been strongly argued that the whole of the concept phase for complex ships, design is different and requires a different design approach to the rest of the ship design process (Andrews, 2013a). The rest of the design process for such complex vessels has been briefly outlined in a contribution to a recent Nautical Institute publication (Andrews, 2015). This contribution drew attention to the issue of CASD and the impact of Integrated Product Models (IPM) together with the use of an Integrated Product Data Environment (IPDE), especially in the later production orientated phases of ship design. Thus that contribution questioned whether ship design teams still understand the steps in granularity that have been observed in the evolution of a design. This is because, historically, there were distinct steps between each successive design phase due to traditional drawing evolution, which then assisted the maintenance of design coherence right through to build definition. The issue of design coherence has been recently addressed alongside the issue of Design Authority (DA), in proposing that ship designers adopt a Systems Architecture vision (Maier, 1998) for complex design throughout the product's life, in preference to the less appropriate version of systems practice of Requirements Engineering (Andrews, 2011). The latter usage has already been criticised in reviewing Items ix to xi in Section 2.1.

3. THE FACT THAT THE CONCEPT PHASE IS UNLIKE THE REST OF SHIP DESIGN

3.1 PRELIMINARY REMARKS – VARIOUS VIEWS OF ESSD

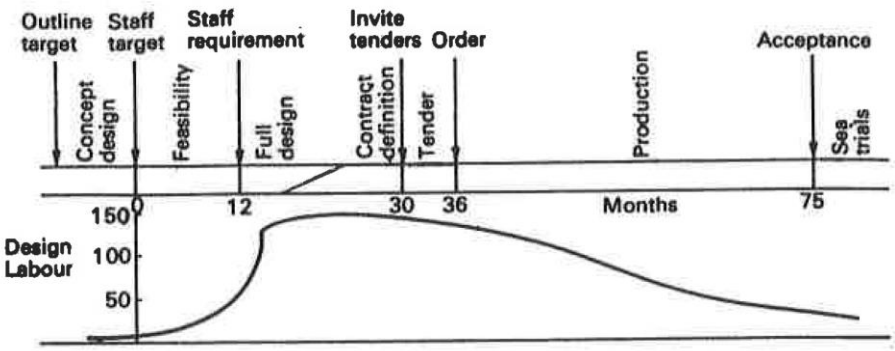
It is often acknowledged that the initial design phase (usually called concept) is the most critical, because by the end of this phase most of the cost implications are incorporated in the design, despite little of the total design effort having been expended (see Figure 2a). However the real issue, now that computers are ubiquitous to ship design practice, is that their usage in the concept phase has been largely misdirected at greater verisimilitude (almost for its own sake) rather than being driven to better undertake this crucial first phase. How to do so will only be clear from a proper understanding of the real (and quite different) nature and objective of the concept phase. While a lot has been written on ship concept design, there would appear to be divergent views as to its nature – in part due to there being different types of ship design processes and the different perspectives of those involved in what appears to be or is understood to be concept design. These different types of ship design and the associated designer perspectives are considered below.

A generalised perspective of ship design is often made from a commercial (transportation) ship application view, where there is a relatively straight forward and overriding economic driver, namely minimising required freight rate. When this is compared with the quite different service (e.g. naval) ship environment, the differences are most marked in the early stages of ship design. In particular the approach appropriate to designing transportation vessels starts with a very market oriented requirement exploration by a prospective ship owner (historically with an in-house team (Meek, 1964, 1970), but now more likely using a ship design consultancy). This outline study and emergent, and very specific, requirement set is offered to the shipbuilding industry, who normally only have just six weeks to respond. Thus each shipyard offers a single solution, including a build cost and delivery time, to which the selected shipyard is subsequently contractually committed. This means the shipyard has to produce a quick and "commercially low risk", and hence conservative, proposal based normally on built solutions that they have recently produced themselves. Thus concept ship design in the commercial world, particularly for the vast bulk of transportation vessels, covering both the pre-bidding (owner's) exploration phase and the six weeks response, is heavily constrained. Consequently design innovation by the designer/builder is limited as it commences with a clear overriding specific performance based ship requirement set (often with specified equipment) and a clear measure of merit (MOM) on which "to turn the handle" – usually that of achieving a RFR.

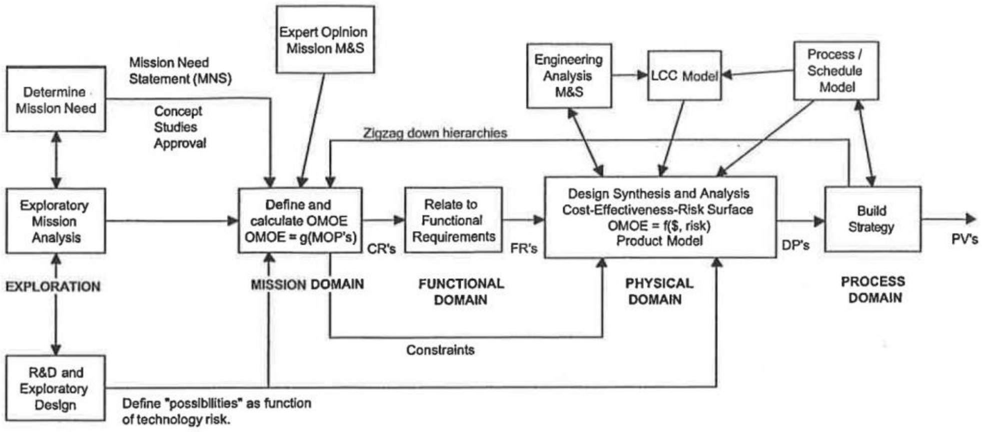
For the archetypal service vessel, the naval ship, the approach to concept design couldn't be more different, particularly for major navies such as the US Navy and the Royal Navy, where the process has been written about extensively (Gale, 2003, Andrews, 1993). Furthermore, this process is highly political and, despite the recent paper on that environment pertinently entitled "Why is naval design decision-making so difficult" (Kana et al, 2016), is still best captured by Benford's biting description (1979):-
"Multi-disciplinary, multi-million dollar Navy design extravaganza where every decision must be analysed, traded off, massaged and documented to the point that the basic design issues are often lost in the process."

This process complexity is in part due to the vast sums involved with the acknowledged complexity of concurrently developing and integrating a mobile system of systems, including major new weapon and sensor sub-systems alongside the ship design. But it is also the design task itself, which is well caught by Graham's claim (1982): "It is understandable that today's warships are the most complex, diverse and highly integrated of any engineering system, produced on a regular basis". All this means the design process in the concept phase is particularly protracted, given the search for innovation to solve what can be seen as the squaring of the circle of (impossible) needs with an extremely intense focus on the initial procurement cost, itself resulting from tax payers' dislike of what in peacetime is seen to be an exorbitant defence "insurance premium". This then results in a concept phase, which is distinctly different to the downstream design process to a much greater extent than that for most merchant vessels. This paper largely explores the naval and some other service vessel cases at this extreme. However, it is believed it is also a likely indicator of the manner in which all major ship acquisition could be undertaken in the future, especially given recent moves in merchant ship design to do so from first principles and to justify solutions using risk based approaches (Papanikalou, 2009).

Rawson and Tupper's (1976) core naval architecture text book not only sees ship design as the *raison d'etre* of naval architecture but, in their penultimate chapter, they outline both "preliminary (design) studies" (in which they focus on space allocation, main hull dimensions, displacement, form parameters, and weather deck and machinery layout) and show this activity within an overview of the whole warship design process. Thus Figure 2 contrasts Rawson and Tupper's overview with a detailed US Navy based process for just the concept phase. Rawson and Tupper call these preliminary studies "feasibility studies" to distinguish them from the subsequent "design studies". This is not the first instance of nomenclature confusion and there is a need to clarify terms, which will be done in the next sub-section, once some other versions of the process have been considered. Figure 2a, although showing some subsequently re-named milestones in the UK naval ship design process, is still considered to be useful in that it indicates both the timescale and the typical shape of the design resource profile. These authors also invoke the design spiral, which has been used not just to represent the iterative nature of routine calculations (or simple synthesis program/spread sheets) to achieve a balanced design study or design option, but also has been used as a description of the whole ship design process, regardless of ship type. (See the IMDC State of Art report for 2009 for some 26 iconic representations of the ship design process, including six versions of the design spiral representation (Andrews et al, 2009)). The issue of the validity of the design spiral has already been touched upon in the introductory remarks and is addressed further by Pawling et al (2017). In an essentially US Navy perspective on concept design, Gale (2003) reinforces the complex picture of Figure 2b by showing an extensive mix of design/acquisition and military/fiscal analyses usually undertaken, thereby exemplifying Benford's quote above. Gale lists some detailed outputs from typical combatant concept studies and shows how they lead on to the much greater definition required in the subsequent phases of design. However, Gale's exposition is largely focused on the management process, rather than particular design issues and techniques, primarily addressed in this paper.



a. "Concept Design" in the Overall Ship Design Process, (Rawson & Tupper, 1976)



b. An Example of the Concept Design Process (Brown & Thomas, 1998)

Figure. 2: Contrasting Representations of the Naval Ship Concept Design Process

The book on ship design by Watson (1998), as an experienced ship designer (like Rawson, Tupper, Andrews and Gale) who led the design team of a major marine consultancy, gives examples of merchant and warship design spirals. Both of Watson's versions of the spiral show (questionably - see this paper's Section 1.2) not just the whole ship design process as though it starts from fully worked up operational/naval staff requirement, but, furthermore, implies there is no feedback from insights obtained through out the concept phase to revise those initial requirements. This is seen to ignore the difficulty, particularly for multirole service vessels, of requirement identification or elucidation, which is discussed further in the Section 3.5. So, while Watson details both methods and data appropriate to the technical specifics of complex ship concept design, his book can be seen to be largely addressing the phases beyond concept, given that he sees the ship design process starting with a "fixed" set of requirements, which is rarely the case for major new naval vessels.

If descriptions of ship design like Gale's and Watson's are considered, it can be seen that they largely detail design management issues, in the former case, or specific technical steps in the latter. Thus the wider design objectives and the difficult philosophical decisions are largely neglected, despite the fact that it is these that truly drive the initial or concept phase and, hence, provide the underpinning understanding for the overall design decisions through-out the rest of the design. This consequential feature of "actual concept design" reflects a vision of the "system of systems" nature of such physically large and complex (PL&C) systems and echoes the conflict the naval architect has in being both the hull engineer and the ship's overall architect. This conflict arises through he/she being the principal ship designer yet also contributing to the effort of the wider design team as the "hull engineer" (i.e. responsible for ship hull hydrodynamics, stability and strength). It is this additional vision in taking on the role of overall ship concept designer, beyond the "hull engineering", that this paper seeks to foster amongst ship designers.

The managerial based approach seeks to manage ship design beyond concept, essentially through the working up the General Arrangement and the Work Breakdown Structure (Bose, 2003) employing management tools, such as the Design Structure Matrix (Eppinger & Browning, 2012), to efficiently organise the sequence of design activities. The latter organisational task become significant once the team effort greatly expands (see Figure 2a). It is then that Systems Engineering (S.E.), as an over-arching "philosophy", which has been extensively applied across the wider defence equipment acquisition domain, has been seen to be appropriate (Calvano et al, 2000). With regard to the latter, the author has argued, in the RINA forum addressing S.E. in maritime design (Andrews, 2016), that the Systems Architecture variation of systems practice, originating in complex software design projects (Maier, 1998), is considered a more appropriate philosophy for the design of PL&C systems than are traditional systems engineering approaches. This is, in part, due to the strong emphasis in S.A. on the concept phase (and the concept designer), which Maier sees as absolutely key in ensuring the coherence of the downstream design process, especially in the final design acceptance, having seen very large software projects lose coherence without this.

3.2 WIDER VIEWS ON THE DESIGN OF PL&C SYSTEMS

In order to appreciate the unique nature of the concept phase for complex design, it is worth consulting key publications on wider design practice encompassing general design, architectural design and engineering design, as well as the design of PL&C systems, typified by complex ship design. Several early books on design actually have concept or conceptual in their titles. Thus French's "Engineering design: the conceptual stage" (1971) states the conceptual is the phase that makes the greatest demands on the designer and "takes the statement of the problem and generates broad solutions to it." However his first diagram of the process shows this phase following on from not just "Need" but also "analysis of the problem" and "statement of problem", albeit with a feedback from "conceptual design" to analysis – to which we will return. Whereas Pugh and Smith (1976) in talking of CAD, see the conceptual stage as being "or should be concerned with synthesis", which leads back to Alger and Hayes' "Creative Synthesis in Design" (1964), where they provide several comparative statements of the design process. From these they conclude that, while it is "important to define and understand the design process", the exact words adopted to do so are of "little importance in themselves". This is useful advice against being too hung up on the variations in the terminology for describing the overall ship design process phases, even if the initial/early/concept phase usually can be taken as the first design phase.

Given this level of uncertainty in these general descriptions, what the current paper seeks to do is to at least explain the distinction, for complex vessels, of what is the underlying motivation behind the concept phase, as it is this that makes it noticeably different from the subsequent phases of ship design. The reason why this is not generally appreciated is because descriptions of design in general, including the design of most engineering artefacts, see the concept phase as coming after the problem definition (see Fig. 2.3 in Dym and Little, 2000) or as even to be the response to a worked up specification, as in the case of Watson's (1998) approach to ESSD. The latter clearly echoes commercial ship practice with the ship owner's call for shipbuilders' six weeks bid responses to a precise set of requirements and, often, includes actual equipment specifications.

A closer analogy to the engineering design of PL&C systems, including complex vessels, than that invoked in general design texts such as those above for mass produced engineering products, is probably found in architectural design. However, the architect's motivation is often overlaid with cultural, psychological and artistic issues, which are seldom indulged in engineering design, even on a grand scale. The nearest maritime analogy to such architectural practice is that of mega-yacht design, where industrial designers have a significant artistic input alongside the ship designer (see Woods (2008)). Importantly in bespoke buildings, human usage of a building figures highly and Broadbent (1988) has specifically sought to bring the new human sciences into architectural design practice. Nevertheless, architectural design had been (and largely remains) a highly subjective and artistically inspired approach. Furthermore, the design of the architecture of these PL&C systems, such as airport termini and large chemical processing facilities, has been characterised as being a "wicked problem" (see Section 3.5). This then helps significantly to explain why the above descriptions of the general engineering design process, including the general perception of the underlying nature of the concept phase, are wrong for complex ship design and the design of other PL&C systems.

3.3 THE CONCEPT PHASE IS ABOUT BIG DECISION MAKING

One of the significant criticisms of the use of the design spiral to describe the ship design process, beyond the fact that ship design just isn't like that (except at the micro-level of design iteration to a weight and space balance – see Figure 5 discussed shortly), is that it appears to be a closed process. An early attempt by the author to address this was a three dimensional representation of the spiral as a "cork-screw" (to reflect the progressive and iterative nature) so that the various external constraints could be emphasised and categorised – see Figure 3. This figure shows three broad types of constraints on the ship design process, which apply whether it be best represented by a spiral or any other description:

a) Constraints directly placed on the design by an explicit statement in the requirements or later in the build specification;
b) Constraints directly limiting the design team's scope in executing the design;
c) Wider constraints, sometimes explicit but more often implied, that originate in the environment in which the design team have to operate.

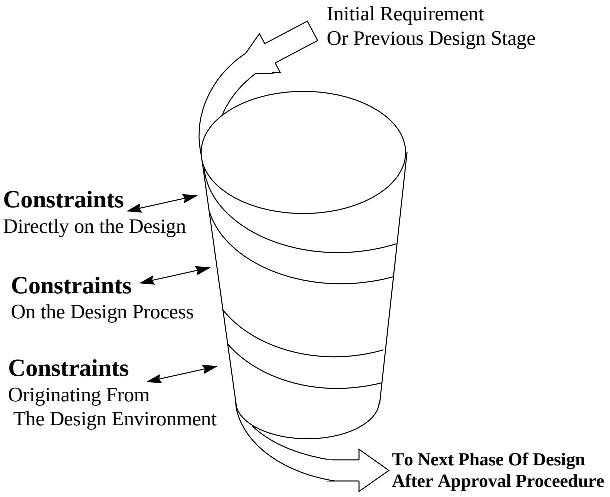


Figure 3: A three dimensional representation of the "design spiral" with three types of external constraints (Andrews, 1981)

Table 2 gives examples of each of the categories. This listing from Andrews (1981) is still surprisingly in general largely valid. Perhaps two significant additions to the third category can be seen to have arisen in subsequent decades, namely:

i) the adoption of commercial practice in naval ship engineering and acceptance;
ii) the increasing emphasis on meeting government initiatives of an ecological nature.

The fact that such constraints can have a dominating impact on a design through direct requirements, the design team's ability and the political (in the widest sense) environment in which the design process takes place, leads on to a quite different representation of the ship design process to that of the design spiral, even in its most sophisticated representations (Andrews et al, 2009). Figure 4 shows the whole ship design process as not just a series of tasks to be performed in sequence but rather as a sequence of major decisions that a ship designer or design organisation, but not a CAD toolset, has to make in order to proceed. Most of these decisions are taken in the concept phase (which further emphasises its importance). In fact the decisions made in the concept phase take up the bulk of the diagram, such that the subsequent phases of the design process have been summarised as being ever more detailed design iterations, through the repetition of the last three steps of Figure 4. This diagram is an up-dated version of the 1986 process flow model (Andrews, 1986), which incorporated the architectural element in initial design synthesis, outlined in Section 6. It is worth highlighting that this is a top level representation and that, while designer decisions ("Selection") have to be made before their related design tasks can be executed in the process, sometimes the sequence of the steps may be different when specific aspects drive a particular design. (Each step is spelt out in some detail in Appendix A, which with actual design cases, shows further the complexity of the decision making in the Concept Phase, if that is undertaken in the proper manner this paper advocates for the most complex programmes.)

Table 2: Three categories of Design Constraints on a Complex Ship Design (Andrews, 1981)

Direct Constraints on the Design	Constraints on the Design Process	Constraints Originating from The Design Environment
Minimise Building Time	Structure of the Design Organisation	Physical and Natural environment. Political climate
Consider foreign sales potential	Relationship of the designer with customer	Economic Climate
Reduce manpower on the ship	Attitude of the design organisation to the latest design techniques	The exact manner in which money is funded
Reduce specialised manpower on the ship	Past design type ship data available	The need to comply with new laws (eg health and safety during build)
Minimise the maintenance load required at the ship	Countries of origin of designer or design methods	The political necessity to support ailing shipyards
Simplify production process in the shipyard	The need or ability to buy-in talent to the design team	The strategic and political necessity to spread work round the shipyards
Fit up-to-date equipment which is being concurrently developed with the ship	Specialisation and training of design team	The decision to reduce direct government research
Minimise time in refit	State of the art in the various fields	Collaboration with NATO allies on equipment
Minimise time in port	Computer facilities directly on tap and their limitations	
Comply with international rules existing or likely to come into force	Quality of general engineering data directly available	
Minimise training load to operate ship	Research facilities directly under the designers' control	
	The idosyncracies, prejudices, rivalries, personalities of the design team	

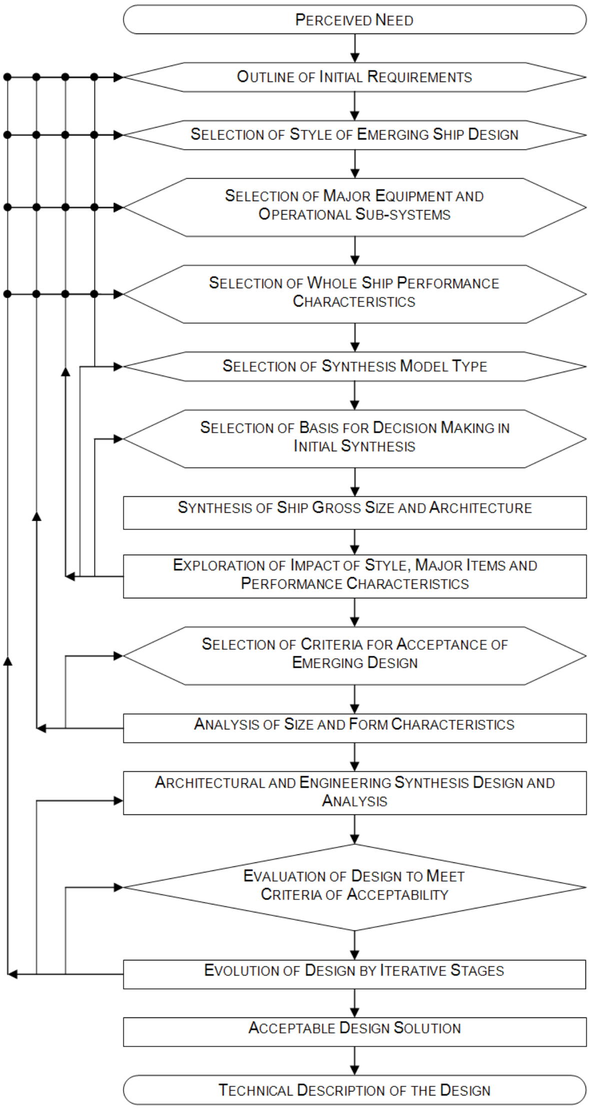


Figure 4: A representation of the overall ship design process emphasising key decisions

Given the decisions in Figure 4 are made prior to each computational and configurational design activity or task, these decision-making steps are themselves design activities, which the designer makes, hopefully, in a conscious manner. Emphasising the selection choices that have to be made (consciously or unconsciously) distinguishes this diagram from most representations of the design process, which just specify the direct design activities, such as synthesis and exploration of features. Amongst the designer's choices is the selection of the "style" of the design solution (already considered in Section 2.2) and selection of the synthesis model (which historically has been just a numerical sizing model). Such choices are often not questioned by the designers or, worse, not even by the design organisation, to which they belong, or indeed the end customer, yet they are likely to have major impacts on the eventual solution. The other feature that Figure 4 emphasises is the amount of feedback, which should be undertaken in any properly conducted concept process. This feedback even extends to the questioning of the *outline* of the initial requirements, which should occur due to a large range of insights arising from the designer's insights on the requirement and design issues that will emerge as the design progresses down the diagram. This can be seen as the essence of Requirements Elucidation.

Other decision points, shown in Figure 4, such as the basis for decision-making on an initial synthesis output, criteria for acceptance of the design, and evaluation (against a selected set of criteria of acceptability), might be considered, to some degree, by the design organisation. However, all too often, they are laid down by the customer or an acceptance agency, such as the designated design authority or a classification society, or, yet again, just adopted from previous practice, without questioning their relevance to the particular project. Such acquiescence was, perhaps, understandable before computers enabled a more scientific approach to both analysis and, at least a numeric, synthesis. However, this now can be seen to be an unacceptable stance. As Nowachi (2009) justifiably emphasises, the necessary level of rationality in the development of wider ship design practice has grown over the last 40 years. It is important that the facility of option exploration through computation is also tied to graphically modelling the design to incorporate the architectural element, if innovative options are to be investigated more comprehensively in early design (Andrews, 2013a) – see Section 6.

Having spelt out the main decision steps for a major new ship concept design process, it is worth focusing on the specific technical step in the Figure 4 representation of the overall ship design process. This step has been expanded as "The Warship Initial Sizing Process" which is often just seen to be a numerical synthesis. It is important to appreciate that even such apparently straight-forward, iterative sequences have significant caveats underlying their usage. This was reinforced by Andrews (1986) who highlighted the seventh step (reproduced at Figure 5) in the decision-making representation of the overall ship design process (captured to some degree in Figure 4). However the main reason for reproducing this second diagram is to re-emphasise the typical range of caveats associated with any such synthesis sequence. The complete figure shows, in some detail, typical Assumptions and Sources behind such a numerically based synthesis and thus reinforces both the item in the second column of Table 2, on design data available to the design team, and underlies the decision at step six in Figure 4, namely Selection of Synthesis Model Type. Finally for Figure 5 it is necessary to say, unlike Figure 4, which reflects the more up-to-date combined architectural and numerical synthesis process, it only shows a simple numerical sizing sequence, now recognised as being super-ceded in a proper ship synthesis by an integrated architecturally driven approach, summarised in Section 6. The first realisation of the architectural approach, by simply modifying Figure 5 (a), is shown in the second diagram as Figure 5 (b). This approach has now been endorsed in a standard naval architectural textbook (Tupper, 2013).

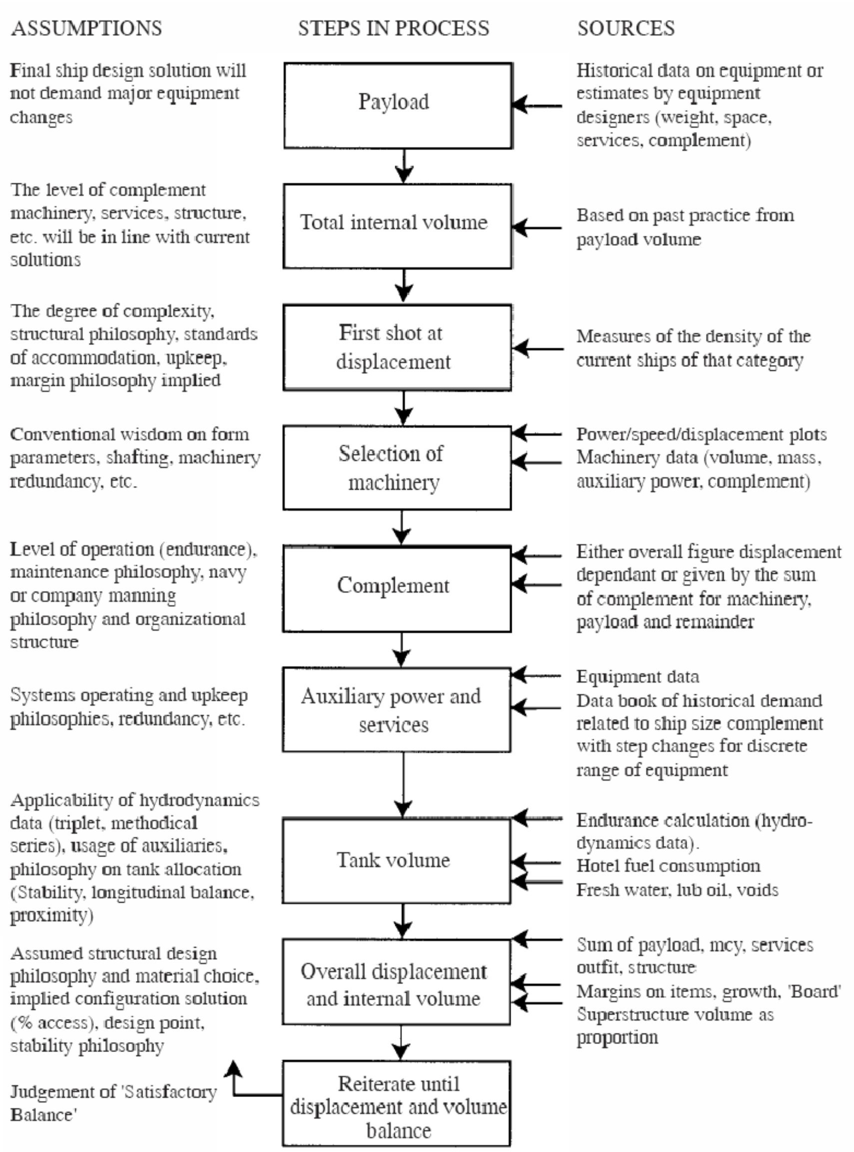


Figure 5 (a): A simple numerically balanced ship Synthesis with associated Assumptions and Sources (Andrews, 1986).

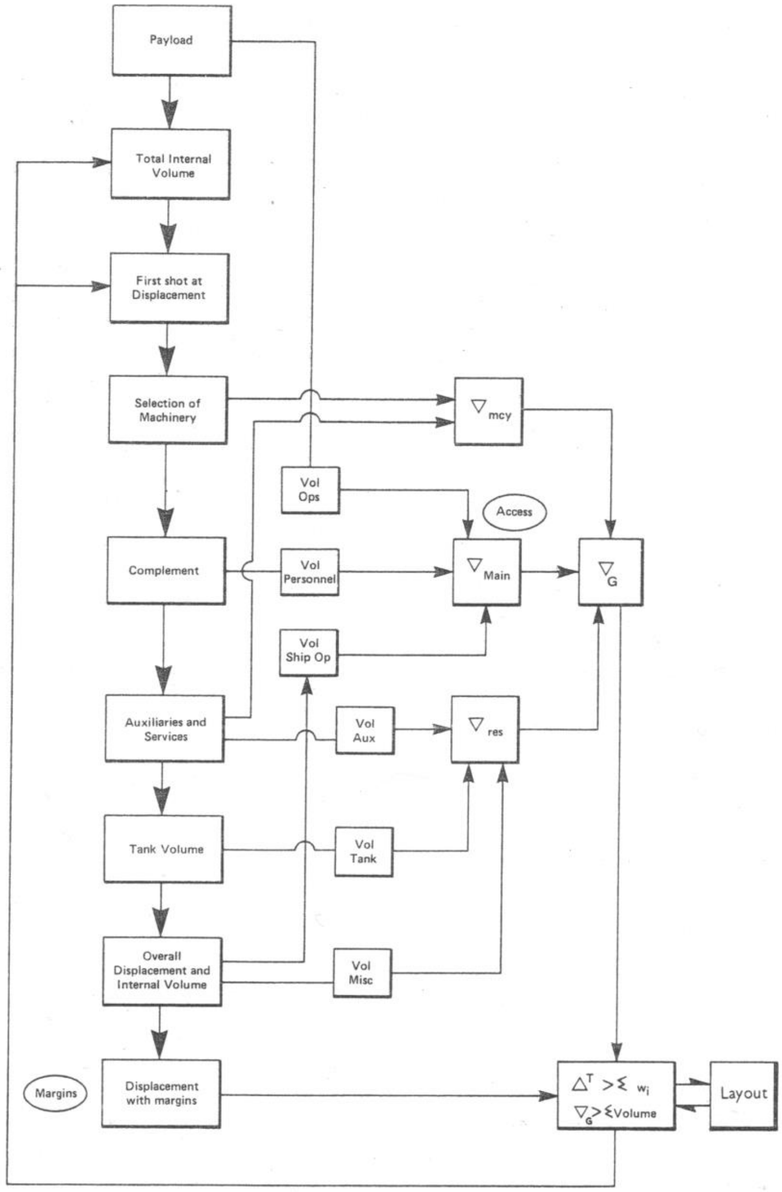


Figure 5 (b): The initial realisation of the Architectural Synthesis (Andrews, 1986)

3.4 DIFFERENT DESIGN PROCESSES DISTINGUISHED BY SOLUTION NOVELTY

As part of these overview remarks, it is important to distinguish between the types of ship design that are commonly undertaken. This is considered necessary before outlining, in Section 4, a coherent process for the concept phase of complex vessels. While one can think of many apparently different ship design processes that have been adopted (see the 26 examples in Andrews et al. (2009)), it is considered that the most useful discriminator is that which is associated with the distinctly varying levels of novelty that can exist in ship design practice. This is summarised in Table 3 with examples of increasing design novelty. As previously mentioned it is the case that most commercial ships, which are part of a wider transportation system, are designed on a relatively straight-forward evolutionary basis. This often draws on a successful design, already built by the bidding shipyard, which is modified to meet the new requirement while minimising the risk to the cost bid and likely to ensure technical reliability is achieved. However, most published discussion on ship design tends to address the exciting novel cases, as can be seen from presentations to learned societies which tend to be on specific ship designs considered innovative (Andrews, 2010). In addition it could be argued that advances in design practice and tools are primarily driven by the perceived needs of such novelty. The appropriate design process for each of the types of design in Table 3 is outlined in more detail in Section 5.

Table 3: Types of Ship Design in terms of Design Novelty

Type	Example
second (stretched) batch	RN Batch 2 Type 22 frigate and Batch 3 Type 42 destroyer
simple type ship	Most commercial vessels and many naval auxiliary vessels
evolutionary design	a family of designs, such as VT corvettes[1] or OCL container ships [2]
simple (numerical) synthesis	UCL student designs
architectural synthesis	UCL (DRC) design studies (see Section 6.2)
radical configuration	SWATH, Trimaran
radical technology	US Navy Surface Effect Ship of 1970s [3]

[1] *(Usher & Dorey, 1982)*
[2] *(Meek, 1970, 1972)*
[3] *(Lavis et al, 1990)*

3.5 THE "WICKED PROBLEM" AND REQUIREMENTS ELUCIDATION

The concept of the "wicked problem", first coined by Rittel and Webber (1973) for urban planning and largescale architecture, was then suggested to be appropriate to complex ship design, since "identifying what is the nature of the problem is the main problem, and that attempting to do so without recourse to potential material solutions verges on making a difficult operation impossible" (Andrews, 2003b). The next sub-section explores the implication of this for the concept phase of the design of PL&C systems, such as complex vessels. In addition, the concept design phase, as properly practiced for the most complex of vessels, is itself in several stages (or overlapping sub-phases), as is spelt out in Section 4. Within each of these stages are a series of operational steps whose order should not be prescribed since the order in which they are employed should be responsive to the particular imperatives of a given new design project.

In 2003 the author produced a paper, entitled "Marine Design – Requirements Elucidation rather than Requirements Engineering", (Andrews, 2003a). As indicated by that paper's title, it concluded that the practice of first investigating, in considerable depth and, importantly, solely in non-material specific terms, the requirements for a major naval programme were:

a) not appropriate for major warships;

and

b) bad Systems Engineering practice – corroborated, at that time, by the views of a senior Systems Engineering theorist (John, 2002).

Requirements Engineering's emphasis on abstraction is clearly counter intuitive to designers of engineering physical systems (such as ships). It is also considered that this abstraction also presents operational users, trying to spell out what they want, with immense cognitive difficulties. This is because they have to identify appropriate capabilities to do future tasks, by clearly drawing on their experiences of operating current real ships and systems, yet are expected to spell out such capabilities without ostensibly picturing potential physical solutions. The 2003 paper argued that this is a wholly false and highly inefficient approach, which further extends the front-end decision making for such politically sensitive programmes in a quite wasteful manner.

If we agree that like large complex buildings or sets of buildings, such as airport termini and town centres, the design of naval ships is characterised by the "wicked" nature of the design process, then

"formulation of a 'wicked' problem is the problem. …setting up and constraining the solution space… is more essential than the remaining steps of searching for a solution." (Rittel & Webber, 1973)

With a background in urban planning Rittel and Webber listed ten characteristics of their wicked problems, however, not all of these seem wholly appropriate to the design of PL&C systems, such as complex vessels. This is considered further in Appendix B, which reveals that there is still a large degree to which the "wicked problem" concept can be said to apply to the design of PL&C systems. It is important to appreciate that the "wicked" issue applies specifically to the problem formulation (i.e. Requirements Elucidation) and is not just another slick way of saying "naval ship design is complex", however true that might be. To put this in the ship synthesis context, as the great Sir Rowland Baker said in describing the process behind producing his St LAURENT Class frigate design, when he was seconded to the Royal Canadian Navy in the early 1950s:

"*Which came first the chicken or the egg, it is quite clear the ship comes before the staff requirement*"
(Baker, 1956)

The comparison drawn in Appendix B with social and urban planners (and indeed architects who have also adopted the "wicked problem" concept) explains, in part, why the formulation of requirements is inherently difficult, but also why this is intimately interwoven with the search for and exploration of solutions. Sorting out what a multi-functional, semi-autonomous very large vehicle, containing a hundred or more highly trained personnel, might need to do in a very uncertain future can only be explored in terms of possible design options. Furthermore cost, time and risk have to be taken into account from the beginning of the Concept Phase, as is shown in the first bubble in the version of the systems engineering "Vee" diagram produced by a working group of the UK's most eminent systems engineers (Elliott & Deasley, 2007) and reproduced at Figure 6. This initial scoping is essential to moderate any needs expression by the achievable and the affordable, which means there is a necessity to explore possible solutions. This is not just to inform the requirements owner but also to ensure the designer is an equal partner in the requirements dialogue. This seems patently obvious and such a dialogue is precisely what is meant by the author's term of Requirements Elucidation.

3.6 WHY THE CONCEPT PHASE OF SHIP DESIGN HAS A DIFFERENT MOTIVATION TO SUBSEQUENT PHASES

From the above consideration as to the overriding nature of the concept phase of complex ship design, there are seen to be five highly interrelated aspects that characterise the initiation of the process of designing such physically large and complex systems. From these characteristics it will be seen that this phase is fundamentally different to the rest of the design process.

Firstly, the process is characterised as a wicked problem. Unlike the downstream process, which is of a highly convergent nature and can be seen to be like gradually "peeling off the layers of an onion" to reveal more technical detail to gain design assurance, followed by working up sufficient detail to manufacture the eventual ship, this phase consists of working out what is really wanted and what can be afforded. It is characterised by starting with a, or even better, several blank sheets of paper and producing as many design concepts as possible to gain insights on performance, cost, time and risk, as suggested by the first bubble of Elliot & Deasley's Vee diagram (Figure 6).

Next, this is the key phase in the whole design process, since it is where the major decisions ought to be made. Design has been characterised as decision-making in its entirety but, as shown by the overall ship design process (Figure 4), the crucial decisions are made at the very front of the process. At a level below these strategic decisions (as revealed by the assumptions and sources examples shown in Figure 5 albeit for a simple (numerical) sizing sequence), there are many detailed decisions necessary for the designer to make to synthesise any potential solution. Many of the strategic choices are often not appreciated by the two key players in the initial design phase, namely the requirement owner (the naval staff for naval vessels or the shipowner/operator for complex non-naval vessels) and the concept designer. This lack of awareness of the substantial extent of the crucial decisions being made can arbitrarily narrow down the options that should be considered and thus inhibit the task of tackling the, essentially, wicked problem.

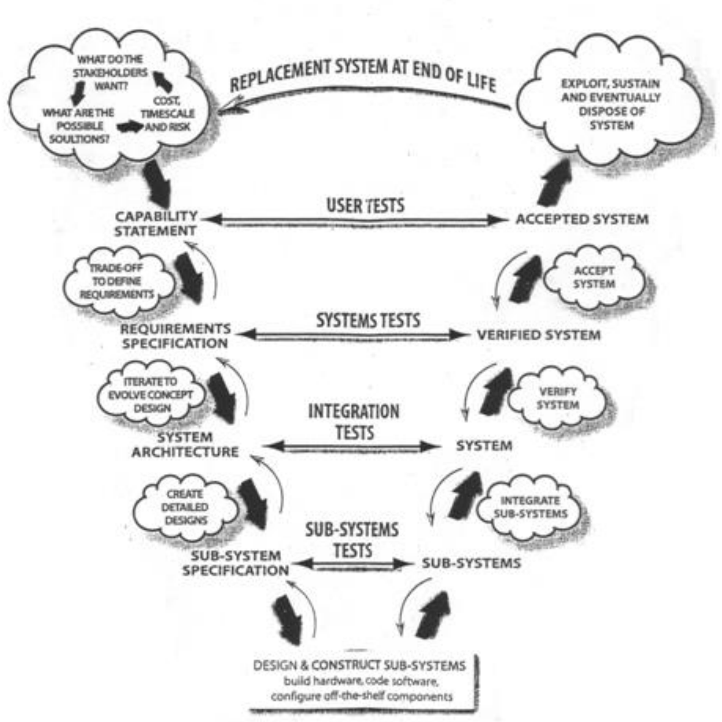


Figure 6: The Systems Engineering Vee Diagram starting (top bubble) with material solutions to facilitate Requirement Elucidation (Elliott & Deasley, 2007)

Thirdly, in coming to the conclusion of this largely divergent and exploratory phase in order to proceed into “engineering design proper”, decisions have to be made as to which one, or possibly two, outline design concepts, balanced to the limited extent appropriate to inform the decisions, is to be taken forward. Classically, this part of decision-making is a “trade-off” process, where distinctly different options with inevitably different attributes and levels of uncertainty have to be assessed. There are tools available to assist in decision-making but there is a risk in using them blindly, particularly if the process has not been recognised as “wicked” and full of (potentially) unappreciated constraints. So there is the need to ensure that a comprehensive and challenging design exploration is conducted. This has to be done before a comprehensive set of more, solution focused, trade-off studies are undertaken. As such, a design investigation should then inform the extent of any subsequent quantitative trade-off process (see the last two “Selections” in Figure 4). Furthermore, the primary aim of any largely numerical sets of trade-off studies should not be to give the “right choice” (ostensibly that with the highest score, however that is defined – see Hockberger (1996)) but to provide a part of the insights regarding the viability of the evolving requirement and associated design choice, rather than such scores being the sole basis of decision-making for the emergent design.

Part of the nature of this wicked, decision-making and complex trade-off process is that choices have inevitably been made as to the “style” of each of the various design concepts investigated. Thus the next crucial aspect is the exploration and then confirmation of the style, which is appropriate for the emergent solution. Importantly what this does, in the concept phase, is to bring to the fore many issues, which are of crucial importance to the ship operator (see Table 1). These were either hard to recognise in the traditionally narrow (and largely numerical) concept exploration, or not considered addressable by the traditional naval architectural (largely stability and powering) considerations undertaken to ensure the ship concept design studies were naval architecturally balanced. In what has been argued to be a paradigm shift, due to advances in computer graphics (Andrews & Pawling, 2003, Andrews et al, 2008), ‘softer” design concerns, especially those dealing with the human factors aspects of PL&C systems, can now be more readily addressed by undertaking architecturally based ship concept studies.

The final aspect, not surprisingly, is that of Requirement Elucidation, which brings together much of the first four considerations but strongly emphasises that this first phase of design is not about a blinkered rush into the subsequent design phases but, rather, is a process of elucidating what is required. Furthermore, requirements elucidation can only be done properly by an open and un-constrained dialogue between the (naval) staff and the concept ship designer, where each helps the other in the decision-making necessary to cope with the wicked nature of the process. That the process must be done in a manner using the design skills of the ship designer should be all too obvious. However, it is also the case that ship concept designers have the obligation to properly explore those (second level or major) style issues, which are beyond their naval architectural comfort zone (i.e. S^4 see Section 2.2) and the consequence of this amounts to a significant paradigm shift. This then leads on to a clear statement as to what must characterise the output produced by ship concept design tools, if component elements of that output are to assist the ship designer in properly undertaking requirements elucidation. These elements of an appropriate tool set have been summarised (Andrews, 2003b) to be:

- Believable solutions, that is to say solutions which are both technically balanced and sufficiently descriptive;
- Coherent solutions, which mean that the dialogue with the customer and other stakeholders should be more than a focus merely on numerical measures of performance and initial (procurement) cost, by including at least a comprehensive visual representation and the basis behind it;
- Open methods, in other words the opposite of a ‘black box’ or a rigid/mechanistic decision-making system, so that the description addresses those issues that matter to the customer, or are capable of being elucidated by the designer from dialogue with requirements owner/user teams;
- Revelatory insights, in particular early in the design process, identifying likely design drivers to aid design exploration in initial design and the subsequent “working up” of the selected design’s feasibility right through to the build description;
- A creative approach, not just providing a ”clear box” (showing how each design option has been produced) but actually encouraging exploration “outside the envelope”, including radical solutions, and as wide an exploration of design and requirement as possible, in order to push the requirement elucidation boundaries.

All this is consistent with the message as to what is needed for effective requirement elucidation in the concept phase, before choosing the “right” design option with which to proceed.

4. THE STRUCTURE OF THE CONCEPT PHASE

Having considered the fundamental motivation behind the initial or concept phase of ship design, it is sensible to spell out the overall concept process, which has been applied to a major new naval ship design (i.e. the third and fourth design types in Table 3). This can be done in terms of three initial overlapping design stages, comprehensively presented in the Transaction paper on the preliminary design of warships (Andrews, 1994) – see Figure 7. Each stage is outlined below.

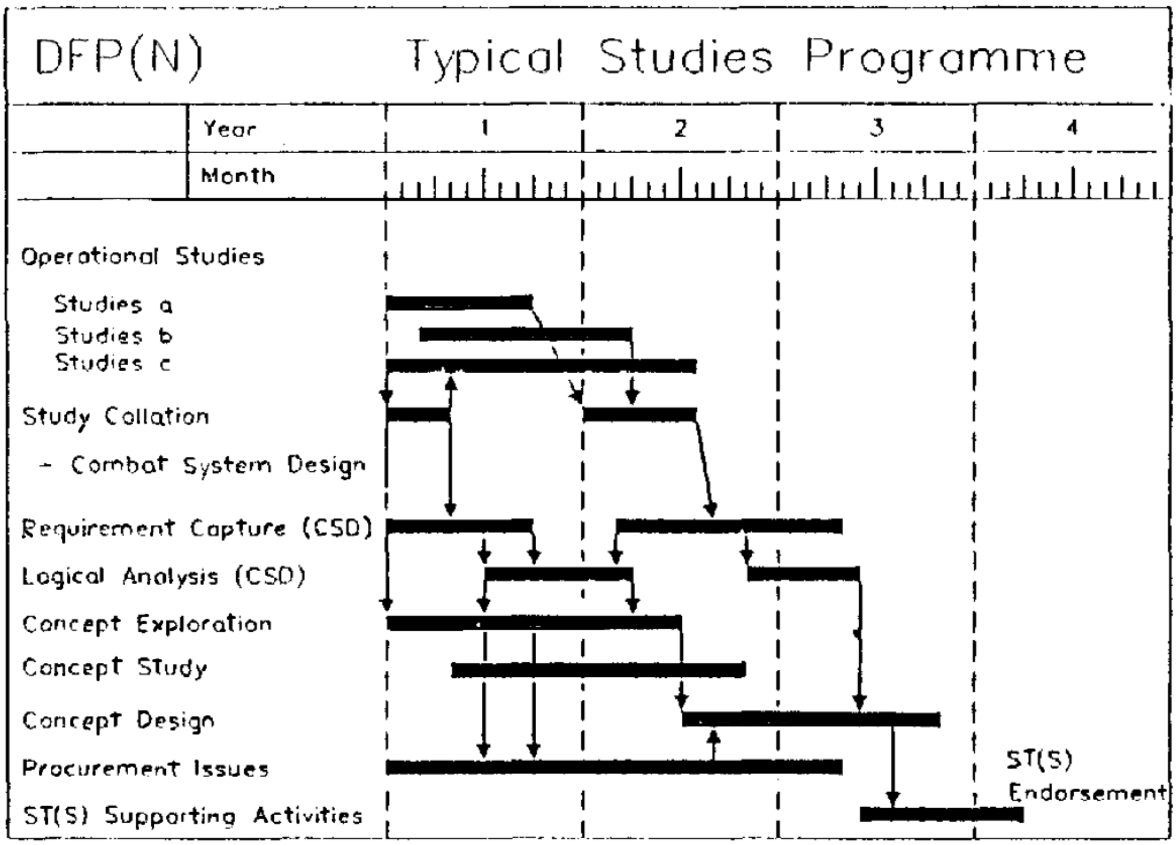


Figure 7: The three stages of the Concept Phase for a major Complex Naval Programme (Andrews, 1994)

4.1 CONCEPT EXPLORATION

This initial design stage can be said to comprise a wide-ranging exploration, which starts with the initiation of investigations for a new ship design. It should be an extensive consideration of all possible options and, typically, include the option of modernising existing ships, modifying existing designs and exploring the full range of, for example (see Figure 8):

i) packaging of the primary function (e.g. aircraft, weapons or sensors or operational command and control for a combatant; cargo/passengers for naval auxiliaries or, even, sophisticated commercial service vessels);
ii) capability of the ship to deliver the (largely) ship functions (e.g. speed, endurance, standards);
iii) technology options to achieve the functions and capabilities (e.g. existing technologies, enhanced materials and systems, enhanced technological/configurational options, reduced technology levels).

Some of these explorations may well be cursory or may show the need to further pursue more than one distinct option. Some of the novel or technologically advanced options may require research programmes to de-risk key technologies, or result from revisiting (not for the last time) the initial operational concept in the light of any of the novel option types, further outlined in Section 5.

There is also the issue of whether to consider a reduced utility solution (see Brown (1991) and Keane and Tibbitts (2013)). A resort to a “Parent Design” generally arises from bad thinking by the highest-level decision makers. The argument in Keane and Tibbitt’s paper (backed up by analysis of several major US Navy designs) is that (despite the political and bureaucratic hierarchy’s belief) actually using an existing design (sometimes called “modified-repeat”, second batch/flight or parent vessel) is not usually attractive. This is particularly so if this is being explored because it is seen to be low risk and a means to constrain performance and control price growth. Rather Keane & Tibbett conclude that “experienced early stage ship design engineers.. (*can*) rigorously explore the design solution space” rather than higher government decision makers assuming “mature designs” can be easily and cheaply adapted. Another approach chosen “to avoid a new design” is the ship life extension of an existing ship (e.g. the SLEP of the US Navy’s super carriers well beyond 40 years operational life), the conversion of an existing (merchant) vessel (e.g. RFA ARGUS – item viii in Section 2.1) or adopting a lower standard, “utility” design (e.g. HMS OCEAN – item vii in Section 2.1). All these alternatives should be considered but need to be appreciated as being, more often than not, poor options with considerable risks.

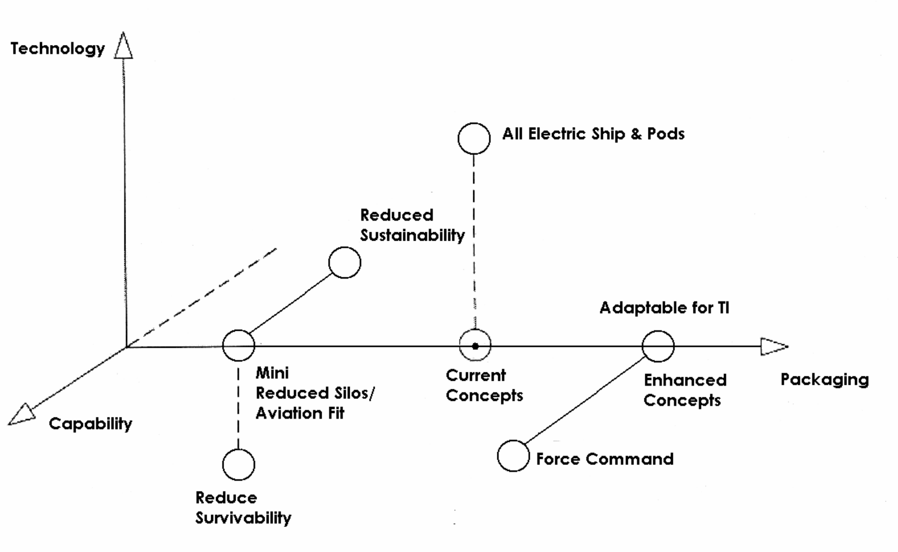


Figure 8: A Representation of the Solution Space showing the range of options to be explored

4.2 CONCEPT STUDIES

Assuming only one or two options are to be taken forward, from the wide exploration, that wide ranging but cursory initial exploratory stage is unlikely to have investigated, in any depth, the perceived design drivers and the impact of various choices on function, capability and technology. This next stage is dependent on the type of vessel (e.g. combatant, amphibious vessel) and degree of novelty (e.g. conventional mono-hull, unconventional configuration), as well as a range of issues from varying payload demands, through the impact of speed and endurance to style issues; such as those associated with design life, signatures, survivability and complement standards (see Table 1). All these issues normally merit investigation before the design is too fixed (see Andrews (1994) for a more comprehensive discussion of these and other typical issues worth investigating in general). Such issues can also significantly influence the downstream design of the likely options seen to be attractive but, more importantly, they need to be debated with the requirements owner, since their impact on the ship's performance and affordability should be part of that dialogue, before the overall (or macro) style and hull-form of the preferred solution (and, importantly, the emergent requirement) are too precisely fixed.

4.3 CONCEPT DESIGN

This final stage, prior to approval to commit to a more substantial design effort (i.e. in UK MoD terms, prior to Initial Gate decision – the current term for approval of the "Staff Target", see Figure 2a)), is primarily focused on the design (and costing) information. This is necessary to ensure the approval to proceed is based on sufficient information and that the process, beyond that initial approval, can then proceed coherently. Typically, this stage in naval ship design is dominated by cost capability trade-off studies and the interaction with any associated operational analysis. It can be appreciated that it would be unwise to enter into this last stage of the concept phase, with inadequate exploration of the solution space or of the style and performance issues. This because any submission to proceed is then likely to be vulnerable to probing by approval authorities as to the impact of such issues and, too often, can lead to concept level design studies being re-opened in the next (Feasibility/Assessment) phase.

This need for a wide initial exploration just emphasises the inherently "political" nature of naval ship acquisition at the front end of the process and why it is often protracted and seen to be unsuccessful and apparently costly, in comparison with the process for even the most sophisticated merchant vessel. However it is still nothing like as expensive as the development processes for major aircraft programmes, given these include producing several full-scale prototypes and designing the specific tooling facilities required for a large production run. Rather than investing in such extensive preproduction development for very limited numbers of large vessels, there are distinct issues in the case of major naval programmes that are seen to need exploring. The latter issues are often more related to the environment in which such design and acquisition is undertaken (see Table 2) than the direct drivers of a given ship design (see Table 1). This is a complex world has already been alluded to at the end of Section 1.1.

5. NOVELTY AS THE DISCRIMINATOR IN THE PROCESS FOR SPECIFIC SHIP DESIGN STUDIES

The various types of ship designs listed and exampled in Table 3, in terms of design novelty, now need to be discussed in somewhat more detail in this section.

5.1 STRETCH

The least novel form of a new ship design differs from those below in that the solution is already predicated i.e. the solution is that of an existing worked up design with just the addition of a parallel mid-body section (usually a complete watertight compartment). Thus the concept ship design process is not one of iterative sizing and selecting hull dimensions and form parameters, to achieve an "optimum" hull form. Rather at most, the beam may need to be checked to restore acceptable GM for the new KG changed from the existing design's KG and with BM altered due to the modified (and now non-optimal) underwater hull form. The form parameters (e.g. C_B, C_P) will change but due to extra ship's length will most likely result in a higher top speed than that of the parent form. Then the additional equipment and distributed systems in the parallel mid-section, plus additional structure and fluids are usually used to bring the ship's weight back to ensure the original design draught is restored for the increased displacement. So in essentially all respects the design process is much curtailed, even in the concept phase, and then quickly worked up to detailed design, given that most of the design will be unchanged and the style of the design of the new section (apart from any new equipment) will be that given by the original ship design's style.

5.2 TYPE SHIP

Here the fundamental question is how far will the new ship design differ from the chosen type ship? Beyond that, the major design decisions (the "Selections" in Figure 4) are essentially accepted as unchanged from those for the chosen type ship. Thus the ship design approach, design tools, design criteria, etc. will be the same with the only new "improved" features inserted being those warranting a new design. These are typically those to achieve a change in speed, range, payload or adopting some discrete enhanced technology (e.g. new power plant or operational equipment, such as a new radar, weapon silo or even change in crew numbers or facilities, in the case of a naval combatant). However when it comes to the initial sizing (seventh step in Figure 4), even if this is a fully architecturally driven synthesis (see Item 5.5 below), this will require a fully iterative process to ensure even a crude naval architectural balance.

However, it may not be necessary to just achieve a new balanced solution (in weight, buoyancy and stability) but also a form parameter investigation may be required to get the "optimum" hull dimensions and form coefficients, for the new performance and "payload" requirements. This form parameter investigation is likely to be highly constrained in the design choices, as the new design's style will follow, in almost all regards, that of the type ship. Thus quite often the same form parameters will be adopted with just a slightly different set of dimensions necessary to meet the improved performance with regards to payload, speed range or, even, seakeeping/manoeuvrability, if those for the type ship had been found to be inadequate. This design approach could be said to generally match that used for most commercial ship designs, where the approach is very much to modify the last successful ship design produced by that shipyard. This approach also applied pre-World War II to Royal Navy vessels, such as destroyers, when a new class was ordered almost every year. This is no longer the case for modern combatants with new designs often separated by a decade or two and so requiring wholly new designs.

5.3 DESIGN LANE

This approach can be seen as a somewhat less specific variation of the type ship approach, where instead of a single type ship a series of design points of previous successful designs are used. Thus design lanes are produced to guide the choice of appropriate hull-form parameters, or weight group estimates early in the sizing process, as was typified by the use of weight equations (Rawson & Tupper, 1976). The criticism of the design lane approach is that the designer using them does not necessarily know what were the motivations behind the choices made for the particular designs used to populate the chosen design lanes (see Figure 9 for a typical combatant hydrodynamic example from Saunders (1957)), and hence whether they are applicable to the new emergent design. Furthermore, it could be argued that any design lane is likely to be produced by averaging out a set of previous design and therefore unlikely to produce a winning new design. This averaging might well produce a low risk design solution, should that be a motivation in times of high risk aversion, however the relevance of "old designs" to new circumstances might not even be "low risk" and may, at best, be irrelevant to a new set of design requirements and new constraints or technologies?

5.4 NUMERIC SYNTHESIS

Having a series of algorithms for sizing the ship, provided the design is accepted to be pretty conventional in style, usually provides a basis for an exploration of size drivers and some exploration of form variation. This can be seen to be an improvement on the design lane approach through a numeric synthesis of weight and displacement together with ensuring internal space available is at least equal to space required, and then both iterated (see Figure 5) to a reasonable balance (typically ± 1.0% for both weight and volume). Even this crude balance can be used as the basis for exploring cost capability trade-offs by varying, say, speed or payload demand to see how this changes build cost, based on weight group cost factors. However beyond that it is usually necessary to refine the dimensions and hull-form parameters assumed in the weight and space algorithms by a simple stability check (essentially GM driven by waterline beam and an assumption for KG) plus estimating the resistance at top speed from a set of assumed hull-form coefficients (typically hull length and prismatic coefficient). This sounds like a rational approach – especially given the ability of modern computer tools or even multi-level spread sheets to provide a very large number of apparent design solutions (McDonald et al, 2012).

However as a design approach, without proper regard to the internal disposition of spaces in the hull and superstructure, it is little more than a sophisticated design lane approach. This is because it relies on the "hope' that the numerically defined sum of the required volumes (critically in the main deck areas) can be sensibly allocated, well downstream from the Concept Phase, rather than just being shoe-horned in. A further artifice occurs from thinking that the form parameters are actually being rationally selected, given that while for stability BM is given by the selected displacement form, the actual KG is the final outcome of the disposition of weights. Yet many of the weights have yet to be allocated or even designed and therefore their final summed centroid can only be guessed at the concept stage. It could be argued that when this approach is applied to the ubiquitous naval combatant, with a typical speed of some 30 knots, it is easy to select hull-form parameters (e.g. Circular M = 8.5 and C_P = 0.6). However, this makes the approach sound pretty much like going back to a type ship approach. Of course should one be designing something that is clearly configurational driven, such as an amphibious warfare vessel or an aircraft carrier (see Section 8.1), this whole numerical approach cannot be the main basis for design synthesis, any more than it can for ocean going multi-hulls (e.g. SWATH, Trimarans or Hybrids), which are considered under Item 5.6.

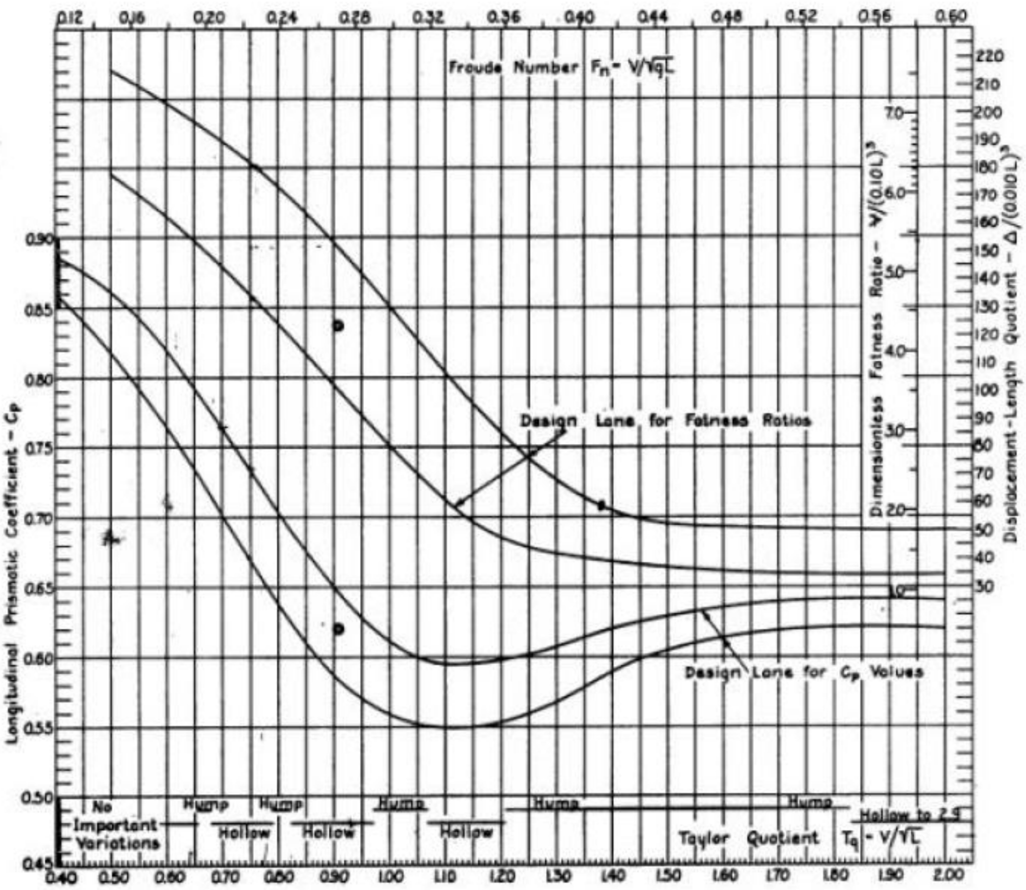


Figure 9: A Typical Hydrodynamic Design Lane (Saunders, 1957)

5.5 ARCHITECTURAL SYNTHESIS – OR DESIGNING INSIDE – OUT

The author has argued for many years, particularly with respect to complex (naval) vessels, that such ships really ought to be initially designed in a manner similar to the configurationally driven ships mentioned at the end of the previous sub-section (as are sophisticated commercial vessels, such as cruise liners (Levander, 2012)). Thus the synthesis should commence with a preferred disposition of the primary operational and support spaces of such service ships. This architecturally driven approach then requires a putative hull (and superstructure) to be "wrapped" around the spaces, which is readily possible with modern CASD systems (Andrews & Pawling, 2003). Table 4 summarises the steps to be followed in such an architecturally driven approach and can be compared with the numerically based ship synthesis of the first diagram in Figure 5. This preferred design synthesis to the other approaches to producing new ship concept options is outlined in further detail in Section 6 along with a series of applications of the approach to both new ship concepts and design research investigations, which show the approach's credibility - albeit in academic use.

Table 4: Summary of the steps in the UCL architecturally driven initial ship design synthesis, spelt out in case study (Andrews & Pawling, 2008)

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

The UCL version of this approach is known as the Design Building Block (DBB) approach and has been shown to produce naval architecturally balanced *ab initio* design studies. The approach enables the ship designer to much more readily derive designs, which can explore design decisions beyond the classical (S^4) issues, thus addressing wider "Style" decisions. Furthermore such an approach can enable Simulation Based Design (SBD) to be used to explore (say) human factors aspects well before the hull design dimensions and parameters are essentially fixed. Thus the design exploration in the concept phase can then be used to question many of the major design decisions that have previously been largely ignored (or, traditionally, not even recognised to be capable of being or necessary to be considered) so early in the overall process. This is despite the fact that they can actually determine the choice of design options being used to produce the selected design solution and the emergent requirement, both of which then go forward to be developed (see Figure 4).

5.6 NOVEL CONFIGURATIONS

There can be said to be two main categories of novel ship configurations beyond the purely mono-hull form of most ships. The first are those still currently consist of, essentially, small non-oceangoing high-speed craft considered in the last category below. These craft go really fast by not relying wholly or at all on buoyancy for lift and so require novel lift enhancing technologies. The other type of novel hull form is that of the multi-hull displacement vessel and this (at oceangoing displacements) largely uses the same technologies as oceangoing mono-hulls. The novelty is then in the configuration – be it a SWATH form, usually for enhanced seakeeping, or a trimaran, which essentially avoids the challenging interaction between stability and resistance in form parameter selection for mono-hulls discussed in Item 5.4.

The trimaran example of design synthesis is actually the form of vessel used in the example of the DBB approach outlined in Section 6. This uses the DBB approach but essentially avoids the details of the issues in sizing a trimaran, which is outlined more specifically in Section 8, where a broader range of ship types, beyond the classical naval combatant, are briefly considered. This example well emphasises how the ease with which a mono-hull frigate can be sized, with default form parameters (spelt out towards the end of Section 5.4), cannot be done for a multihull. For the latter it is necessary to size the hulls' additional form parameters, such as the length of side hulls and of the cross structure, together with their locations relative to the central main hull. These have to be determined to synthesise the design and these parameters significantly interact with the emergent broad layout and capabilities, such as stability and resistance. Thus the sequence proposed for synthesising a new trimaran ship is essentially to fix the main hull as a long slender form (Circular M > 10) and then position the side hulls to both achieve as low as possible an interaction with the main hull wave pattern and to provide sufficient intact and damage stability. The latter has to be appropriate for the operations of the ship (be it a commercial ferry or, more demandingly, a naval combatant). In addition the disposition of the main spaces in the hull and the cross deck structure/superstructure interacts with these form choices, which of course strongly justifies adoption of an architecturally driven ship synthesis, instead of the numerically based traditional synthesis.

5.7 NOVEL TECHNOLOGIES

As already mentioned, there are currently few oceangoing high-speed vessels, however as this paper considers the future scope of ship design approaches it is worth briefly addressing this issue. Furthermore it could be argued some semi high-speed ocean-going vessels have been produced, the obvious example being the problem riven US Navy LCS (in both its fast trimaran and semi-planing mono-hull variants – see Warship Technology (2016)). What distinguishes all high-speed marine craft is that they originate not from the conventional shipbuilding and the technologies of the shipbuilding industry, but rather from the aerospace industry with its necessity for lightweight high power to weight ratios. The latter is necessary to lift such hulls out of the water if they are to achieve speeds impossible with displacement hulls. Thus for an appropriate design approach one needs to look at aerospace design practice, which has traditionally dealt with the design of new craft by constructing full scale prototypes. This is quite unlike the design of all PL&C systems, of which marine vessels and structures are just one important domain.

One good summary of aerospace practice at the most complex end is given in a paper on the Lockheed Martin “Skunk Works” (Miller, 1995). This article on the “Principles of the SKUNK Works” largely focuses on the management culture that enabled a relatively small team to bring into US service high performance spy planes and the first stealth fighters (see the list of 14 short Operating Rules (Miller, 1995)). However in regard to its relevance to the design of maritime vessels with less novel technologies, such high end aerospace practice is characterised by: “simple brief systems specifications“ (with three critical performance parameters); focus on engineering design; a concurrent engineering approach; and early development of prototypes. Given the size of the high speed marine craft relative to ocean going vessels, full-scale physical prototyping is possible and thus *de rigueur* for such novel technologies, but of course the consequence is an extremely high investment in early design development, which has been an anathema in the marine industries. The only exception to this being naval weapons development (e.g. sensors, command & control and weapon delivery systems), which has much closer links to aerospace practice than to the traditional marine industries. It is thus not surprising that advanced technological options for even naval vessels have been very rarely pursued beyond the research phase and there are no high speed oceangoing vessels – genuine high speed (e.g. 80 knots) has so far only been applied to high speed small coastal ferries and small naval craft (e.g. USN amphibious LCACs (Lavis & Band, 1986) and Jetfoil PHMs (Lavis et al, 1990)).

6. DESIGNING INSIDE OUT – THE ARCHITECTURALLY DRIVEN SHIP SYNTHESIS

6.1 THE STEPS IN A DBB BASED SYNTHESIS

The UCL Design Building Block (DBB) approach (Andrews & Pawling, 2003) alters the initial design focus to produce a gradual joint evolution of the inside spatial disposition, ship weight and displacement, and hull dimensions and form. This evolution for a naval combatant is shown in Figure 10 and numerically summarised in Table 5 for the four steps of Table 4 and each step also indicates the number of building blocks at the end of that step, so the granularity of each concept model can be appreciated. The example is actually for a trimaran combatant variant, of the US Navy’s Littoral Combatant Ship (LCS), as this was a UCL study, where the detailed synthesis steps of Table 4 were identified during the concept study process.

The philosophy behind the DBB approach is shown in Figure 11, where a preferred first broad internal layout with adjacency preferences can then be turned into a series of deck allocations for key compartments and combat equipment. This could even be initially attempted without a specific hull form wrapped around the deck allocations, although in the case of the trimaran example hull forms were used from the start. Clearly the choices in allocating the compartments are not just dependent on the various numerical values exampled in Figure 11 (see Andrews (2003b) for the explanation of the adjacency values shown). They are also determined by various other issues, which are associated with whatever ship category and style is appropriate to the particular case in question (see Figure 12 for the typical combatant architectural drivers). Typical choices for a combatant, affecting both internal and upper deck layout allocations such as those summarised in Figure 12, come into play. Such a set of design issues then produce, given the four steps of Table 4, the progressive outcomes shown in Figure 10 and Table 5.

The approach to initial ship design using the DBB version of the architecturally driven design approach has been the subject of many UCL authored papers and it is probably best summarised in Andrews and Pawling (2003) with the underlying justification by Andrews (2003b). The following sub-sections provide respectively summary outlines of a set of ship design studies and of a set of ship design research investigations. Together these are considered to demonstrate that the DBB approach is

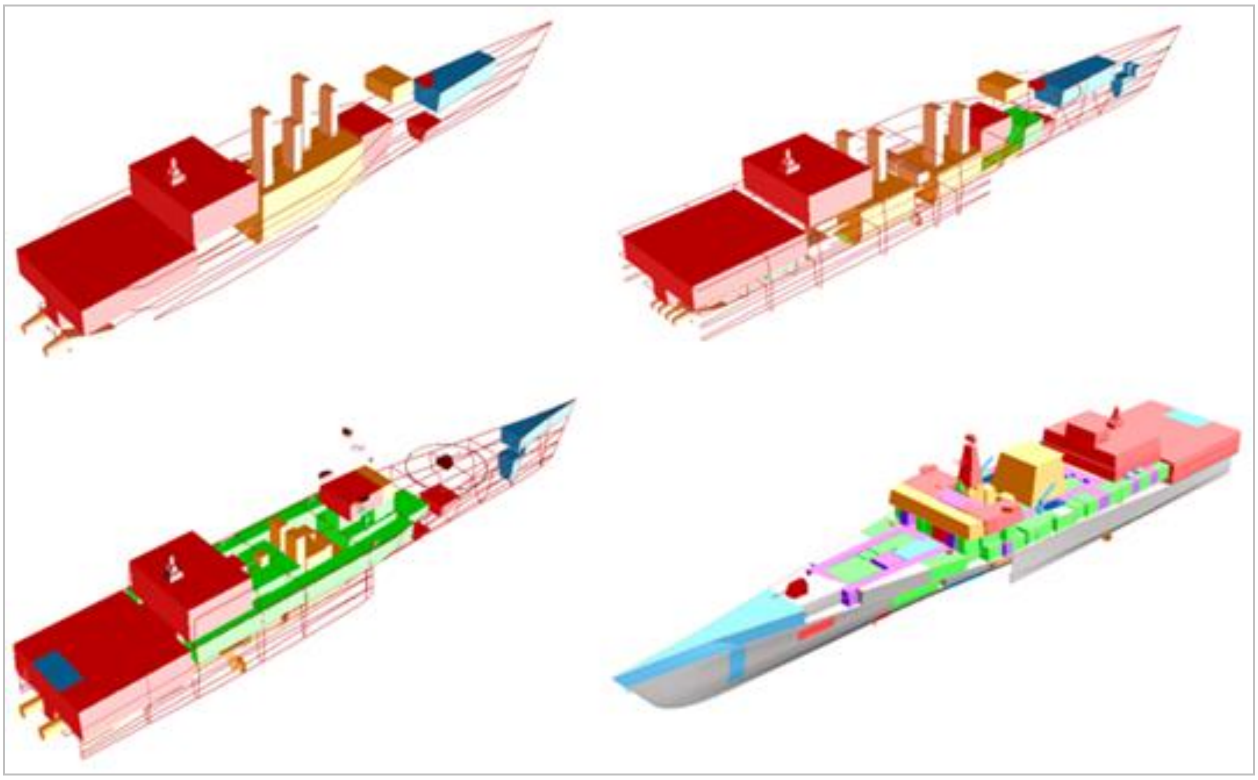


Figure 10: Architectural representations of the UCL LCS study showing the design building blocks at each of the concept design stages for a specific design option (Andrews & Pawling, 2008)

Table 5: Summary of the UCL LCS design stages shown in Figure 10 (Andrews & Pawling, 2008)

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 (SBB) 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)

a proven design method, rather than just a research proposal to improve future ship design. This work has mainly used the SURFCON module within the GRC-QinetiQ's Paramarine ship design tool set of naval architectural analytical modules (www.paramarine.qinetiq.com). UCL has also developed a less sophisticated DBB tool (Pawling et al 2015) without direct access to all the analytical capability of the Paramarine system, given the latter is also intended to assist ship design well beyond the Concept Phase (Munoz & Forrest, 2002). The UCL tool is therefore limited to use in very early low level design exploration, with subsequent recourse to Paramarine level of naval architectural analysis on those options deemed worth pursuing.

The next two sub-sections briefly summarise the use of the DBB approach to date, following setting up the UCL DRC in 2002. The first of these were early stage ship design studies each investigating a range of ship design options in response to a wide variety of taskings. Many explored discrete design problems, often where the requirements are far from clear and certain, so the architectural dimension was ideal to investigate novel and unconventional options. They also cover a wide set of ship types and levels of design novelty. The second set consists of employing ESSD designs to investigate particularly concerns or issues in ship design that can be readily addressed in ESSD, once the architectural dimension has been adopted. In both sets of studies the object of listing them in this paper is not to detail the study (see main reference for each) but to point out how the study was facilitated by the DBB approach and what was particular, in each instance, about that design task or issue that could be addressed at ESSD. It should be noted that only the SURFCON graphical model has been presented below, but that each design study is a naval architecturally balanced design (usually for stability, hydrostatic balance and powering) with at least one digit level weight and space breakdown, consistent with concept study design level of definition.

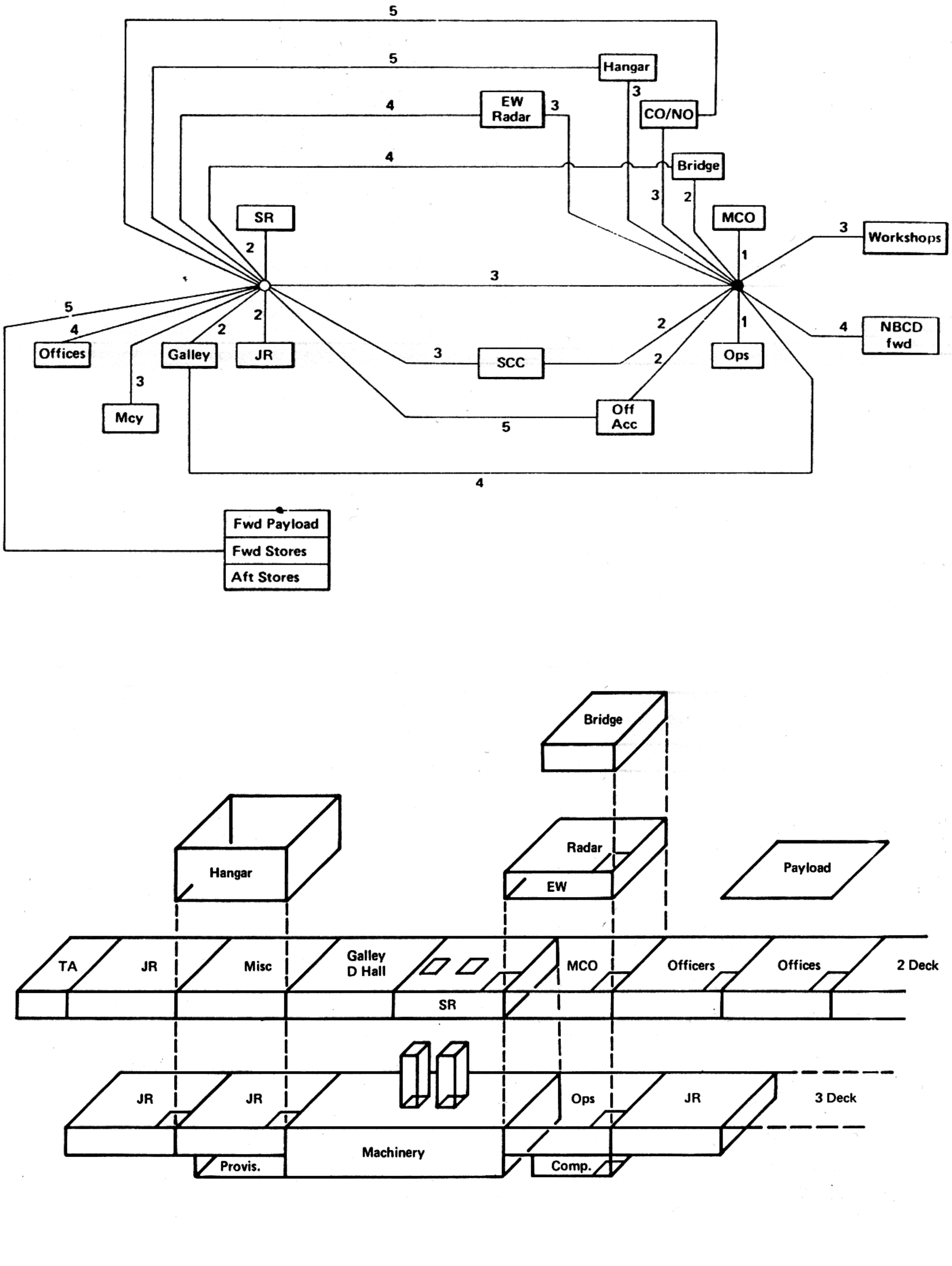


Figure 11: *Ab initio* Frigate Compartment Block Synthesis (Andrews, 2003b)

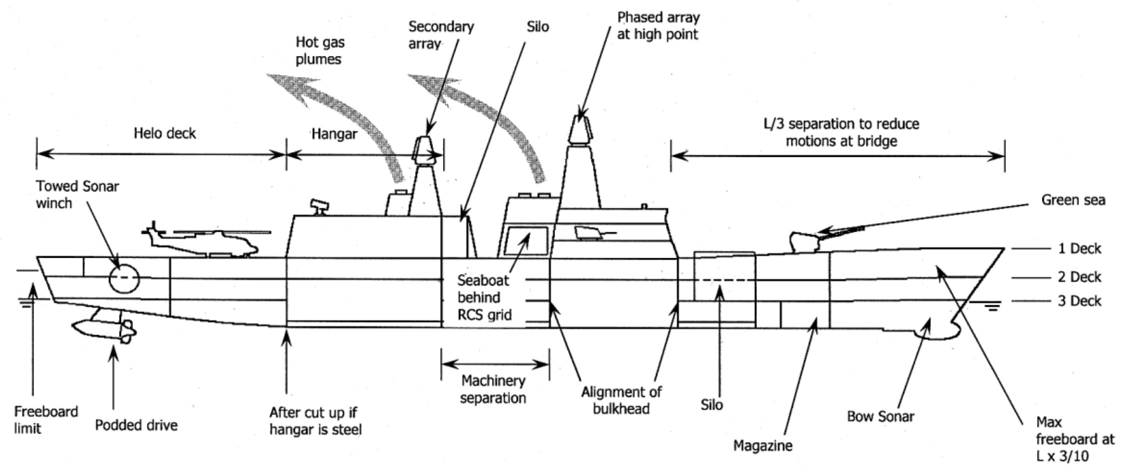


Figure 12: Frigate Layout Considerations (updated from Brown (1987) (Andrews, 2003b)

6.2 HOW DESIGNING "INSIDE-OUT" HAS ALREADY EXPANDED THE SCOPE OF ESSD – UCL SHIP DESIGN STUDIES

i) Design studies on requirement allocation (2002)

These studies, based on a supplied option for the R.N. Future Surface Combatant (precursor of the Type 26 Frigate), were undertaken using Paramarine–SURFCON and investigated the apportioning of the various elements of the requirement among the UK MoD Operational Requirements "customers" (known as DECs at that time). This was achieved by producing a set of design variants, each one of which had one customer capability set (e.g. Force ASW defence) removed and was then compared with the fully capable solution. This assessment of capability allocation was assisted by the architectural representation alongside the numerically balanced description as a measure of the ownership of capability (and associated cost). The basis of the (unpublished) study was outlined in Andrews and Pawling (2003) and the baseline design SURFCON model is given in Figure 13.

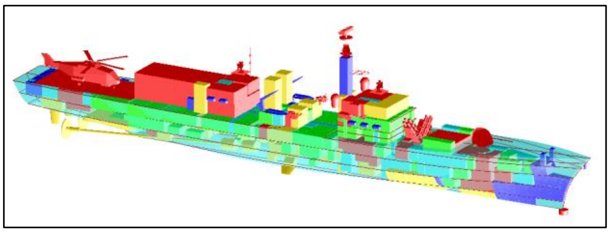


Figure 13: Typical SURFCON Representation of UCL FSC Requirement Study

ii) Littoral Mothership (2004)

The UCL task for UK MoD was to produce a series of distinctly different ship types (i.e. five configurational ship types providing different lift and deployment arrangements to the same requirement plus two requirement variants). These options were produced to meet a broad concept of fast long-range deployment of small Littoral Combatant craft by a large "mothership". Without recourse to any type ships for this novel operational concept only a DBB type approach could generate believable and comparable concept studies. Figure 14 shows the SURFCON model for the Crane Ship option (see Andrews & Pawling, 2004).

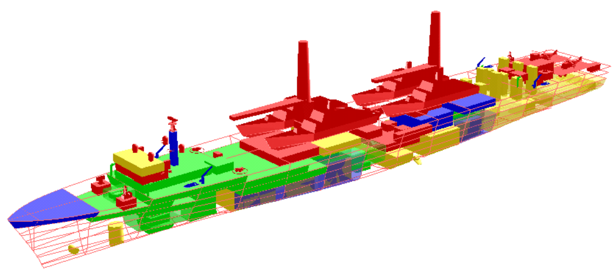


Figure 14: One case study (Crane Ship) of the UCL Mothership Studies (Andrews & Pawling, 2004)

iii) US Navy Littoral Combatant Ship (2006)

This study was undertaken to show how Paramarine-SURFCON modelling could reproduce an in-depth concept design to a set of (US Navy) requirements for the Littoral Combatant Ship. The Trimaran variant was selected to highlight the ability of the UCL DBB approach, incorporated in Paramarine-SURFCON, to produce a worked up novel multi-hulled ship solution. (This has already been described in opening part of this section, see last model in Figure 10 for the DBB representation achieved at the end of the UCL design task (Andrews & Pawling, 2006)).

iv) Canadian joint support ship (2007)

This study was undertaken in support of a commercial bid team responding to a bid request from the Canadian Navy for their Joint Support Ship requirement. The UCL DRC produced a series of internal configuration options to reveal which one was preferable. This study demonstrated how a quick investigation of a complex multi-role capability for a novel naval auxiliary can be investigated without completing the concept design for all the variants, provided an architecture based synthesis is employed (Andrews & Pawling, 2007).

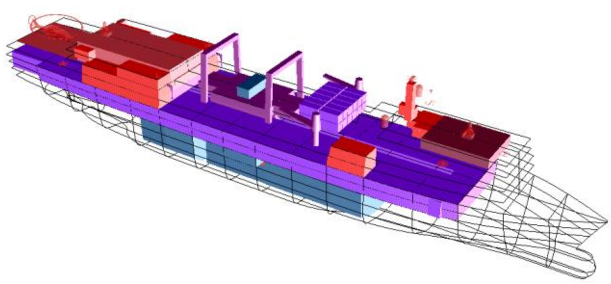


Figure 15: The final configuration for the JSS concept design showing Fight DBBs (Andrews & Pawling, 2007)

v) Carrier concept (2004)

This design investigation was an in-house study to demonstrate how the DBB approach could facilitate aircraft carrier investigations. Given carriers are configurationally (inside-out) design driven (Andrews, 2003b), Figure 16 shows the conflict between machinery intake/uptakes, hangar and lifts, plus air weapon lifts all competing for space in a three dimensional arrangement. Such a slice through the graphical model reveals that resolving such three-dimensional conflicts is key to the design of such ship carriers of aviation platforms from design initiation (Andrews, 2005).

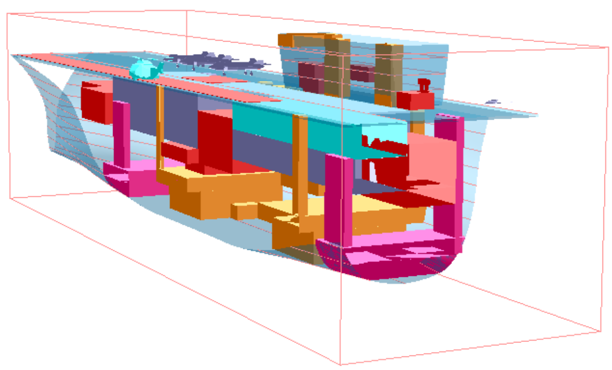


Figure 16: A SURFCON image of a section through a carrier design study (Andrews, 2005)

vi) Various uxv design studies (2009-2015)

A series of ship concept designs have been produced by the DRC looking at novel ships to host UAVs (Pawling & Andrews, 2009), UUVs (Pawling & Andrews, 2011a) and USVs (Pawling & Andrews, 2013). Given the driver for such dedicated "UXV carriers" is the launch and recovery system (LARS) and the stowage of these autonomous vehicles, an architecturally driven design synthesis is clearly necessary, as is revealed by the SURCON models presented in Figure 17.

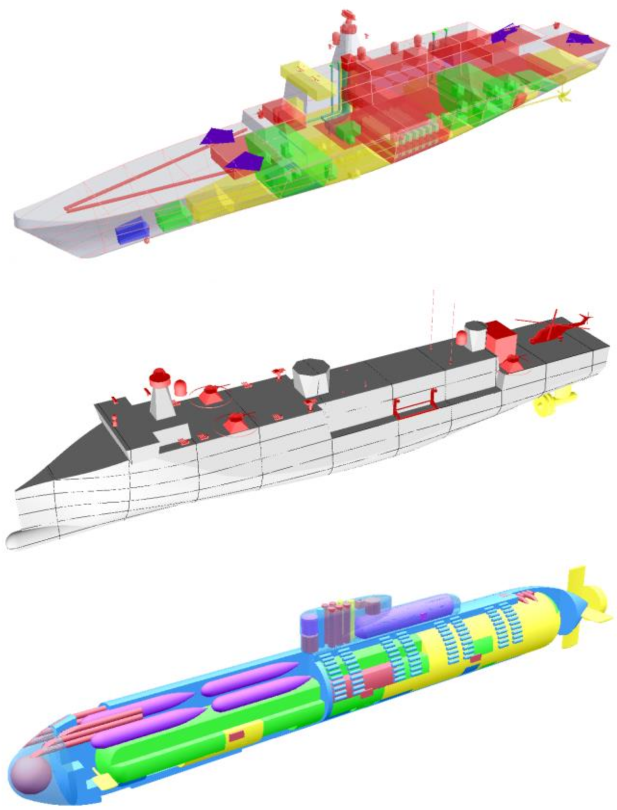


Figure 17: Three UXV carrier vessels – Air Vehicles (Pawling & Andrews, 2009), Surface Vehicles (Pawling & Andrews, 2013) and Submarine "carriers" (Pawling & Andrews, 2011a)

vii) Configuration variants for offshore patrol vessels (2010)

Three novel styles of ship solutions to a RN Offshore Patrol Vessel (OPV) requirement were produced for the UK MoD in 2009. Given the key feature, regardless of the three configurations proposed by the DRC as alternatives to a "conventional naval OPV" solution, was to provide a mission bay for manned and unmanned vehicle deployment, again the design synthesis was built around the DBB approach (Pawling & Andrews, 2010).

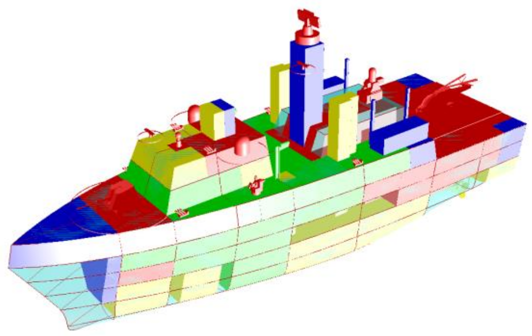


Figure 18: A wide transom option for an OPV requirement (Pawling & Andrews, 2010)

viii) A design study for a light frigate (2015)

This study was produced for a foreign navy to provide the basis for an independent check at ESSD for a future indigenous design and build option. The use of Paramarine-SURFCON not only gave the navy's design team assurance but enabled the design to be presented to the naval staff and high ranking decision makers, revealing the three dimensional complexity of the design option.

ix) Future weapon design study (2010)

This design study explored, using data in the public domain, an appropriate configuration of a large combatant able to deploy future directed energy weapons (DEW). Given the ship fit challenges posed by such a large-scale weapon systems, again, a DBB based synthesis approach for both mono-hulled and trimaran variants produced proved essential (Andrews, et al, 2010).

Figure 19: A mono-hulled variant of a future DEW armed combatant (Andrews, et al, 2010)

6.3 HOW DESIGNING "INSIDE-OUT" HAS ALREADY EXPANDED THE SCOPE OF ESSD – UCL SHIP DESIGN INVESTIGATIONS

i) Design for production (2002-5)

This investigation (funded by UK Department of Trade and Industry) considered, for both a North Sea Offshore Support Vessel and a Corvette proposal produced by industry, how, as part of the concept design, exploring the internal layout and major equipment placement could reduce the outfitting task. The Paramarine-SURFCON models could explore major rearrangements in initial concept design while allowing the ship size and overall configuration to be altered to make such alternative Design for Production improvements. Figure 20 shows a radical SWATH option of the Corvette (adopted for seakeeping) exhibited a very rectilinear form which could then simplify arrangements for producability (Andrews et al, 2005).

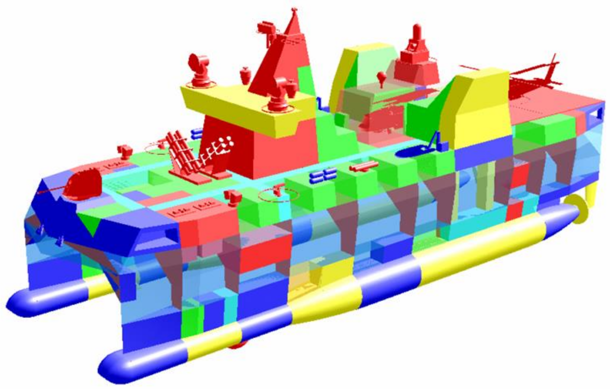


Figure 20: Typical SURFCON Representation of DfProduction study of a SWATH corvette (Andrews et al, 2005)

ii) Personnel movement investigation (2004-8)

This major investigation (funded by a UK Research Council) took a personnel evacuation simulation tool (i.e. University of Greenwich's maritime EXODUS) and integrated it with the Paramarine-SURFCON ship design tool to investigate operational movement evolutions on a Type 22 Frigate (see Figure 21). In particular the logic of passageway arrangements for MoD specified evolutions (such as evacuation and evolutions by NBCD teams) were investigated (Andrews et al, 2008). This is seen as another example of how an architectural based approach to ESSD can enable issues requiring architectural features to be given early prominence in design choice, well before a specific ship design is selected. Early architectural definition is also seen as key to better Human Factors recognition in future Simulation Based Design incorporating graphical representation of the results of complex simulation, as exampled in Figure 22 (Andrews, 2006).

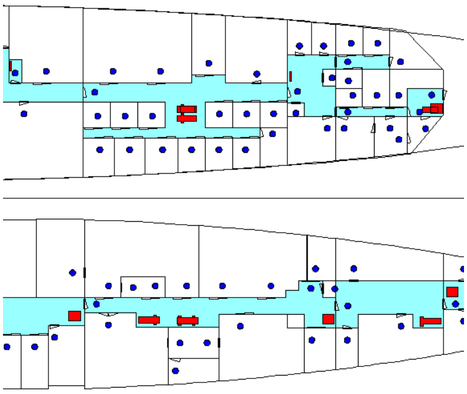


Figure 21: Typical SURFCON Representation of a Type 22 Frigate for Personnel Movement Investigation (Andrews et al, 2008)

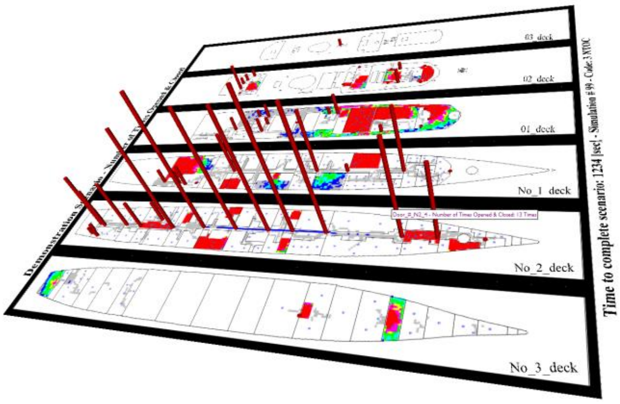


Figure 22: Example Representation of outcome of Personnel Movement data to Enhance Internal Configuration of a Frigate (Andrews, 2006)

iii) Design of topside (2010-14)

Following an earlier use of architectural modelling to consider all of the myriad conflicts in the topside design of a frigate (Andrews and Bayliss, 1998), a study for the UK MoD Naval Design Partnership (NDP) focussed on EMI and EMC for a combatant's topside. This numerical and architectural modelling was then validated both by physical modelling of a Type 22 Frigate and by being applied to an early NDP concept study to test out the approach applied to that level of topside definition (see Figure 23) (Gharib et al, 2016).

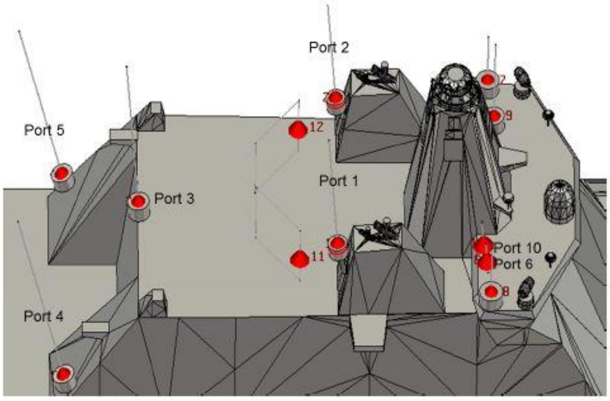


Figure 23: Example of Topside Modelling of an NDP Frigate Study (Gharib et al, 2016)

iv) IFEP Ship and Machinery Study (2003-04)

This was a UCL internal study to test out the degree to which adoption of IFEP could open up naval combatant layout choices. The DBB approach produced balanced designs for an AAD destroyer with progressively more novel electrical powering features to identify the whole ship impact. Thus potentially removing the "tyranny of the shaft line" could open up the choice of internal compartment disposition but only if the machinery plant was sufficiently unitised (see Figure 24) (Andrews et al, 2004).

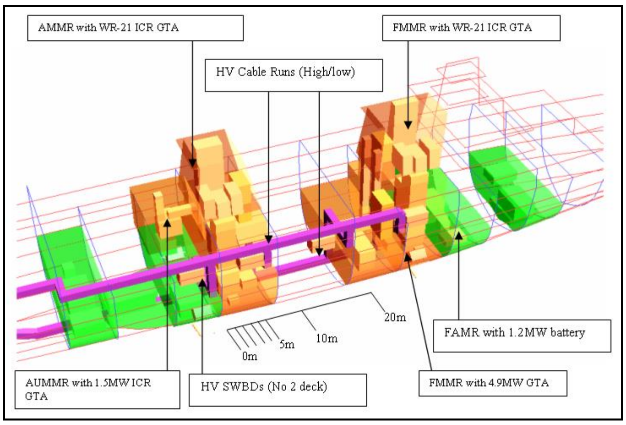


Figure 24: An Example of an IFEP Investigation for a Nominal AAD Destroyer (Andrews et al, 2004)

v) D for Survivability (2009-13)

This was a comprehensive investigation for UK MoD Dstl, which not only addressed the combination of the three component elements of Survivability (i.e. Susceptibility, Vulnerability and Recoverability), rather than the ship designer's traditional focus on Vulnerability (Manley, 2008) but also particularly explored Recovery, which was possible given an early architectural (DBB) definition. The investigation not only considered the classic frigate Survivability response but also explored two ship design style variants (small superstructure and trimaran) as well as size variants (light frigate and large destroyer) plus two variants of naval auxiliary design in order to test out the integrated approach to Survivability (Piperakis & Andrews, 2014). The use of the DBB approach enabled a comprehensive comparative measure of the Survivability of the significantly different designs (see Figure 25).

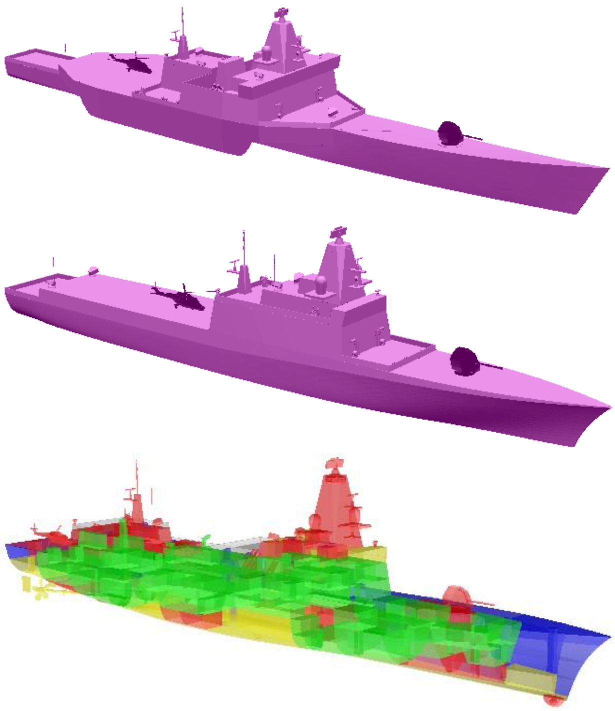


Figure 25: Example of a set of comparative ESSD Frigate Studies on Survivability (Piperakis and Andrews, 2014)

vi) D for UXVs Mothersub/SSHN/Fleet (2011-16)

An investigation of a future nuclear powered submarine concept (designated a SSHN for "Host") for carrying a large number and several sizes of UUVs as the primary combat system, was undertaken for Babcock International (Purton at al, 2015). This drew on Operational Analysis of a network of UUVs deployed from a large submarine. The study led to producing a nominal Pareto Front representation of a large number of possible submarine solutions, which were then refined by a "packing" tool and basic naval architectural balance checks on selected options to achieve a balanced PF with a few designs worthy of detailed consideration (see Figure 26). Again recourse to a 3-D internal layout enabled believable concept investigations to be produced, refined from a very large number of purely numerically synthesised "nominal designs".

vii) D for Support (2013-18)

This on-going study with support from BAE Systems is looking at whether early consideration of certain features in a combatant could be investigated very early in the concept phase (see Figure 27 for study overview). Aspects such as removal routes, which can only be realistically taken into account by an architecturally based synthesis, are being pursued (Esbati et al, 2015), using a simplified UCL developed DBB ship design tool (see Figure 28).

viii) D for Layout (2010-2015) and D for Distributed Systems (2015-20)

A multi-centred research programme, with the University of Michigan, the Technical University of Delft and (since 2015) Virginia Tech has been looking at how different versions of incorporating the architectural approach to ESSD could be compared. The UCL contribution has included a new simplified layout tool based on the Excel tool, see Figure 28 (Pawling et al, 2015). The second phase of this collaborative work has turned modelling distributed ship systems due to the likely demands to the supply very intense powers to future ship based weapons (see Figure 29 from Brefort et al (2017)).

The conclusion from the large number of DBB based research investigations by UCL is that many aspects, traditionally unable to be addressed in ESSD, can now be considered, albeit at a broad level, through the architectural approach to ship synthesis. Given the wide range of aspects presented above, this is considered to indicate a significant additional design facility, which could markedly improve the scope of concept level decision-making. However, many of the UCL (PhD based) investigations, for academic purposes, have had to focus on "proof of concept" in the application of the DBB based design syntheses. Thus it is seen that further work is required:-

a) these studies need to be followed up after their PhD based investigations by more applied research led by industry;
b) further scrutiny of these concept studies of the various topics presented need to be extended to include both operational analyses and through life costings, together with the application of a formal safety regime, if the worth of investigating such issues very early in design is to be accepted as Value for Money (VFM) beyond academia;
c) while these studies are predicated on the naval architect being best placed to undertake such ship design studies, future education of the profession will require new skills, particularly those that need to adequately address the human factors sub-disciples (Broadbent, 1988).

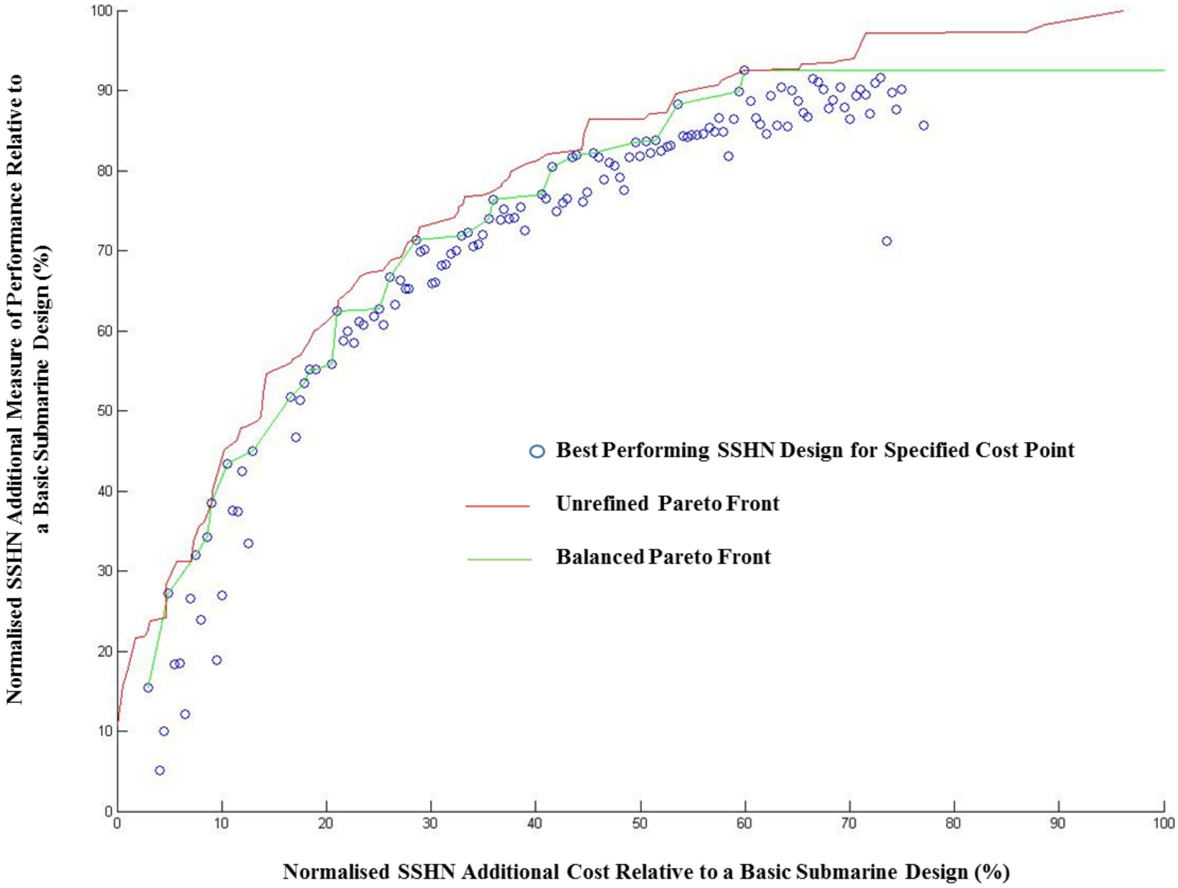


Figure 26: Balanced Pareto Front for a Submarine Mothership Study (Purton and Andrews, 2015)

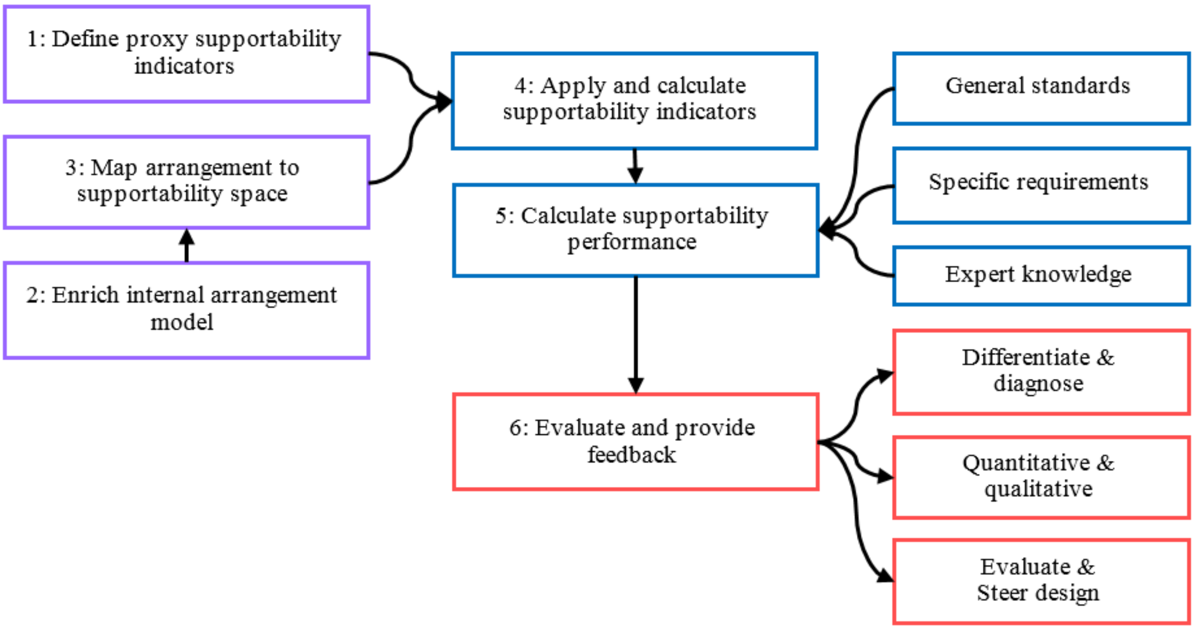


Figure 27: ESSD Study Investigating Design for Support (Pawling et al, 2017b)

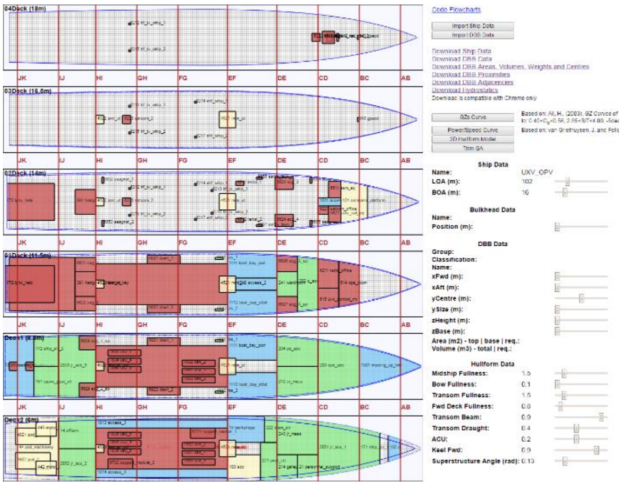


Figure 28: Deck Plans of a typical ESSD model in the UCL Layout tool (Pawling et al, 2015)

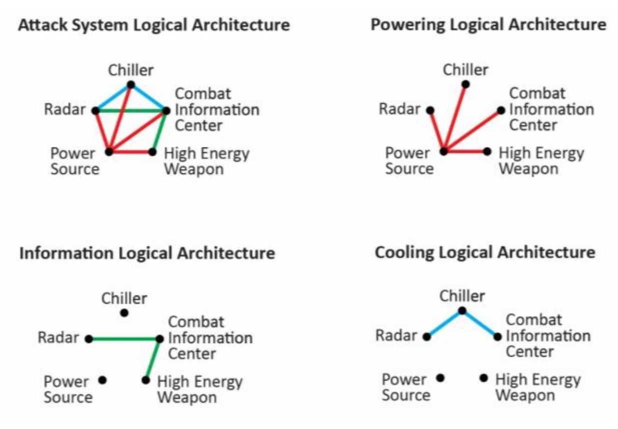


Figure 29: ESSD Exploring Vulnerability of Distributed Systems in Naval Combatant Design (Brefort et al, 2017)

7. PROPOSED SHIP DESIGN APPROACH FOR COMPLEX VESSELS

7.1 BROAD OUTINE FOR AN EXAMPLE NAVAL COMBATANT

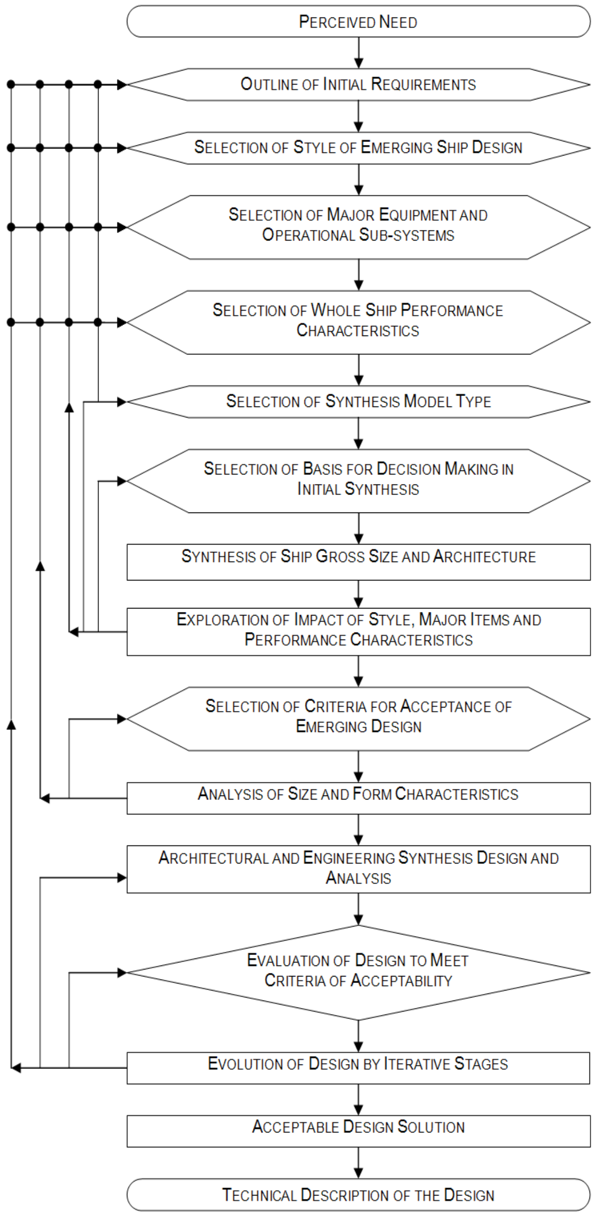
Having gone through the earliest stages of a new design process, as outlined in the first three steps of Figure 4, what now needs to be considered is how a given design option, within the overall solution space to be explored, is then produced. This is assuming such an option is just one of the many explorations in the solution space shown representatively in Figure 8. If that option is also a relatively sophisticated but not a highly radical solution (as in the last two categories of Table 3), then the likely sequence in the technical synthesis of this design option would follow steps somewhat like those in Table 4. This assumes an architecturally based approach as this author has strongly proposed. This can be summarised as follows for an option with a given set of (necessarily preliminary) requirements:

a) Select the relevant (macro) Style and key style aspects (see Table 1) (or at least the key ship type/novelty and overall design style issues necessary to progress ESSD);
b) Select an appropriate range of each of the following to be explored: payload items (including appropriate "uncertainty" (Design) and "future" (Board) margins, speed, endurance (and endurance speed or operating profile), days endurance, survivability philosophy, "design life" (Design Point at which design criteria (e.g. S^4) are still met), breakdown of complement and accommodation berths plus commissariat facilities and assumed standards;
c) Confirm where this option is on the "Novelty Spectrum" (Table 3) to select the basis of the synthesis;
d) Confirm whether the configuration has any novel features (e.g. large hull and small superstructure – see for example Figure 25).

Andrews and Pawling (2008) presented a specific example in considerable detail. That shows the four main synthesis steps of Table 4 with the intermediate "designs" shown diagrammatically in Figure 7. This was a design option for a selected style/configuration (a trimaran) to achieve a particular putative requirement set and specific set of major styles choices and so did not encompass a full set of ship concept explorations (see Figure 8). Figure 30, by giving an example as to how one design option would progress through the Concept Phase, tries to provide an indication of a range of various explorations that should be undertaken in meeting the decision-making approach of Figure 4. Just like so many process sequences, it cannot show all the interactions that go on with the mass of stakeholders, which often upset such apparently systematic logics as this or, even, the (hopefully) regular dialogue with the (naval) staff or requirements owners (noting in this instance no proper Requirements Elucidation occurred.)

Beyond the above decision process for a given design option (and minor variants of certain ship drivers, such as top speed, endurance, payload and helicopter fit, and complement), the exploration of the packaging, technology and capability solution space (Figure 8) should be extensive. This would test out the initial requirement set for robustness and search beyond (initial) cost minimisation. If as has been argued, the synthesis being performed for each option type (see Figure 8 and macro-style choices) should be architecturally based (as outlined in Section 6.1), then the process would be a series of sequential examples progressed down the middle portion of the right hand side of Figure 30.

PROCESS



EXAMPLE

A Future Combatant

Helicopter(s), Towed Array, Land attack, single ship communications fit, etc.
Macro Level: Conventional mono-hull
Main Level: Current practice – Table 1

Propulsion: IFEP, Systems: Standard redundancy + Zoning

S^4 (really Stability + top speed/endurance) + Some specific Style sub-elements/standards

DBB approach using Paramarine i.e. example in Section 6.1

UPC while meeting simple balance criteria (Stability informed by DBB derived KG + top speed/endurance)

Actual synthesis summarised by Section 6.1

See note below

This is not just cost but also the relevant ship and engineering aspects, especially mission specific aspects

This depends on how far this option is to be taken – it is likely only one or two options proceed further

The extent of layout work up and interaction with engineering analysis will depend on both apparent design drivers and the level of engineering assurance required for Feasibility and beyond

Evaluation should now be extensive and associated with emerging detail, such as structural approval and eventual safety assurance.

The last three boxes describe the total ship design process well beyond concept design of the chosen option.

Figure 30: A partial representation of ESSD for complex vessel in support of Requirement Elucidation with example steps

Note to Step 9: Exploration would be limited for a given design option to exploring a narrow range of performance and payload variations. The fuller exploration, following a Figure 8 like exploration with a wide extent of design choices, is dependant on the design process novelty level applicable to the relevant options (see Section 5).

7.2 SUMMARY OUTLINE OF AN ARCHITECTURALLY BASED SYNTHESIS EMPHASISING THE DECISION DRIVERS

Table 6 summaries the architectural synthesis of the new design option outlined in general in Section 6.1, progressing through the steps shown in Table 4. This was for the specific (trimaran frigate) example summarised in Figure 10 and Table 5 and so Table 6 provides the detail on the specific main design decisions actually made in order to progress the three first steps for this example following the DBB approach.

As Table 6 indicates (and is spelt out in more detail in Andrews and Pawling (2006)) several drivers and significant interactions in the design were observed

Table 6: A Summary of the key decisions made in order to progress each step in the architecturally driven synthesis of a UCL Trimaran Study (Andrews and Pawling, 2006)

Number of DBB	18 (in 11 discrete SBBs and grouped BBs)
Displacement	2830te
Enclosed Volume	14100m^3 (Required) 15300m^3 (Available – includes voids)
Length, main hull, waterline	126.2m
Major Decisions	
18 basic SBB placed to generate the design. Overall configuration established Strong interaction between FIGHT and MOVE groups identified CIC initially placed forward Split GT Main Machinery Rooms amidships Decks placed Hull length corresponding to estimated displacement greater than required for layout alone Approximate side hull configuration defined	

Number of DBB	47 (in 15 discrete SBBs and grouped BBs)
Displacement	2900te
Enclosed Volume	21000m^3 (R) 24000 m^3 (A)
Length, main hull, waterline	135m
Major Decisions	
46 SBB placed to be confident in the design Fuel tanks placed Initial Auxiliary Machinery Rooms placed forward and aft Hull lengthened due to increased displacement Cruise pods placed amidships Waterjet configuration changed to a row of 4 smaller jets Bulkheads placed based on configuration	

Number of DBB	110 (in 33 discrete SBBs and grouped BBs)
Displacement	3100te
Enclosed Volume	18913m^3 (R) 22700m^3 (A)
Length, main hull, waterline	135m
Major Decisions	
Both main GTs moved to a single MMR Defined cruise GTA machinery spaces Moved cruise pods aft of midships Waterjets changed to final staggered configuration Position of main items in all SBB defined Accommodation placed as 6 large blocks Possible conflict between cruise GTA ducting and superstructure identified Side hull dimensions defined	

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 or a similar architecturally based synthesis tool.

The initial layout in the Major Feature Design Stage 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 waterjets positioned at the transom and led to selecting the staggered waterjet arrangement (see Figure 14 of Andrews and Pawling (2006)). The MOVE and FIGHT groups also interacted due to the large ducting for the propulsion gas turbines, which restricted the position of the hangar and drove the flight deck to be positioned at 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's height from the waterline under the after end of the box structure.

Although the payload requirements played a key role in generating the initial design, the high-speed requirement (i.e. 40 knots) had more influence on the ship configuration and the selection of ship equipment than the mission payload. In addition to the interaction with the FIGHT group, the long and narrow hull required for this high speed led to large voids forward and the four waterjet shaft lines aft occupying most of the hull aft, which could otherwise have been used for stores, tanks or support spaces. The need to minimise resistance at high speed also led to the adoption of several advanced lightweight technologies, such as composite secondary structures and shafting, as well as notational advanced cycle gas turbines for low speed propulsion. Design and growth margins were reduced relative to current combatants practice because of the additional propulsion power demands these margins would have entailed. This increased the perceived 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 led to a ballasting system to compensate for the usage of fuel, stores and weapons by the end of the littoral warfare mission scenario. 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 study time available. Further detailed comments on this UCL Trimaran LCS study are made in Andrews and Pawling (2006), which also details the (final) Stage 4 balanced concept design. This LCS study could be seen as a very detailed concept design and as such is consistent with the remarks in Section 4 that only one or two design options should emerge from the concept exploration stage. However, the example on the right hand side of Figure 30 should be seen as an option that would, in general, contribute as one of a fuller set of design options, as outlined by Figure 8 and Chapter 4, if one was properly exploring options and elucidating requirements, given the latter were fixed in the LCS study.

7.3 THE PROBLEM OF OPTION OVERLOAD

Thus if we consider the number of variants of each option required to explore the perceived critical style aspects and "payload" and ship characteristics needed to be investigated for each and every likely technology solution (such as unconventional or novel configurations or major style choices, such as commercial or "utility" styles) then an adequately conducted concept exploration (plus a range of specific Concept Studies – see Section 4.2) the task in the concept phase might be seen to be excessive. However, the current outline states the generality, whereas actual ship programmes from early on often have a clear focus imposed by the requirements team or, too often very senior management. What is being argued here is that the option consideration/exploration is usually too readily made to converge and then fails to remain sufficiently divergent to ensure potential winning options or requirement insights have been adequately considered.

However there is a further issue of a mass of design alternatives. Most concept or synthesis tools or data bases are relatively simplistic (see Figure 5) and are readily automated to produce a vast number of seemingly comprehensive options. These can then be placed in a Pareto Front (PF) plot (see discussion in Section 9.4). However this then raises the question as to whether the performance measure (often called Measure of Effectiveness or Performance), which is plotted against cost (often crudely initial procurement cost of the ship and installed combat equipment) is really no more than (possibly arbitrarily weighted) summing up a lot of capabilities. The latter usually consist of a mix of both operational and ship performance features. Thus one is really just plotting more capability against more cost, plotted in a vain hope there is a "knee in the curve". Furthermore the choice of design may be made from a set of scenarios, reflecting current operational concerns, which are then used in assessing the operational capability of a multi-role, highly adaptable, system of systems to be used in unforeseen scenarios for several decades into the future.

There are of course examples where the PF approach has been useful as guidance on requirement elucidation and also where the production of many design options (to the same requirement) has been plausible. Several examples with which the author has had some involvement are by Burger and Horner (2011), Duchateau (2016) and Purton (2015). Briefly the first describes the use of ModeFrontier to modify PF investigation of what became the UK MARS Tanker requirement. The second used van Oers (2012) Packing approach, which produces a large number of different DBB like ship design options, but then imposes limitations on the locations of critical compartments to reduce the large number of options down to an acceptable number. Purton, while addressing the complex problem of a nuclear powered submarine UUV "mothership", used a PF plot, which was then interrogated at the "knee of the curve" and by a different "packing approach" to that of van Oers found a lower "balanced PF" of naval architecturally balanced solutions (see Figure 26). It can be seen from these explorations that the issue of synthesising new ship options to inform requirement elucidation is both complex and far from the automated process, which simple spread sheet sizing approaches might suggest.

8. OTHER COMPLEX VESSELS BEYOND THE NAVAL COMBATANT

8.1 NAVAL VESSELS OTHER THAN COMBATANTS

Although combatants (i.e. frigates, destroyers and cruisers) are the most common ocean going warships, designed on a regular basis, a surprisingly large number of different types of other naval vessels are also designed on a somewhat less regular basis with regard to each type but taken as a whole are regularly acquired. This wide variety of vessel types ranges from the aircraft carrier and nuclear submarine at the very top of the scale of complexity and price, through a set of amphibious warfare vessels, some of which are comparable with medium size aircraft carriers, down to small and very fast coastal craft some of which are carried by Landing Platform Docks (LPDs), and a series of specialist vessels. The latter include hydrographic research vessels and training ships, plus a lot of auxiliary vessels, such as afloat supply vessels and support ships. Sometimes auxiliaries are procured through extensive conversions of commercial ships or appear to be modifications of commercial cargo carrying vessels. Now, while this can be the case (see RFA ARGUS in Section 2.1), very often the attractiveness of such "conversions" is deceptive. Thus naval fleet tankers may look somewhat like commercial oil tankers but are much faster and require Replenishment at Sea (RAS) rigs as well as military features, such as flight decks, maintenance hangars and air-weapon magazines for military helicopters, which makes their designs far from their commercial cousins.

The issue then arises as to whether the extensive design approach outlined so far in this paper is applicable to all these multifarious ship types. Two specific examples of novel hull configuration outlined in the two last categories of Section 5.6 are considered in more depth in the next two sub-sections, followed by the very special case of submarine concept design. Aside from those cases of extreme design novelty, most of the other naval vessels can be considered to be what the author has termed "configuration driven designs" (Andrews, 2003b). This term certainly applies to all sizes of aircraft carriers and large amphibious ships, as well as most auxiliaries, in an analogous manner to that required to derive the physical description of a passenger, cruise or ferry ship which commences with the arrangement of the public spaces and cabins (Levander, 2003). Similarly the configuration of large naval vessels, such as aircraft carriers and amphibious warfare vessels, are driven by the spaces required to accommodate the primary "cargo", whether that is accommodated in the hangar and on the flight deck or the well dock and vehicles decks in those specific cases. A prime example of how this drives such designs was shown for the INVINCIBLE Class carriers (Honnor and Andrews, 1982) in a diagram reproduced at Figure 31. This schematically indicates personnel routes, equipment removal routes and stores routes around and directly below the primary decks, i.e. the flight deck and

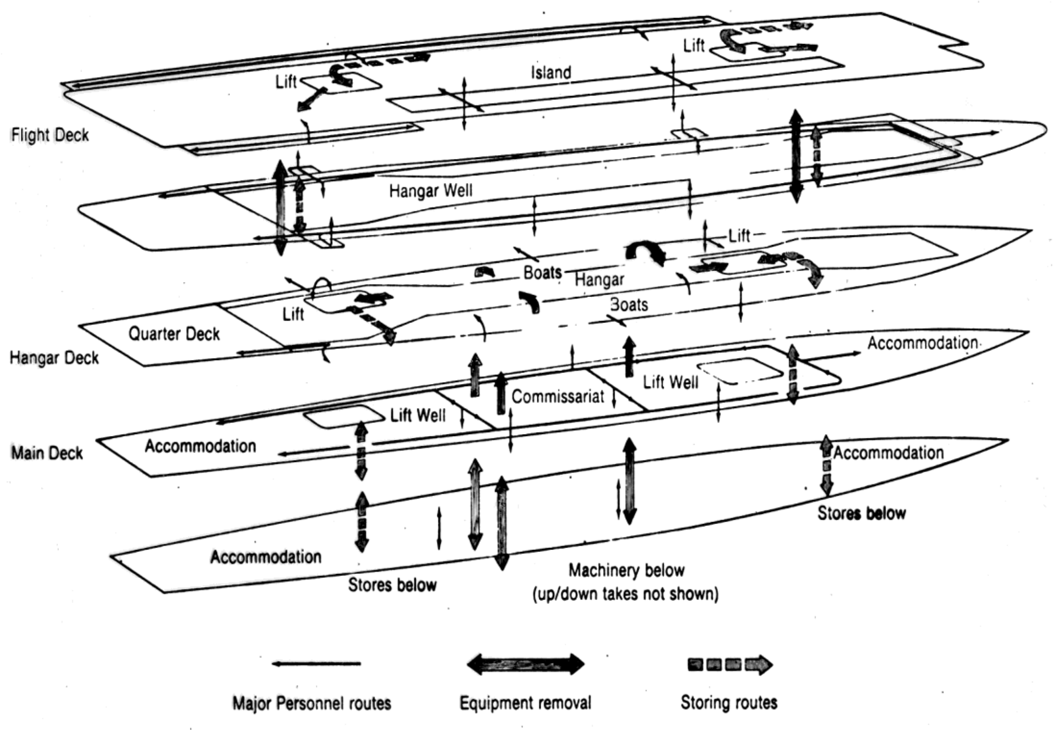


Figure 31: Schematic of INVINCIBLE Class Key Internal Arrangement showing the main flow paths (Honnor and Andrews, 1982)

hangar deck. The INVINCIBLE paper discussed the need for access from the main through deck, below the hangar, and around the side of the hangar, taking into account the other needs for machinery inlets, outlets and removal routes, as well as features such as boat arrangements and ventilation, but omitting details of further military features. A similar logic can be said to drive the design of the US Navy LHA assault ships as shown in a 3-D diagram in the paper by Leopold and Reuter (1971) showing both helicopter and landing craft loading routes. Once these key configurational features, which are best facilitated by an architectural approach on the lines of Chapter 6, have been sized the rest of the ship synthesis follows somewhat directly.

There are currently few oceangoing high-speed vessels, as a consequence of the wave making Froude effect (Andrews, 2016). However as this paper ought to also consider the future scope of approaches to ship design, it is worth briefly addressing the issue of designing large very fast vessels. It could even be argued some semi high-speed oceangoing vessels have been produced; the obvious recent example being the, problem riven, US Navy Littoral Combatant Ships (LCS) (in both its fast trimaran and semi-planing mono-hull variants (Warship Technology, 2016)). Part of the problem with these vessels could be seen in trying to extrapolate to an ocean going naval capability, technologies only current exploitable in smaller fast coastal vessels. Thus these nominally 3,000 tonne designs are intended to operate "in the littoral" at up to 50 knots, which has required not just high powered jet engines (gas turbines) and state of the art water jet propulsors, but also very thin steel (in the LCS mono-hull variant) or aluminium (in the LCS trimaran variant). However the latter structure has to resist the classic deep ocean wave loadings of a hull girder bending nature, with a material both lacking sufficient Young's Modulus and with a fatigue life much less than that of steel. The extent to which there would need to be a major investment, in both very high-speed propulsion and ship appropriate structural material development for much larger very fast vessels, was starkly spelt out by Keane (2003). This drew on the considerable pre-concept research investigations that had then been recently undertaken by the US Navy in its desire to project large land forces "From the Sea" at very high speeds (e.g. 80 knots) over intercontinental distances.

If the Section 5.6 category of radical configuration, rather than radical technology, is considered from a design point of view, design approaches vary in their specifics with the choice of the particular (largely multi-hulled) configuration. The reasons for adopting these various multi-hulls is usually due to an overriding operational need (like the relatively high speed of the LCS Trimaran) being better provided than it can be by the, usually, cheaper and, certainly, less risky conventional mono-hull. Thus lightweight catamarans are designed to achieve moderately high speeds, for short ferry routes, while the SWATH configuration gives much reduced ship motions for larger vessels in rough seas in deep ocean. Two distinct approaches to initial design are considered in more detail in the next two sub-sections, namely for the radical SWATH vessel and, perhaps, the less radical case of the Trimaran. These have been summarised from Andrews (2016).

8.2 THE INITIAL DESIGN OF SWATH VESSELS

The initial design procedure for a SWATH vessel is more complicated than for its conventional equivalent, as there are many more hull variables to be taken into account from the very beginning, in order to get a first estimate of ship size. This does have the advantage that that the geometry of each separate part, namely box structure, struts and hulls, can to some degree be considered separately, although they must then be sensibly brought together as their final selected dimensions are interactive with each other in achieving a balanced design. That complication is further compounded, as with all novel hull forms, by a basic lack of design data and, in particular, sufficient parametric guidance.

In initial sizing, individual space balances are required for the box and the struts plus hulls, with the latter usually containing the tankage, ballast, deep stores and some of the power and propulsion systems. As regards initial weight estimates, most weight groups can draw on mono-hull data. The main exception is the structural weight fraction for which the much higher value for, say, a SWATH naval combatant's steelwork weight to its deep displacement of 0.45 is a more appropriate start point. This is necessary because of the larger relative area of structural material and the dominant transverse structural prying loads (Kennell, 1992). This guidance obviously can be modified if there are clear reasons, from the beginning of the design, to depart from current SWATH practice, for example if greater loads are predicted or if configurational or material differences are intended or imposed.

Further guidance on the initial synthesis is that it is usually sufficient to initially determine the basic ship dimensions using the main underwater parameters and assume that there will be sufficient volume provided in the box structure above. However with a DBB approach, it is readily possible to block in the principal spaces in the box structure, which should avoid a subsequent "shoe-horning" or major rethink to achieve an acceptable box/struts/superstructure layout. Typically the proportion of displacement provided by the hulls relative to the submerged portion of the struts will be between 0.70 and 0.85. Below this range the struts become excessive with resistance penalties and degraded seakeeping, and above this range there will be insufficient waterplane leading to stability and trim plus sinkage problems. For the hulls the primary parameter is their Prismatic Coefficient (C_p), which is defined in terms of hull length and the average diameter. The latter becomes particularly necessary to adopt when the hulls have elliptical and varying cross sections. For low to medium speed forms, that is Froude Number $\leq$ 0.45, then C_p should be between 0.60 and 0.70, while for smaller higher speed craft (such as fast ferries operating at F_n >0.55) then $C_p \geq$ 0.90. The other very significant early design choice is that of box clearance, which is usually driven by the choice of the significant wave height in the maximum sea state for which slamming is to be avoided.

Thus initial sizing requires a greater degree of form parameter and dimension selection (preferably informed by a DBB synthesis) than in the mono-hull case to obtain even first estimates of size, volume and weight. Beyond that the form parameters exploration consists of a more detailed refinement of the initial form parameter selection. In particular, there needs to be an early check that the stability and trim requirements can be met. In consequence the parameter exploration has to tackle the hulls and struts first, before the box dimensions are selected. The latter will be driven by the separation of the struts and, to a lesser degree, by the hulls and struts lengths. Since an excessive overhang of the box structure would have both weight and centroid implications, which the parameter exploration would have to take into account, it is important to give particular attention to longitudinal balance from the start. Andrews (2004) lists a series of further design considerations, such as number of struts per hull, strut length and strut separation. All these aspects show the highly interactive nature of SWATH initial design, which is more akin to submarine sizing (see Section 8.4), with the need for similar care in weight and buoyancy/moment balance not so necessary for mono-hulled ships.

8.3 THE INITIAL DESIGN OF TRIMARAN SHIPS

Although the Trimaran is essentially a slender mono-hull, modified with the addition of side hulls, to initially size the vessel, it is necessary to determine practically all the principal form parameters. This is unlike the case of the conventional mono-hull, where it is possible to delay full parametric selection to beyond initial sizing, since there is a large historical database. This means the mono-hull designer can be reasonably confident that the initial default hull parameter values, adopted to size the option, will only need refining beyond the initial sizing.

Essentially the sizing and hull form selection for the Trimaran are in three interrelated parts, namely main hull, side hulls and cross deck structure:

- *Main Hull.* This is slender to achieve the low wave-making at speed and so the length to hull beam and hull beam to draught ratios should be initially selected to be 14 and 2.0, respectively, for a typical range of speeds and to use available mono-hull methodical series data for the powering estimation. Initial UCL frigate studies extrapolated Taylor-Gertler (1953) data slightly beyond the range of a typical current frigate form to fit the dimensions and chosen form parameters (C_m = 0.803, C_p = 0.581). This choice of parent form was appropriate for a twin shaft arrangement. Clearly the more radical adoption of single shaft or even podded propulsion would require further modification to the parent hull form. The other immediate issue is to check that the main hull (in combination with the cross structure and superstructure) has sufficient (useable) volume, which sensibly requires a DBB approach to explore early arrangement drivers. This is well illustrated by the evolution of the Trimaran example in Section 6.1.
- *Side Hulls.* The dimensions and form of the side hulls are essentially governed by overall stability considerations, while ensuring their impact on resistance (through their large wetted surface area relative to their displacement) and their contribution to structural weight are minimized. The side hulls provide the major contribution to the transverse righting moment and through them a high GM_T is easily achieved. The critical stability condition for a naval combatant would be the damage case with one side hull damaged with a breech of 0.15 x ship's waterline length, which represented flooding of (say) five adjacent compartments in the closely subdivided side hull. This extent of flooding implies flooding 50% of the side hull length, which typically means the side hulls' waterline length have to be just under 40% of the ship's waterline length, whereas in the case of a commercial ship it is unlikely that the side hulls would need to be quite so extensive and demanding on the design. There are other early issues, such as side hull location, which is driven partially by upper deck and internal deck layout drivers (see Andrews (2016)).
- *Cross Structure* The first decision on the cross deck structure is in regard its outboard length and whether it should be the same as that of the side hulls. The most critical parameter is that of wet deck clearance, which for a frigate size is suggested to be 3.5 m. based on the early analysis of symmetric motion seakeeping analysis described more fully in Andrews (2004). Effectively, this choice will drive the depth of the main hull to the upper weather deck, since Depth equals Draught + Wetdeck Clearance + Wetdeck "Double Bottom" structure + Main Deck to Upper Deck (assuming a single cross structure deck height). This consideration means the Trimaran is likely to have an overall excess of volume relative to its monohull equivalent. This could be considered a negative feature of Trimaran designs, since it might seem to imply that the designs are not strictly "balanced" solutions. However, it can be argued that because the excess is in the central portion of the ship high up on the main deck(s), it greatly increases the available "real estate" in the prime part of the

ship, which can then be facilitated by a DBB based layout exploration providing a better basis for parameter selection.

Should other applications than frigates be pursued using the Trimaran configuration, such as fast ferries, cruise liners or fast feeder route container ships or even large naval vessels (see Andrews and Bayliss, 1997 and Andrews, 2004), then the specific nature of the above guidance is likely to be less appropriate, although the sequence is considered to be broadly applicable. While such "radical" solutions tend to be resisted by industry (as being seen as higher risk than the ubiquitous mono-hull) such configurations are worth exploring in the Concept Exploration stage (and even beyond) as they can shine a querulous search light on the nascent requirements. Thus what might be seen to be a major size driver in a mono-hulled combatant, such as a second large helicopter, would just be incremental in an "equivalent" Trimaran. This demonstrates the inevitable interaction of requirement choices and concept solutions.

8.4 THE VERY SPECIAL CASE OF SUBMARINE CONCEPT DESIGN

A recent paper (Andrews 2017b) stated that "Submarine design was not ship design". This was done not just to point out how very critically tuned submarine designs are from their very commencement, due to the unique physics of operating neutrally buoyant at high speed in a narrow vertical plane. However that paper also points out that there can be severe consequences in inadequately conducting the concept phase, thus adding further emphasis to the current paper's argument.

Because it is dominated by interacting physical demands, producing a concept design study for a new submarine programme tends to go into far more detail than is usually considered necessary for a surface ship. However it is still characterised by the (implied) decision making process for the Concept Phase for complex ship design (Figure 4). Furthermore as Burcher and Rydill (1994) detail at their Figure 11.4 (see Figure 32), the synthesis of a new submarine study can be undertaken in a similar manner to that for an option for a naval surface combatant, however the latter is likely to be part of a much wider Concept Exploration investigation. Although this may seem very like surface ship initial design, the above comment on the level of detail in a submarine final concept design makes a considerable difference to the resources employed by the end of the submarine Concept Phase when the decision to proceed has to be made.

This greater level of detail is also necessary to ensure a sensible design balance. This must be done not just for vertical stability and powering, as for a surface ship concept, but importantly also longitudinal weight balance and adequate stability margins. These additional sensitivities could be said to really make submarine concept design distinct. The counter to this need for substantial detail is that the scope to explore the solution space widely is far less than that for even comparably expensive surface vessels. It is also possible, as Nordin (2015) has shown, that quite detailed design decision making can be driven by extensive operational analysis, provide the concept of operations (CONOPS) is tightly defined. Whether this is applicable for a much wider general sea control and littoral warfare vessel, that the post-Cold War SSN has become, is seen to be questionable. Furthermore, Nordin still recognised that going from function to a specific (Swedish) form, even with a precise set of OA senarios, still requires the designer to make a "style selection" of Figure 4, as is remarked in Section 2.2.

While submarine design might be considered a very evolutionary practice, given the highly constrained nature of the design, arising from the many aspects being tightly interrelated and the small margins for error, this conclusion is not that obvious. If one is to take a given successful design and assume it can be easily up dated, then there are a series of issues, several of which have been highlighted by Andrews (2017b), that mitigate against this. Thus only those systems and components that could be readily accommodated, on a one for one basis in space, weight, vertical and longitudinal location (for reasons explained in the 2017 paper in the section on Static Control) could be substituted for existing equipment in an extant design.

The 2017 paper considers UK nuclear submarine development to understand the issue of the degree to which a new submarine design can be a direct variant of a previous design and be regarded as an "evolutionary" design (as in Table 3). Although the UK followed US Navy design style initially, it produced a significant step change in design with the SWIFTSURE Class, arguably a more radical design step from the SKIPJACK parent design than occurred in their USN equivalents. The SWIFTSUREs were followed by the TRAFALGAR Class, which was a true variant or "evolutionary" design, with little change in most features and equipment and, it could be argued, was only achievable because the SWIFTSURE parent design had very generous margins built into that design. Providing such generous margins in the design of any vessel is rarely done and would need to be clearly provided in any potential parent's design philosophy and design specifics, right from the concept design. Even then other aspects, such as a seamless maintenance of the procurement and build programme from parent class to variant, as in that UK case, are probably required to minimise differences due to equipment obsolescence, changes in legislation, operational concepts, technology advances, etc.

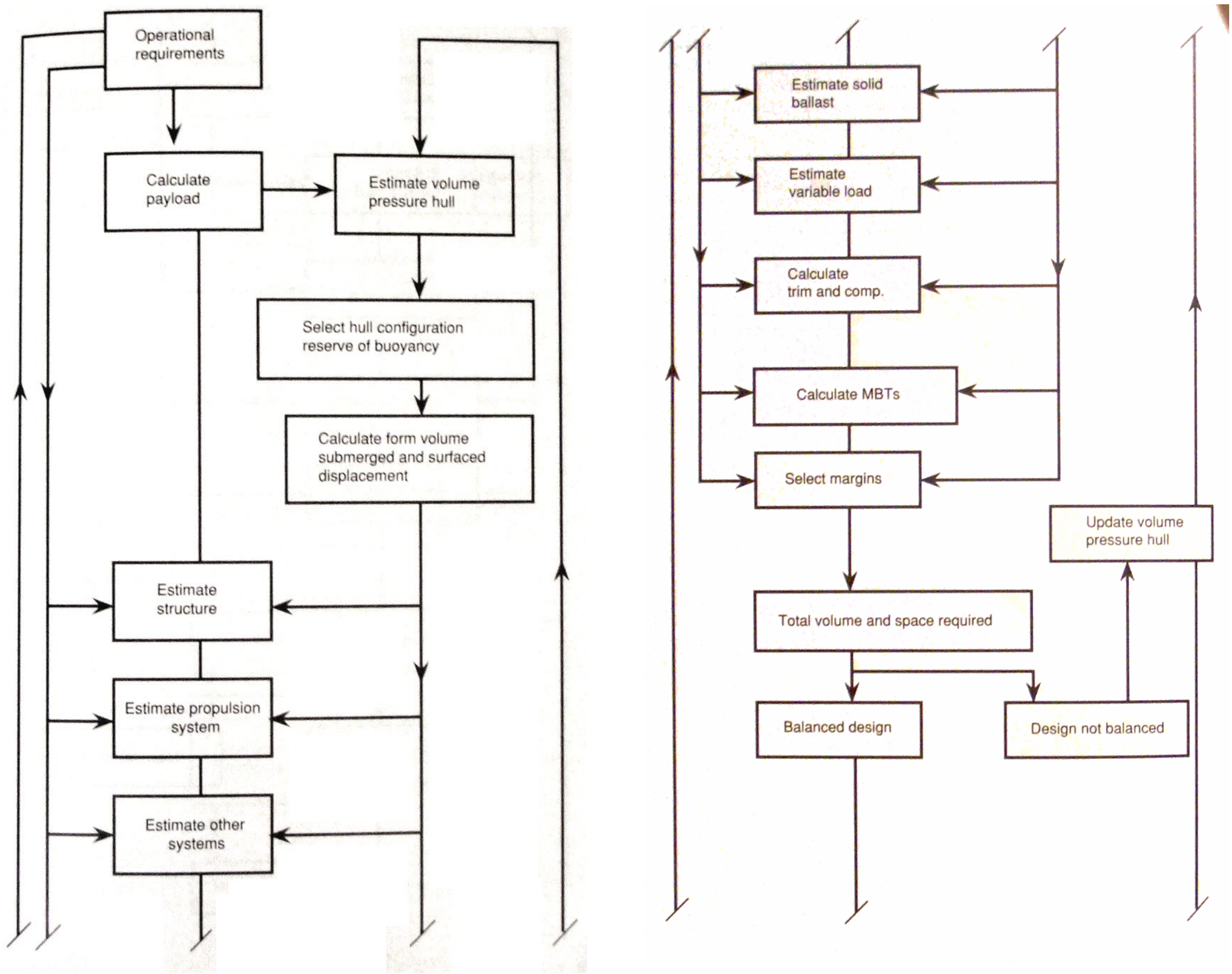


Figure 32. A pre-DBB approach to submarine synthesis (Burcher and Rydill, 1994)

Thus in considering the issue of an evolutionary design option, it should be appreciated that the choice is not analogous to surface ship design practice and, coupled with a likely generational gap in regard to obsolescence of equipment, the choice of a truly "evolved design" looks highly questionable. There may be some scope for, perhaps, some commonality in style choices to be adopted from a successful "parent", but even this should not be assumed. Keane & Tibbitts (2013) even caution the risks with "repeat" designs for surface naval combatants. Such issues would still need to be technically justified as being VFM against alternatives. What a "derivative" design will definitely not give a government is a cheaper, lower risk and less government resource intensive solution. The belief that it would be otherwise may well be the motivation by wider government authorities in seeing an "evolutionary design" or "variant" as an attractive option. If anything such a constraint on the design can be more awkward, more compromised, harder to prove for assurance, and end up being an even more risky and costly design than a bespoke, albeit largely "derivative", design. Despite being "evolutionary" TRAFALGAR still required a completely new design input and resource demands comparable to its "parent (SWIFTSURE) design". So, even for surface combatants, an evolutionary design is not likely to be the route to achieving programme cost savings and is likely to add risk, arising from the mistaken belief that reduced effort could be employed – it could be a recipe for dangerously cutting corners. In the special case of submarine design, given it is a highly interrelated and unforgiving system of systems, the design process must be resourced properly. Furthermore, the inherent sensitivity of submarine design requires each new design to be led by experienced submarine design professionals, who are in short supply.

9. NEW TECHNIQUES WILL ALTER EARLY SHIP DESIGN

9.1 THE NEED TO CONSIDER NEW TECHNIQUES IN SHIP CONCEPT DESIGN

Several decades ago Gallin (1973) stated: “ship design without the computer was no longer imaginable”. Future progress in the practice of the concept design of ships will, in large measure, arise from developments in computer technology, but also from what, in that ever-burgeoning domain, practitioners decide to adopt. Nowachi (2009) in a wide-ranging review of marine design methodology started with identifying the goals in computer technology, which had been “dreamt” of back in 1968. He saw a crucial issue to be that of man-machine interaction and that to be two-fold: assisting in problem formulation, which has been identified in initial ship design as that of requirement elucidation (Andrews 2011), and strategic decisions, which can be taken to be better decision making in regard to design choices. By 2009 Nowachi saw that many of the goals envisaged for CASD seemed to have been achieved but importantly, in highlighting man-machine interaction, he stated: “Human intervention should concentrate on creative problem formulation and critical review of results.” This can be seen as justifying a focus on judging the following summary review of recent developments in ship design methods and applications. This review is split into the need for further naval architectural analysis in ESSD, new techniques and then new processes to enhance ESSD, and finally future needs already discernable to provide better ESSD in the future.

9.2 THE ISSUE OF DEEPER NAVAL ARCHITECTURAL ANALYSES IN ESSD

With recent advances in computational tools, it is increasingly being argued that simulation based design is “replacing traditional experience-based design” (Fach et al, 2009). This has been particularly propounded by advocates of CFD for a range of issues, which not just address external flows but also look at highly non-linear global ship motions, aerodynamic and cavitating flows, as well as HVAC and fire simulation. In addition finite element methods are being extended beyond structural analysis so that the simulation of noise and of personnel evacuation are becoming routine. The question then arises as to how much should these increasing sophisticated methods and tools be integrated into ESSD, given the need to find the “right balance between level of detail and resources (required)” (Fach et al, 2009).

It has been argued that ever greater analysis of a given design at the earliest stages of the design will always be a good basis for taking the design into detailed development (Noblesse, 2010). It would give more confidence in the concept thereby reducing the risk to the project. However this is to miss the essentially different nature of ESSD for complex vessels, such as has been addressed particularly in Section 3 of the current paper. Given the aim of the Concept Phase is to elucidate what is required, not to “bottom out the preferred design”, then the approach to ever greater analytical facility in ESSD must be very focused. The best adage in response to “how much analysis is appropriate to a given concept design study?” is “as little as possible” – commensurate with the needs of Requirement Elucidation to tackle the “wicked problem”. Thus “useful analysis” is only appropriate in ESSD if it is directly germane to exploring the solution space in order to ensure a correct match of requirements, solutions, cost and risk (see Figure 6). Thus it may be that a particularly aspect, such as the damage stability of a novel multi-hulled naval tanker (see Appendix A, item l), might need detailed analysis well before the trade-off of a specific requirement, in order to ensure the baseline for those studies is sensible. But this does not mean that in that case there was any need for (say) detailed CFD analysis of the bulbous bow configuration during the concept design.

To the author the above argument is seen as important and, given the growing computational and systems integration techniques, concept ship designers need to cultivate an attitude of discipline in resisting using ever greater computational techniques “just because they can”. This issue in ESSD can be seen as a subset of a seed change that has occurred in engineering. We have moved from a discipline which said how do we tackle problems (with limited engineering science and computational skills) to now having to decide “what is it we want to tackle (at a given point in a design) and how do we use what is now possible to best answer our needs?” To use a hackneyed term, this is a paradigm shift that engineering designers have yet to fully absorb. It was also behind the motivation for the architectural emphasis in the author’s development of ESSD, which is now an accepted approach (Tupper 2013).

9.3 THE ISSUE OF NEW TECHNIQUES TO ENHANCE ESSD

Gaspar et al’s (2014) paper on data fusion describes a sophisticated exploitation of the Internet using data-driven documents (D3) in early stage ship design. The traditional ship breakdown structure with cost and subsystems elements can be variously encapsulated using tree layout, force layout, pack layout, sunburst layout and Sankey diagrams as analogous representations. The paper’s discussion focuses on how the proposed approach allows the designer to better interact with a conceptual ship design dataset, as well as facilitating better stakeholder engagement. However there is the clear question as to whether overlaying potentially simplistic initial sizing models with a veneer of extensive cloud data, is just a “super black box” approach. There is thus a need to have the equivalent of the interrogational feature in Expert Systems to show the impact of assumptions and the probabilistic validity of design options drawn from such amorphous large databases.

A series of doctoral students under Singer in the University of Michigan have explored the use of network theory to provide insights into ship arrangements (Gillespie, 2012), modelling disparate ship design information (Rigterink et al, 2014), the dynamic behaviour of ship design tools (Parker and Singer, 2015) and the (characteristic and fundamental) process of iteration in ship design (Shields et al, 2015). These applications of the mathematical construct outlined by Newman (2010) have greatly increased our descriptive understanding of the nature of ship design and the subtlety of the process for complex ships in particular, which can be said to have been trail blazed by MacCullum (1982). Research at UCL has built on that at Michigan, firstly, in the application exploring the whole ship implications of a novel propulsion in nuclear submarines (see Figure 1 from Collins et al (2015) and to UCL's post-graduate ship design procedure, ship layout knowledge and to analyse General Arrangements to assist in vulnerability analysis (see Figure 33 from Pawling et al. (2016)). Those authors caution that insightful though this on-going work has been to date:

a) while the most influencing and influenced nodes can be detected, the metrics only show their existence not their consequential impact;
b) the choice of network metrics may questionably influence the values obtained;
c) different decisions in representing a process will influence the resultant network.

9.4 THE ISSUE OF NEW PROCESSES TO ENHANCE ESSD

Nordin (2014) has produced a series of papers, published in various journals and at conferences, to explain in some detail the basis behind an integrated approach to the design of a series of Swedish conventional submarines. They draw on a large amount of classified data for the details of such specialist military vessels. While the submarine design aspects are spelt out in more depth in the companion paper "A functional approach to Systems Design of Submarines during the Early Phases" (Nordin, 2015), the 2014 paper gives the most comprehensive exposition on the application of military Operational Analysis (OA) as part of the early design "requirements elucidation" process for such complex vessels. The OA model used can evaluate requirements aggregated in synthesised initial design concepts (using in this case the Swedish "Play-cards" representations of the (so-called) functions domain) and establish their Measures of Capability (MoC) and Measure of Effectiveness (MoE). Details are given on the OA method, how an OA simulation model was produced for submarines in some ten mission cases, how these were linked to an "aggregated systems function structure", and how a planned operation profile could be decomposed (including a "tactical decision model") and then related to MoEs. Most usefully the MoEs for Surveillance & Reconnaissance and for anti-submarine missions are outlined (without revealing sensitive numerics). Finally, a "simulation example" is provided for "the Gotland raid" with ten alternative submarine designs and normalised OA results for MoE and MoC.

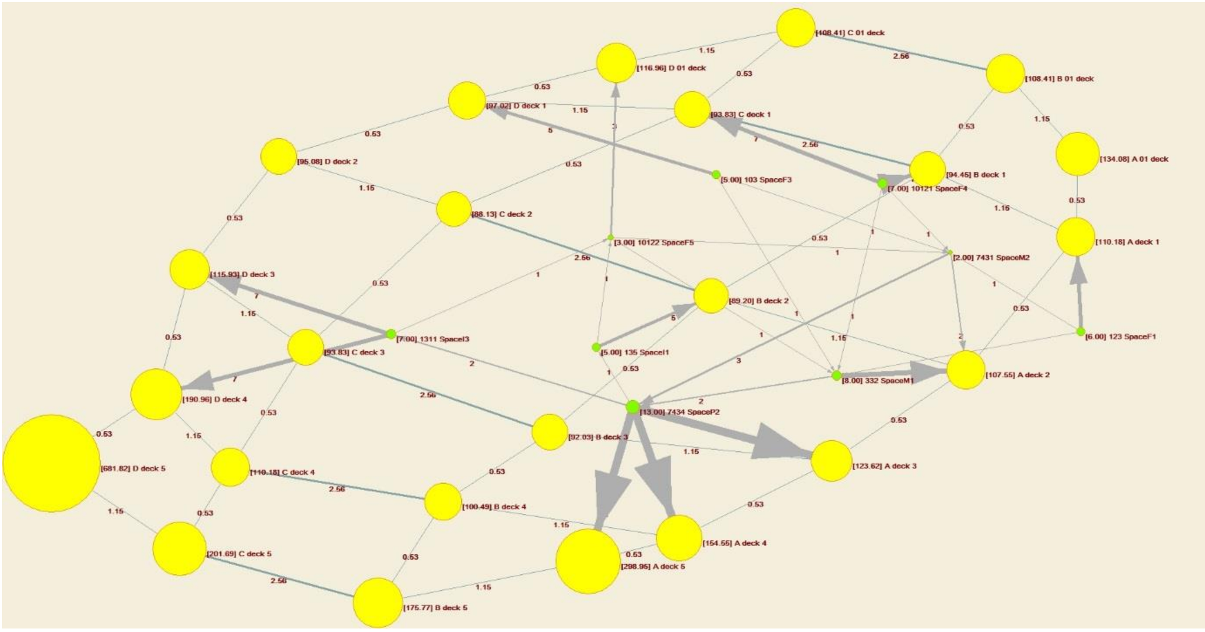


Figure 33: A Network representation of internal blast effects in a typical naval combatant (Pawling et al, 2016)

Nordin's exposition is very comprehensive in showing how OA can be integrated into the "requirements elucidation process" even if all the sensitive aspects (like signatures so critical to submarine design) can only be indicated. It might also be argued that the Swedish submarine constraints ease the decision and design (or "systems") space – to the extent that the apparently "functional design" approach (detailed further in several figures in the companion paper (Nordin, 2015)) actually require the "style" selection to achieve a matching of "functions with form". This recognition that there are philosophical issues in such complex ship design, with importance of acknowledging the designer's fundamental choice of the style of a new design concept, is seen as justifying the strong emphasis on style in Figure 4 and Section 2.2 of the current paper.

Driven by research originated by Singer (2003) at University of Michigan, the US Navy has adopted a Set Based Design philosophy for "Conceptual Ship Design". SBD is to be seen as a "Design method", which is defined by McKenney (2013) as "The way in which design alternatives are understood, analysed and selected" and to be distinguished from both design processes, which implement a method, and design tools which provide information for decision making. Importantly, SBD arrives at a design solution by a process of elimination rather than the traditional iteration. The SBD approach is outlined by Parker et al (2017) with the aim of "better early design decisions" for the very significant US Navy programme for the future US Navy Attack Submarine SSN(X). This does not seem far from the current author's requirement elucidation message for ESSD. SBD requires groups of domain experts to evaluate the design space "semi-autonomously", with each domain providing its evaluation in terms of "feasibility, dominance and preference". Thus SBD is not a specific design tool or detailed process but a philosophy (rather like the architectural approach or a systems approach, such as Systems Architecture (Andrews 2016)). Parker et al (2017) give detail on the SBD approach's characteristics and the issues to be addressed in its SSNX application across four primary domains:-

a) Capability concepts;
b) Technology concepts;
c) SSN concept design;
d) Programme assessments;

and thus encompass the sophistication which is the underlying message of the current paper.

By using Paramarine's naval architecture and DBB facilities, along with the data management capability of modeFRONTIER (www.esteco.com), Burger and Horner (2011) undertook what they describe as "a pre-concept phase" for the UK MoD project for a fleet tanker (designated MARS). However to this author this appears to have been a classic case of requirements elucidation, as outlined in Section 3.5 and leading on to the Concept Design step (see Figure 7). Thus it consists of "design space exploration" to inform an affordable requirement set, albeit not as extensive an exploration as that which should be undertaken according to the current paper (see Figure 8). Their exploration was limited to a narrow range of "capability variables" and "design variables" to be explored to a specific design style – that based on existing RFA fleet tankers. Those input variables, required by modeFRONTIER's optimisation process, were obtained from a Design of Experiments approach, with the tool using a genetic algorithm to output specific "design constraints" and three minimising "design objectives" (i.e. cost, fuel and "unusable space"). The tool also used Paramarine to deal with the balancing of stability, powering and sufficient volume, with the latter informed by the Paramarine module SURFCON to ensure a coherent "basic 3-D layout model". Burger and Horner suggest this mix of ship synthesis optimisation and a layout DBB check could be further developed, with some seven areas of improvement, so that the development would be able to:-

a) explore the design space for a given capability;
b) identify implications on cost (initial and through life) of different capabilities;
c) enable informed design decisions for the completion of the concept phase.

All of these seem consistent with the message of the current paper in arguing for recognition of the inherent sophistication of ESSD for complex vessels.

Gaspar (2013) in a series of papers applies the M.I.T. developed Epoch-Era Analysis (EEA) approach to the marine domain and specifically the offshore support vessel design task, where there is no simple measure of merit, like Required Freight Rate. Given that the requirement for such non-transport or service vessels is liable to future market and contractual uncertainties, this approach is said to widen the design environment for complex vessel design. Thus the traditional "structural" and "behavioural" aspects are added to "temporal", "contextual" and perceptual" aspects (see Gaspar's Figure 2) in order to assess the performance of each alternative design. This is done for distinct "epochs" combined into many possible "eras", each representing a possible life cycle scenario for each vessel. Gaspar concludes that the EEA method in combination with the Trondheim Ship Design and Deployment Problem approach (SDDP) enable such temporal complexity to be tackled in a manageable modular manner.

9.5 FUTURE NEEDS – DESIGN SKETCHING AND A CLEAR PHILOSOPHY BOTH INTEGRAL TO FUTURE SHIP CONCEPT DESIGN

Alongside these developments in techniques applicable to the future needs for the concept design of complex ships, it is seen appropriate to consider two quite distinct but related topics. The first is that general and basic design activity of sketching and how it might be incorporated into design processes where the fundamental activity is via computer interaction with the human designer (HCI). Sketching can be seen as a technique employed by both designers of Physically Large and Complex (PL&C) systems, typified by the most novel and complex ships, and by architects of major buildings and urban structures. However, the HCI concepts implemented in advanced CAD tools for initial design have until now inhibited the use of an exploratory sketching approach. It has been questioned whether the historic approach by designers to use sketching for design exploration and communication of ideas can still be met by CAD based design (Pawling and Andrews, 2011b). Some outline proposals suggest a more responsive and innovative approach to the initial ship design, which would interface directly with the UCL DBB, architecturally based, approach (see Figure 34).

Turning, secondly, to philosophical considerations in the design of PL&C systems, Andrews et al (2006) drew the attention of the maritime engineering design community to: Horvath (2001) with his "gnoseology-oriented reasoning model" of the design research domains; Love's (2000) "Meta-theoretical structure for design theory"; and Galle's justification of the study of the philosophy of design being "helping, guiding, suggesting how the [designer] comes to understand what he is doing and not simply how he comes to do what he is doing" (Galle 2002). Many scientists and engineers find recourse to philosophical "musing" irrelevant, especially given a future of artificial intelligence (Rovelli, 2016). As a repost to that, Rovelli quotes Aristole's three reason as to "why philosophy is useful for practical endeavours":

1) Saying "Philosophy is dead" is reflecting on which methodology and conceptual framework is best for science (and by inference engineering);
2) Analysis of foundational philosophical concepts obviously influences science (and it can be argued also design practices – see below);
3) Philosophy is needed "when perplexities are greatest" and is a "vivid source of inspiration, ideas and critical theory".

The relevance of all this to complex ship design is that it questions the belief held by many engineers that extensive abstract functional analysis is required prior to any materially descriptive synthesis, a significant issue nailed on the head by Figure 8. The eminent US Navy designers Keane and Tibbitts (2013) reinforce this by saying: "a successful ship design starts with establishing the initial philosophy for the "new" design."

From a consideration of integrating simulation techniques into the initial design of physically large and complex (PL&C) systems, Andrews (2012a) addressed a philosophically centred set of issues, which were argued to be of current and future concern to practitioners in the field of general engineering design and, in particular, PL&C system design (including ship design). In summary:-

- How, at least for complex large products, can designers best synthesise a new design?
- How can future engineering designers maintain a healthy scepticism to avoid over reliance on quantification when not justified (e.g. excessive recourse to "optimisation")?
- Do engineers still have a mistaken belief in an outmoded Functionalist philosophy (i.e. Form DOES NOT follow Function)?
- How can it be ensured that computer based techniques enable designers to adequately tackle the integration task in complex design?
- With the advent of Simulation Based Design and Virtual Reality tools, how can engineering designers ensure that the key word in CAD remains "Aided" and does not become "Automatic"?

The author went on to consider the constituents of a philosophy of engineering design. Without being prescriptive and trying to reflect the creativity and sophistication of that practice, it was argued that the earliest stages of complex engineering design need a more inclusive approach to the computer aided practice of design. Thus the basis for the initial design synthesis of PL&C systems, as addressed in Section 6, should itself be a synthesis produced from the physical architecture of the artefact integrated with the traditional numerically based synthesis. This integration of architecture and physics is seen to foster a designer-led approach that is creative and holistic in engineering design terms. However, like most engineering practice, to produce such designs requires domain knowledge and experience. It is thus a challenge to ensure that the development of design tools for the early stages of the design of PL&C systems produces tools that truly assist the designer in dealing with complexity. This can then provide a more philosophically robust approach to complex design.

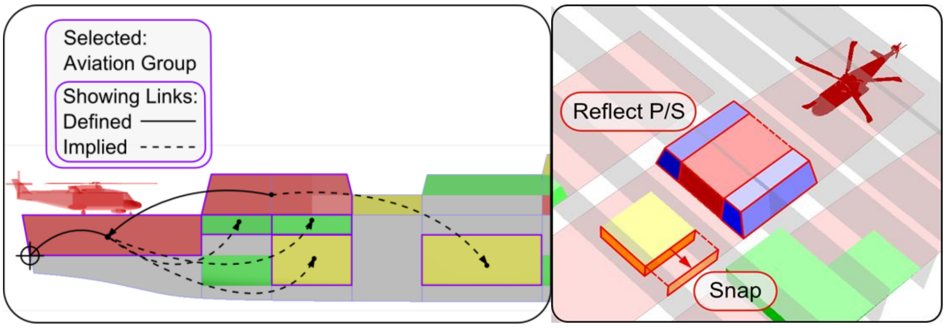


Figure 34. Two suggested techniques to assist in designer led "sketching" in ESSD (Pawling and Andrews, 2011b)

To conclude this specific overview of current high level research and applications of advanced approaches to ESSD it is worth re-stating that any such "improvements" to ESSD practice must:

1) enhance "Requirements Elucidation", especially addressing "Style" issues as widely as is appropriate;
2) be clear in their applicability;
3) and, if producing lots of "nominal design options", there is a need to ensure this is done for requirement and design elucidation insights - not just because it can be done.

10. CONCLUSIONS

"Design is a one-time process that can only add value when we do something different"
Reinertsen (1997) quoted by Keane and Tibbitts (2013)

The assertion in this paper's title is that ESSD is complex and sophisticated. It is considered that this it is inherently the case and can only get more demanding. Although argued for complex ships and particularly naval vessels there are already signs, due to developments such as Risk Based and Goal Based Design in merchant ship practice (Vassalos, 2012), that this will be case for the design of most ships in due course.

Strong support for the sophistication of ESSD comes from the most eminent naval ship designer in USA (Keane et al, 2016) who advocates more types of analyses to be done during "early design development" so that confidence is increased "that the design meets the requirements". However the author would argue further that this only partially recognises the view of this paper that the aim of any such analyses needs primarily to inform Requirement Elucidation and be consistent with the philosophy for the design of PL&C systems propounded by the author.

Adopting an architectural approach to ship synthesis could now be considered to be normal practice (if still not wholly adopted in industry) and has now been taken as read, in one of the latest naval architecture textbooks (Tupper 2013). The emphasis on the architectural or spatial key to design is also seen as right, even by computer scientists. Thus: "Having a visual, geometric representation of a design process is crucial, for designers are spatial thinkers" (Brooks, 2010) and furthermore, an architectural view is the basis of the preferred systems practice for the design of very complex software, namely, Systems Architecture (Maier (1998).

Part of good ESSD practice is the role of the naval staff or requirement (but not design) customers or owners, who must talk without any contractual barriers to the designers and so they have to recognise that concept ship design is sophisticated. The author has called for a return by the UK naval fraternity to the public debates on new ship designs that occurred in the late 19th Century and were colourfully captured in the RINA Transactions of that time (Andrews, 2013b).

There is a major consequence of both recognising ESSD sophistication and that the architectural approach opens up the scope of ship design. Both have as a consequence that naval architects need to be more adept and better trained in working alongside wider disciplines than just marine and combat system engineers. In particular naval architects will need to own the human factors facet if they are to be good whole ship system architects.

It needs to be said that although this is a very extensive paper, a lot of what an experienced ship designer brings to even a very standard concept ship design still has not been possible to outline. Seminal papers like Heather's ((1989) (on ostensibly fast naval craft but actually very much state of the art in naval ship design), Brown and Tupper's (1989) review of (naval) naval architecture and the US Navy equivalent by Reuter et al (1979) and the worked up designs summarised in Leopold & Reuter (1971), plus the comparative ship design studies by Ferreiro and Stonehouse (1993), all show elements of the naval ship designer's knowledge base that the concept designer very specifically draws upon.

One final remark is to recognise that most concept design studies are far less comprehensive than should be the practice, as is suggested by the arguments in this paper. This may be justifiable in some instances but it is more likely that a less than comprehensive process is undertaken and this usually occurs without justification or even realising a fuller process should be undertaken. Thus if, as is likely for complex ship design, the process being undertaken has underlying it the "wicked problem" of arriving at the requirements, then it necessitates a Requirements Elucidation approach (Andrews, 2013a). To proceed, into Feasibility/Assessment and often beyond that, without a comprehensive Requirements Elucidation focus, as proposed here, ends up all too often with the consequence of revisiting the concept (requirement and chosen design) by undertaking what are fundamentally new concept studies well into the overall ship design process. This fundamental revisiting inevitably prejudices the design development with unnecessary uncertainty and often threatens not just previously approved cost and schedule, but even the design coherence and viability of many a project.

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APPENDICES

APPENDIX A

DESCRIPTION OF THE STEPS IN THE SHIP DESIGN PROCESS (FIGURE 4)

a. Perceived Need – This should emerge from the customer's consideration of the market drivers or, in the case of naval vessels, from a threat analysis, the need to get a new sensor or weapon to sea in a new class of vessels or just the replacement of a class of ships that are reaching their end of life. This need is best approached (given the wicked nature of requirement elucidation) in broad terms: thus 'a new general combatant/fleet escort' or 'a replacement amphibious landing (dock) ship'.
b. Outline of Initial Requirements – This should also be very broad in that beyond the basic capability 'everything should be negotiable'. That is not to say that aspects, such as cost and time, are not of major importance but even these should be in the equation as the individual vessel size or style might yet be better met in a manner yet to emerge from the requirements elucidation dialogue.
c. Selection of the Style of the Emergent Ship Design – This is the first design choice – and given the exploration stage should consider a range of technological solutions, each of these may have a specific overall (or macro) (as suggested by Figure 8) There will also be major style choices, often associated with their particular technology (e.g. commercial design standards for a utility helicopter carrier (HMS OCEAN), low underwater signature for an ASW frigate (Type 23)). But also there are generic style choices, such as being robust, highly adaptable, high sustainability or low manning, which should be considered for specific concepts. While adopting such style issues is inherent in commencing any design study it is important that this is done consciously since each one has implications for the eventual design outcome and therefore ought to be investigated before that style aspect is incorporated or rejected.
d. Selection of major Equipments and Operational Sub-systems – Given an indication for a given solution type on the Concept Exploration solution space (such as a fast trimaran frigate or a utility carrier) and its appropriate performance (e.g. fleet speed, sustained endurance, maintenance standard), it is necessary to postulate from a likely ship size the likely power plant. It is also necessary to identify the likely major combat equipment or sub-systems. (Selection of standard items such as medium calibre guns or PDMS but less so if a concurrently developing major combat element, such as the PAAMS for the Type 45 Destroyer or the Towed array for the Type 23, where options may be explored. This could be just the size and split of weapon silos but more likely this would be the subject of trade off studies later in concept.
e. Selection of Whole Ship Performance Characteristics – For a naval combatant these may actually have more effect on the whole ship solution than the combat system choices. Thus classical hull form drivers of stability, resistance and seakeeping, which could be seen as emerging from the style choices above or more directly. As performance characteristics or laid down standards, like complementing 'rules' are likely to be major size and (ship) cost drivers. So again these should be open to revision – probably informed by the Concept Studies stage.
f. Selection of Synthesis Model – Despite the fact that this is a crucial decision, it is often made by default. Individual design organisations have their own synthesis tools and associated data-bases. These can inhibit the scope of the Concept Exploration, if for example a trimaran design cannot then be considered. As was amply demonstrated for the classical numerical synthesis sequence (Andrews 1986) there are inherent assumptions and data/rules in any approach. The real issue is that these are rarely questioned and their limitations can compromise subsequent baseline design definitions and the trade-off studies refining them and the requirements elucidation dialogue – especially if the modelling tool is a 'black box'.
g. Selection of the basis for Decision Making in Initial Synthesis – This should be a conscious choice before the (selected) synthesis modelling tool or approach is used. Again this is often made by default choice of the synthesis tool. Thus classical numeric sizing will balance an option in weight& displacement and volume required & volume available, while subject to crude checks of stability and powering. Often the metric sought is then (an equally) crude initial (weight based) costing – or at best RFR for merchant ships. Whether this is the right basis for decision-making is questionable – particularly as the main design drivers may yet to emerge (e.g. underwater noise signature, amphibious force offloading, air wing sortie rate). The more sophisticated architecturally driven synthesis realised by the UCL Design Building Block (DBB) approach opens up the synthesis and enables a Simulation Based Design practice, where the 3-D configuration can be investigated for human factors aspects or other simulations (such as Design for Production, Design for Support and Design for Survivability). This can then ensure that the balanced synthesis reflects more than a crude initial cost and simple stability and power checks.
h. Synthesis of Ship Gross Size and Architecture – With the initial choices consciously made the baseline and subsequent concept studies, and then the Concept Design options can be produced.

Provided an architectural definition has been included in this many of the style issues and the requirement elucidation (providing the basis for the dialogue with the requirements owner or customer) can be investigated.

i. Exploration of Impact of Style, Major Equipment and Performance Characteristics – Although style is seen to be the most crucial exploration, without an architecturally centred synthesis it is questionable that many style aspects can be explored at this stage. Rather most exploration tends to be focused, in the Concept Design trade off stage (Brown & S) on 'payload' and powering. If, as well as style issues, different solution types such as SWATH and Trimaran configurations are to be properly considered in this exploration the an architecturally based approach should be employed.

j. Selection of Criteria for Acceptance of Emerging Design – This is really setting up the basis for the Concept Design stage trade off studies and sensibly informed by the Concept Studies of what might be the crucial style choices. This should not just be dependent on the perceived overall project needs but also which of the technological (and packing/capability) alternatives have been revealed as relevant and significant to be pursued in more depth in the trade-off exercise, when agreement to proceed to the next project phase needs to be robust for high level approval.

k. Analysis of Size and Form Characteristics – If just a simple numerical synthesis has been undertaken in the Concept Studies stage then only default hull form parameters are likely to have been assumed. Before the Baseline Design for each of the (few) selected option from the wide Concept Exploration solution space from which Concept Studies have been performed, then it is necessary to conduct an investigation of the main hull dimensions and principal form parameters (typically for a monohull this includes C_p, C_m, B/T, L/D and superstructure percentage). This is called a parametric survey at UCL, which is different to US Navy practice where the same term denotes a trade-off of hull sizing. If a proper architecturally based synthesis is performed it is likely that the parametric survey will already have been informed by the internal compartmental disposition so that overall hull sizing and shaping will merge from realistic hull form options. If not then hull form dimension and parameters will be wrongly selected and this will only be revealed later in the design development. If unconventional configurations, including multihulls, are being properly considered and then taken forward the likelihood of an unrealistic parameter selection will be even greater, weakening the conclusions from trade-off studies.

l. Architectural and Engineering Synthesis and Analysis – This step reflects the need in a given project to undertake (as part of Concept Design prior to finalising any comprehensive trade off of requirements, style, configuration etc.) specific detailed engineering design and preliminary analysis. Such more detailed first principles design work is not undertaken comprehensively in the Concept Phase – this being the task of the early iterations of the selected Concept Design solution in the next (and subsequent) phase of design (i.e. Feasibility or Embodiment Design). However it may well be for a given project that in the concept phase that a certain aspect needs to be investigated in more depth. (An example of this being done, was that conducted by the author in the early 1990s in the concept phase of what became the RFA WAVE Class Tankers (AO). This AO was the first RFA fleet tanker required to be doubled hulled. It was therefore necessary to undertake detailed damage stability analysis of all the ships' likely operating conditions. This would not normally be required pre-feasibility and reinforces the adage that 'the minimum detailed engineering is undertaken in the concept phase', however sometimes the 'minimum' is comprehensive in a specific aspect (namely extensive damage stability here)). The inclusion of the 'architectural element' in this step's title is deliberate as once any detailed engineering synthesis and analysis is undertaken, it must be with reference to the internal architectural arrangement or, once again, conclusions drawn will be found to be inadequate or even misleading once Feasibility is underway.

m. Evaluation of the design to meet the Criteria of Acceptability – This evaluation occurs both in the trade-off exercise from which the final Concept Design is selected and essentially to the subsequent design development of that design. Clearly it is necessary to have a basis for evaluation to make that selection and to spell out the criteria for acceptability. These criteria will be quite high level for the Concept Phase and of ever greater detail once downstream. Given that the task of Concept is Requirement Elucidation, it is important that the evaluation is consistent with the evolving refinement of the requirement that emerges from the dialogue with the selected Concept Design. That design provides the start point for the Feasibility Phase with the matching requirement statement providing the specification (along with associated standards and style statements) that can be used for the main design development.

n. The remaining three steps in Figure 2 indicate the rest of the design process, once the Concept Phase has been correctly conducted, and is a process of ever greater detailing of the design through the various design phases to achieve sufficient definition for building, setting to work and through life performance. Given these phases constitute the vast bulk of the time and design resources this can seem a little glib. However the point of this current exposition is to emphasise that all subsequent design is based on both the emergent concept design and the matching requirements, such that the initial process as requirements elucidation is quite different in intent and hence process. That far too many major (naval) ship designs revisit much of the concept and requirement effort is clearly indicative that the Concept Phase is too often inadequately undertaken. This is not least because all too often it is seen as the first part of the rest of the design and not the ship design half of Requirements Elucidation.

APPENDIX B

DISCUSSION OF THE APPLICABILITY OF RITTEL & WEBBER'S TEN 'WICKED PROBLEM' CHARACTERISTICS TO COMPLEX SHIP DESIGN (Section 3.5)

1. There is no definitive formulation of a wicked problem – because formulation of the problem IS the problem. (The author has remarked that the "classical systems approach" is inadequate for dealing with wicked problems and the methods of Operational Research can only come into play AFTER the most import decisions (see Figure 4) have been made.)
2. Wicked problems have no stopping rule. There are no criteria to say when THE solution has been found. Thus the wicked problem terminates due to reasons of time, money, etc., when the solution seems good enough – a rational but subjective decision.
3. Solutions to wicked problems are not true or false but good enough. This is seen as due in part to the many "stakeholders", which again rings true for complex ship design.
4. There is no immediate and no ultimate test of a solution to a wicked problem. The classic problem for the designer of a naval combatant is how good is the design? (The issue is well caught by C S Forrester in "The Ship": "*Then one ship which is a mass of compromises meets another ship and one loses and those who survive blame the design while those who win consider is was their effort not the design*.")
5. Every solution to a wicked problem is a 'one-shot operation'. This sounds like a more social planning issue, but one can see resonances in naval ships also being unique social constructs due to naval practice?
6. Wicked problems do not have an enumerable (or an exhaustively describable) set of potential solutions. It is not possible to prove that all solutions to a wicked problem have been identified and considered. This is certainly true for complex ship design and, worse, many prospective solutions (in, say, a Pareto Front) may prove to be "false" (i.e. unbalanced) and therefore not credible solutions. This is often overlooked in using optimisation approaches such a genetic algorithms.
7. Every wicked problem is essentially unique. This rings true with complex ship design. The list of 11 recent RN ship projects in Section 2.1 reveals each has its own peculiarities and while lessons can be learnt also the temporal shift can render the applicability questionable.
8. Every wicked problem can be considered to be a symptom of another problem. This is another more sociological planning aspect, although the classic systems stance that every system is a sub-system of something else is analogous – as every naval ship is part of a wider fleet, however the physical bounding of a ship makes it a very special mobile construct.
9. The existence of a discrepancy representing a wicked problem can be explained in numerous ways. The choice of explanation is said to be arbitrary. Again less obviously applicable to ship design directly but the "political" nature of the naval ship design environment reinforces the remarks at item 7 above.
10. The planner has the right to be wrong. Just as the planner (unlike the pure scientist) is not trying to find a truth, but to improve some characteristics of a social/organisational construct, so the designer of a complex ship is aiming to produce a better/satisfactory design (both hard to define adequately) and must approach the detailed design task from a proper exploration (sensibly with the requirements owner) of the solution space before immersing the whole team in evolving the preferred option.

DISCUSSION

THE SOPHISTICATION OF EARLY STAGE DESIGN FOR COMPLEX VESSELS

D Andrews, FREng, PhD, FRINA, RCNC (Vice President), Professor of Engineering Design, University College London

COMMENT

Charles Betts CB, FREng (Fellow)

This is an important and valuable paper. I recommend it to all involved in practical ship design work, not just those with an academic interest. For that reason, I am glad that this paper is published in a special edition. This increases the chances that the paper will be seen and recognised as worthy of close study by designers and others who might otherwise be put off by its length.

The paper is long because it effectively summarises over 35 years of pioneering work by Professor Andrews, supported by his colleagues at University College London and within the Royal Corps of Naval Constructors. This work he has shared in a continuing series of papers published and discussed in our Transactions, conference proceedings and elsewhere, as the work developed over the years.

In the early years, his work was considered controversial by some (including this contributor!) who saw it as unnecessarily complicating the process of concept design in a time when computing power seemed inadequate to meet his expressed aims. The huge and rapid increase in computing power that has occurred since then has overcome the perceived drawbacks remarkably quickly, Today, Professor Andrew's work is seen by those who have followed it, and those who have benefited from it, as both innovative and valuable, offering a considerable improvement in the design process for vessels of all kinds, particularly those required to meet complex requirements in an innovative, practical and efficient way. The development of the concept design computer programs incorporating his work are now widely used, with commercial developments of his building block design method now used around the world for warship and submarine design, including almost all the newer current Royal Navy warships, as well as for commercial shipping and mega-yacht design (see for example www.paramarine.qinetiq.com and, with apologies for shameless promotion on my part, Betts (2018).

Among many insights, the paper includes some excellent expositions on important aspects of ship design. For example:

Section 3.1 on the dangers of indiscriminate use of Systems Engineering in design. This technique is a useful, and sometimes vital, tool in complex engineering design and can work very well for systems having a clearly defined role, such as weapons systems. However, it is has to be used very carefully in design of a warship or submarine, which invariably has a multitude of roles and tasks to perform which often conflict in their requirements. It is then essential for the designer to be able 'to see the wood for the trees' and make decisions with experienced judgement informed by, but not completely reliant on, systems engineering techniques. Perhaps developments in computers and artificial intelligence will one day change this, but I do not see that happening any time soon.

Section 3.3 which discusses the real purpose of concept design which is too often misunderstood by requirement setters.

Section 5 on various design approaches and their pros and cons.

Section 9.2 where the author makes the important argument for only looking at what is actually needed in Early Stage Ship Design, not at detail for its own sake (what originally worried me about his approach back in the 1980's when computing power was far less advanced; the author wisely had more faith than I at that time).

Appendix A is very useful as a succinct summary of the author's method of approach to the ship design process.

On the detail of the paper, I have little to discuss that has not been covered by the many contributors to the author's various papers on individual aspects of his work. I would add a general point on requirements elucidation as it affects warship design, as described in Section 3, Appendix A and elsewhere. The 'wicked' problem he describes can be even more wicked these days in the UK Ministry of Defence in that it now usually requires an initial look at meeting requirements by wider options than ships or submarines alone. Thus early comparisons are required of vessel options with other possibilities such as aircraft, space solutions or perhaps a fixed array. This reinforces the author's point in Section 9.2 mentioned above.

Looking to the future, Operational Analysis is mentioned by the author in several contexts in his paper. Some people have been cynical about the value of operational analysis, partly because it is often forced to use rather artificial scenarios and it is also often based on very simplistic designs of vessels and their weapon systems. However it can be popular among requirement setters such as the Naval Staff who see it as useful in justifying proposed requirements to central

Ministry of Defence committees. Operational Analysis has occasionally been closely combined with concept design work, a recent example being given in section 6.3 (vi) of the paper. Modelling and Simulation technology leading to 'virtual prototyping' to predict operational performance is also being increasingly used to reduce risk in the post-concept stages of ship design. Indeed it is NATO policy to do so, to support and enhance defence acquisition processes.

I would be interested in the author's view as to whether there is there a better way - and likely to be real benefit - in integrating operational analysis and/or 'virtual prototyping' more closely with the process of concept design?

Austin A. Kana, PhD, Assistant Professor Ship Design, Production, and Operations, Faculty of Mechanical, Maritime, and Materials Engineering (3mE), Delft University of Technology

I would like to congratulate the author on this significant body of work and on his contribution to early stage ship design over his career. This article lays out in good detail the goals, challenges, and uniqueness of this special phase in the design process for complex vessels. I agree with the majority of the arguments the author makes in regards to what makes early stage design of complex vessels unique. As a teacher of complex ship design at the Master's level, I sometimes find it challenging to communicate the specialties and nuances of this design phase to the students, as the rationale required for a successful design activity is indeed different than that of classical ship design. His comments on page A-10 regarding how the concept phase is traditionally presented as coming after the problem definition phase is especially pertinent. At upper level university education we introduce ill-defined ship design problems, where part of the student's tasking is finalizing the problem definition. This can be challenging for some students.

One area that needs stressing is that there is no consistent definition of what exactly a complex vessel is. There are several active theories from the author himself, David Singer at the University of Michigan (Shields and Singer, 2017), Henrique Gaspar at NTNU (Gaspar et al., 2012), and myself (Kana et al., 2016). While these theories all aim to address a similar topic, there are subtle differences between them, and thus the proposed approaches that stem from them also differ. The author justifiably focuses most of this paper on naval vessels, which are indeed highly complex. However, I believe a broader discussion of complexity of some special types of commercial vessels (such as some service vessels, or cruise ships) would add value and is necessary in extending this conversation beyond the primarily naval focused.

I appreciate his list of tool elements for requirements elucidation at the end of section 3.6 (page A-17). As much effort is placed on requirements elucidation of the vessel itself, the requirements of the design tool also need to be scrutinized and tested. There is a difference between design tools that are developed to generate detailed information and those that are designed to facilitate knowledge generation. The former is applicable for accurately modeling the physical design, while the latter is better suited to help a designer make a decision. Both are required for the complete design activity. When developing techniques to aid in this special area of the design phase, ensuring that your design tools work towards the goal of that particular design activity can sometimes get lost during tool development.

In Section 8 the author discusses the special aspects of various complex vessel types, however the focus is again primarily naval. The subsection of submarine specific concept design is an important aspect as it details the significantly different approach to concept design for these complex vessels. I teach a course with a concept design project of a submarine, and addressing many of these concepts that the author discusses has proven to be challenging within the university environment. The details of this course, the challenges we faced, and a description of an educational tool we developed to address submarine concept design are discussed in Kana and Rotteveel (2018).

Again, I thank the author for his efforts in assembling this manuscript and I look forward to using it as a teaching aid in my courses on complex ship design.

Robert G. Keane, Jr., President, Ship Design USA, Inc., Chair of the SNAME Ship Design Committee and Former Chief Naval Architect of the US Navy

Professor Andrews is to be highly complimented on providing our profession a comprehensive dissertation on naval ship design based on his extensive experience in senior leadership positions on a large number of naval ship designs. I am particularly appreciative of his very kind words for me, especially coming from a world-renowned ship design leader like Professor Andrews.

Professor Andrews has provided an enormous amount of all-encompassing technical content on which to comment. I have selected two of his more significant principles to elaborate on for successful naval ship design. The first is that modern naval vessels are essentially space driven and when initially sizing a naval ship the design engineer needs to adequately address weight and space, for if the ship is undersized, unnecessary complexity is designed into the ship that stays with the ship throughout its long service-life and has a huge adverse impact on total ownership cost and availability of the ship. The second is that Professor Andrews rightfully emphasizes the concept design phase is distinctly critical for success in the rest of the ship design and construction process to produce an efficient and effective warship.

Adequately sizing a naval ship. Keane et al (2017a) note that the US Navy ship design philosophy in early stage naval ship design in the 1970's and early 1980's was that "smaller is better" and "lighter weight is cheaper." This philosophy was incorporated in the first ship synthesis computer models developed during that time, and is still embedded in too many ship design tools in current use. This "smaller is better" design philosophy also influenced a generation of surface ship designs that are in the US Navy fleet today, as well as legacy designs that continue to be used as parent designs for future ships. This "lighter is cheaper" design philosophy is manifested in many ships in the fleet today in terms of overly dense outfitted ships, highly dense machinery spaces, ship arrangements that do not contribute to efficient operation and repair, and in general unnecessary complexity in the design and construction of new ships and operation, repair, and modernization of in-service ships. Since the predominant weight of a ship is the ship structure and weight drives the size of the ship, lightweight structures with all their complexities and problems are a major contributor to excessive total ownership costs of US Navy ships. However, since the 1970's the US Naval Sea Systems Command (NAVSEA) has invested in a number of Design for Producibility initiatives, the results of which have been applied on a design-by-design basis but still need to be incorporated in early stage ship design tools. With dramatic advances in high performance computing, higher fidelity, physics-based models can now be integrated into early stage integrated design environments. We describe a design strategy and approach to provide the early stage design engineer the capability to assess alternative ship concept designs and "optimize" for multi-objectives of adequate structural performance throughout their in-service life, minimal construction work content and minimal weight, in that priority order of design space exploration; thus, producing robust ship structures enabling the US Navy to avoid billions of dollars of unnecessary acquisition, maintenance and modernization costs and significantly increasing the number of days that ships with robust structures are available to the fleet.

Keane (2012) reports that being able to efficiently produce and own a warship must be addressed during the earliest stages of design. The US Navy needs to dis-continue the practice of first starting with the hull form and based on the false economies of cost and size, arbitrarily constraining the design - "outside-in design". The Way Ahead for efficiently producing and owning a warship can be achieved through the use of more early-stage physics-based design tools and a different approach to the Design-Build-Own Process; that is, creating the baseline ship by: (1) matching the internal volumes to the hull form; (2) then finalizing the baseline design - "inside-out design". Designing inside-out of the hull is a proven methodology for significantly reducing the Design-Build cycle times and the total ownership costs of new ships.

Keane et al (2017b) emphasize that under sizing the ship during concept design studies increases ship outfit density and adds unnecessary complexities to the design and construction of the ship. We report that a recent study of foreign naval ships validates that early stage design decisions on properly sizing the ship are a major contributor to reducing complexities of designs leading to work content reductions in Detail Design and Construction and providing more flexible naval ships for future upgrades and modernizations. We identify the need for early stage design measures of complexity and new design space exploration ship design methods including new ship costing tools that are more sensitive to these measures of complexity and not primarily weight. Finally, we propose solutions that will aid design engineers and decision-makers in designing out complexities early, putting ship designs on a path to becoming flexible warships which are easier/more affordable to build, operate, maintain and modernize throughout their full service-life.

Concept Design: The Fuzzy Front End. According to an old proverb, if we do not change our direction, we might end up where we are headed. For naval ships, we know what needs to be changed: the design, acquisition and construction process. Hootman and Tibbitts (2004) and many others give testimony to the many changes to this overarching process over the past 50 years. We can also gain insight and knowledge into what we need to do by studying the best practices (including processes and tools) and lessons learned from other product developments.

Return to a "User-Based" Design Approach. MIT's Eric von Hippel (1996), who has done pioneering research in new product innovation and the fuzzy front end requirements, contends that when it comes to innovative product concepts, sometimes it is a waste of time and resources to try to understand user needs. Over the past 20 years, the key principle of the US Navy's acquisition reform, however, was to acquire a warship from industry based on performance requirements (the "fuzzy front end") not the traditional shipbuilding specifications. Von Hippel says sometimes it is less expensive and more efficient to let your customers define the needs, limit yourself to offering solutions, and let the users design based on that. For a naval ship, the user is the fleet operator; for the US Navy, the fleet operator is represented by the Office of the Chief of Naval Operations (OPNAV).

This is the basic user-focused design approach that the US Navy utilized successfully for over 50 years. NAVSEA sent senior ship design managers to the Ship Characteristics Improvement Board (SCIB) in OPNAV to work directly with the requirements decision-makers (users), while ship designers at NAVSEA conducted numerous, iterative ship concept feasibility studies until OPNAV decided on the operational requirements for the ship. Even so, requirements often changed during the early stages of ship design when more technical information was generated by the design studies. However, since NAVSEA was doing the design, the US Navy had the agility to respond to such changes without costly and time-consuming contract changes.

Von Hippel (1996) identifies three main paths to concept innovation. The first, "manufacturer-based design", is the most traditional in the commercial market: users have information about their needs, manufacturers have information about solutions, manufacturers get need information from users and put it together to design a customer-responsive product. This was the basis for acquisition reform in the US for the past 20 years and was the approach used on the troubled DDG 1000 design and acquisition. Says von Hippel:

"Manufacturer-based design is the guiding assumption in many early marketing research methods, and can still be seen in many fields. In software development, for example, it is known as the 'waterfall' method. Systems analysts begin the development of a new software product by meeting with users at the start of a project to determine user needs and agree on a written product requirements specification. Manufacturer-based developers then worked isolated from further user contact until the completed product is delivered months or even years later."

The second is what von Hippel calls an "iterative user – and manufacturer-based design": based on needs information a user specifies a desired product, a manufacturer develops a prototype to meet the specs, the user evaluates the prototype and upgrades the specs, the manufacturer continues until the user is satisfied, and the user keeps upgrading the specs until satisfied. A lot of back-and-forth activity and information transfer can be costly and time consuming especially for a warship. This was the US Navy's experience on the LCS.

The third, as noted above, is "user-based design": users assess their own needs, the manufacturer has information about solutions that the user acquires, and the user creates the design concept to satisfy his or her needs. Says von Hippel:

"User-based design can be seen wherever and whenever users assemble 'systems' of their own devising. They may acquire the solution information they need for user-based design by drawing on solution 'kits' provided by a manufacturer for that purpose or by assembling the solution information and components and tools they need from a range of manufacturers and other sources."

Von Hippel argues that the "fuzzy front end" is a domain he calls "sticky information." He underscores that employing either a manufacturer-based design process or an iterative user-and-manufacturer-based process necessitates capturing specific user need requirements up front. The problem is, however, general users often do not know what they need. Or, they may know what they need but only tacitly: the information is "sticky", not readily transferable. Von Hippel emphasizes that one of the most important steps to innovative concept development and cutting concept development time and cost is for manufacturing (production) engineers and lead users jointly develop new product concepts and specifications.

This leads to answering the paramount question of Hootman and Tibbitts (2004): "Is the [US] Navy following the cost effective path by maintaining competitions that are held repeatedly between the same two industry giants and the combat system integrators they team with?" The view for years of many highly experienced naval ship design leaders (Keane et al, 2007) has been that the "Collaborative Design" model should be used from the earliest phase of warship design. This results in more emphasis in the acquisition strategy on increased collaboration between the US Navy and the shipbuilder(s). Von Hippel's "user-based design" approach requires Collaborative Design.

The only US Navy ship designs that have come close to this Collaborative Design model are the LPD 17 Detail Design, where the NAVSEA design team was collocated with the Shipbuilder design team at the shipyard, and the VIRGINIA submarine design with its Design-Build teams comprised of NAVSEA and Shipbuilder members. This Collaborative Design acquisition strategy challenged the different cultures of the US Navy and the shipbuilders, but in the end, it demonstrated the many advantages of Navy-Shipbuilder collaboration and the resulting process innovations.

Professor Andrews' final remark that most concept design studies are far less comprehensive than should be the practice is very valid. NAVSEA learned during the build-up to the 600-ship fleet in the 1980s that organizations applying the principles of rapid product development learn how to develop products much faster routinely. They learn the critical cultural lesson that each new product does not have to be a clean-sheet design - incremental innovation can be a winning strategy. In addition, cycle-time reduction was primarily attributed to collocated, cross-functional, full-time teams and also to an uncompromising obsession with understanding and meeting or exceeding customer (Chief of Naval Operations) needs and up-front supplier (shipbuilder) involvement. The concept design studies phase is the "bargain basement" for buying cycle - time reductions.

Dr. Alan Brown, NAVSEA Professor of Ship Design, Capt USN (ret), Virginia Polytechnic Institute and State University

This paper is a remarkable compendium of ship design wisdom and I heartily congratulate the author on yet another outstanding effort. I have had the pleasure of knowing and collaborating with David for many years. Once I got beyond our often confusing differences in terminology, I began to realize how common our experiences and thoughts were in regards to ESSD, what I call Concept and Requirements Exploration (C&RE). Of all the critical issues David describes, his discussion on requirements elucidation may be most important for our design community to appreciate. The further emphasis I would add is the need for the designer to fully understand the relationship between effectiveness, cost and risk before setting requirements and making any early design decisions. This understanding can only be obtained in the context of concept exploration so sufficient time and effort must be allocated to this critical part of the total ship design process. It is a "wicked problem", but so important to solve at the very beginning. My perspective of this topic is covered in my ref (Hootman & Tibbitts, 2004), which is an update article to David's ref (Brown & Thomas, 1998).

I also heartily concur with David's emphasis on early consideration of space and geometry which he accomplishes using his DBB approach. David's is an "inside-out" approach, and provides an important perspective for the designer that traditional "outside-in" design alone does not. In our concept and requirement exploration (C&RE) process we attempt to pursue "inside-out" and "outside-in" simultaneously, also using blocks, but in a manner better called "outside-in meets inside-out" considering hull subdivision and allocating compartments and eventually vital components to subdivision blocks (SDBs) which include topside blocks and some port and starboard blocks, making it a 2.5D method. This has proven essential for all the reasons David points out, but most importantly for assessing ship vulnerability and including vulnerability in ESSD decisions. This vulnerability approach is discussed in my ref (Keane, McNatt, & Beach, 2017a) although we are now using much more of a network architecture framework for this exploration more in line with ref (Keane, Mierzwicki and Grogan, 2017b), and in the context of distributed system design. Propulsion and distributed system design are an integral part of the overall ship design and must also be considered in ESSD at a sufficient level of detail for making early design decisions and moving on to later design stages without costly backtracking. Early stage ship design decisions based on total ship cost, effectiveness, risk, balance and feasibility are impacted greatly by early propulsion and distributed system design decisions.

Finally, to the concept of "style": I don't know of anyone other than David and also Rachel Pawling who have really grasped the significance of this topic. Funny, I didn't even know I had a style until David and Rachel told me, the point being that we have to look outside of our style box in ESSD. We have to "go beyond our naval architecture comfort zone" if we are to find many very important and possibly the best design solutions. Not easy to do, but it must be done and must be done early and with discipline. David's discussion of style here and in his 2017 paper is essential reading.

In summary, there is a lot to be learned from this IJME paper and I strongly recommend a thorough reading by all current and perspective ship designers and acquisition managers.

Comment is submitted by Professor Gaspar in the form of the following Technical Paper:

DATA-DRIVEN METHODS TO HANDLE COMPLEXITY AND ENABLE SOPHISTICATION DURING SHIP DESIGN

H M Gaspar, Dept. of Ocean Operation and Civil Engineering, Norwegian University of Science and Technology, Ålesund, Norway

SUMMARY

The discussion here presented attempts to propose a definition of complexity and sophistication during early stages of design that matches the topics presented by Andrews in the main paper of this Transactions RINA issue. Complexity is understood as all the relevant information to define a ship, while sophistication is connected to the knowledge to use this processed information during the early design practices towards valuable decision-making. A data driven approach is thus proposed to extract information and knowledge via efficient analysis of the ship (product) and design (process) data, proposing a modern development and operations computational approach for ship design, focusing on recurrent feedback of analysed data to ensure that new information is properly engaged to modify and improve the solution space of the wicked problem. This discussion closes with a selection of six topics commented by Andrews that will instigate the next generation(s) of ship designers, namely: quantifying style; comprehensible synthesis; success factors for ship design; design as a learning process; aided vs. automatic; and architecturally driven-data.

1. A DEFINITION FOR COMPLEXITY AND SOPHISITCATION IN SHIP DESIGN

The comprehensive work from Professor Andrews in *The sophistication of early stage design for complex vessels* presents an impressive compilation of the key arguments that the author has been developing and advocating for the improvement of the conceptual phase of ship design in his career. The paper can be read as a *master class*, with the author presenting main issues from the ship design practice not as a pure theoretical *persona*, disconnected from the real domain, but as a field researcher, combining experience, from real naval designs, with high relevant academic content that he and his team have been constructing during the last decades. Such type of work, combining extensive experience with consistent academic relevance, is rare in the ship design community and it should be praised not only as a milestone, but as an incentive to motivate other qualified designers to share their experience with the community – besides Andrews I recall too few other recent examples in the conceptual design field, such as Levander (2009) and Ulstein & Brett (2012, 2015), that systematically published work merging practical argumentation while extending the theoretical contribution.

Andrews closes the introductory section of the paper stating that modern practices to approach conceptual design of *complex* vessels are inherently *sophisticated*, linking his assumptions to the main title of the paper while presenting, in the Introduction, diverse questions that are tackled in the rest of the document. I want to start my contribution using his statement as the main line of reasoning to argue that sophistication and complexity in ship design are connected via the amount of data that is captured, analysed, understood and used to converge relevant information into useful knowledge during the early stages of design. This is heavily influenced by the rise on computational data-driven design methods (Anderson, 2015; Bostock et al., 2011; Provost & Fawcet, 2013) To support my argumentation, I propose a definition of complexity and sophistication that matches the conceptual ship design problem, connected to the data, information, knowledge and wisdom hierarchy (DIKW) (Rowley, 2006), and finally propose modern computational data-driven methods to achieve such sophistication (i.e. DevOps).

The idea of a ship as a complex structure is so established in the field that even in classic works, such as Evans (1959) and Benford (1967), it is possible to find a reference to the word (my emphasis):

- Evans (1959): *Ships and aircraft are examples of such extremely* complex *problems. Not only are they structures, but vehicles as well. Furthermore, they are vehicles whose efficiency or, in fact, whose very ability to perform at all, is strongly dependent upon weight economy*.
- Benford (1967): *The selection of ship size has in the past been rather arbitrary simply because the* complexities *of the problem precluded any sort of rational approach.*

The classical understanding of complexity commented by both authors is commonly based on size: larger the system, more components it has, therefore more connections between the parts and more work is required to grasp a full understanding of its construction and behaviour. Although useful, only using the number of elements seems rather incomplete, and insights from the algorithm information theory (Kolmogorov, 1983) can refine this approach. If any object is simply constructed, then a small quantity of information is sufficient for its description, but if it is complicated, then its description must contain much information. Kolmogorov argues that the more information an object has, the more information is needed to describe it, and therefore the more complex the object is. Note that information here is considered as captured and processed data, and it can be quantified, especially when we use digital systems to store and analyse these data (bytes, number of operations, processing time). When Andrews comments about physical large and complex systems (PL&C) and argues for an architecturally driven approach, he seems thus to go beyond the weight (Evans) and size (Benford) idea of complexity in ship design, arguing that a designer should focus on correct type of ship design process based on the level of novelty, capturing the relevant functional and spatial information of the concept of a new ship. The latter must not only be connected to the size of the data set (drawings, analyses), but must also include the amount of all relevant information required to describe our system (the ship), such as components, interconnections, performance evaluations, and scenarios, with an emphasis on the style topics. It seems not wrong to speculate that the contrast between an architecturally driven approach and a systems engineering approach lies thus in the type of information that one is able to capture and analyse from the ship, with the first giving strong emphasis to style (the 5th “S”), while the second looks for precision in the first four “Ss” (speed, stability, structure and seakeeping; (Andrews 2017a)).

In this context, by defining complexity in terms of relevant information to define an object, sophistication should be connected to the efficient handling and understanding of this information to manipulate the (design of) this object, that is to say, the knowledge to make good use of it. The sophistication in the conceptual practices will be achieved when a knowledgeable use of the ship design theories and tools are in place, whilst this knowledge is extracted via efficient handling of the ship design information across the multiple actors in the process, especially among designers, engineers and operators. In this sense, a sophisticated set of actions is here understood as how these actions reflect the knowledge extraction as early as possible, while keeping the freedom to modify key style topics as long as possible. The classic trade-off on knowledge and freedom during the preliminary phase (Erkistad, 2006) is the challenge to overcome, given that only the continually modification of the problem space through retrieval of new information from long-term memory seems to properly handle wicked (ill-structured) problems (Simon, 1977).

The determination as to which type of information is necessary to establish whether a design specification is sophisticated enough is a central question in Andrews' work. Clearly the amount of information required has increased over the years even when a design is controversial or it is unclear as to how to manage this information (Gaspar et al., 2016). Lack of focus on information related to design analysis makes it difficult to track the history of that information. It is possible, however, to affirm that some type of information appeared relevant just after a certain base was developed. For example, the optimization algorithm for calculating hull resistance is valid because of development of the first estimations based on the hull shape are already available. The trigger for focus on environmental performance, nearly absent in ship design references more than 20 years old, was primarily due to the strengthening of environmental regulations and a need for fuel efficiency, given fuel price increases. A similar exercise on the novelty of the new information required can be done for every item in the *Style Topics* table (see Table 1, Andrews).

2. DATA-DRIVEN APPROACH TO HANDLE COMPLEXITY AND ENABLE SOPHISTICATION DURING SHIP DESIGN

Keeping the assumption that complexity is related to the amount of relevant information and that sophistication is related to the knowledge on how to properly use this information during design, the next step is to connect these concepts to the raw and unprocessed facts about the world that we can capture through data. A common point among the studies is the idea that good decision making during early stages comes from good data, here exemplified by the DIKW and data-driven decision making (DDD). These concepts are not necessarily new but have been heavily revisited in light of the large amount of computational power that we have today to process the data and (hopefully) extract knowledge. Anderson (2015) explores the DIKW idea to deeply focus on data itself, defining the pre-requisites for an efficient data-driven implementation, here exemplified for the ship design domain (Gaspar, 2018):-

- Data Collection: the gathering of all data related to the business among all its sources, such as previous designs, suppliers' information, rules, 2D and 3D drawings, sea trial results and operational logs;
- Data Quality: connected to the reliability of data. It can be observed in many facets, such as accessibility, accuracy, coherence, completeness, consistency and relevance. Extracting non-relevant (dirty) from relevant data is a key challenge when talking about good quality data, as well as handling missing data. A good conceptual design is strongly connected to the quality of data used to develop it, from the regressions and empirical formulas used to define main lines and dimensions to the proper elucidation of requirements when defining how the key subsystems of the ship are able to perform the mission, when neither the ship or the mission are clearly defined;
- Data Access: as important as having the data is fetching it, especially to connect one entry with another, querying all available datasets and sharing information with others. This can be exemplified as accessing previous designs drawings or being able to include a new system in the suppliers' database. More important is the idea that efficient access to data is paramount to a proper data-driven design, and that data should be as easy as possible available by everyone included in the design process, bounded by legal constraints, proprietary assets and level of risk;
- Data Analysis: concerns the transformation of data in the required layer (DIKW: data, information, knowledge and wisdom). A report from the design office, for instance, saying that 2500 hours were used in the conceptual project is pure data. Analysis is to compare it with other similar projects and get the information that previous designs used 10% less hours. Knowledge is the understanding of the consequences of these additional numbers of hours, e.g. higher cost for the designer but a more efficient ship to be constructed, saving hours later in the construction phase. Wisdom is connected to using this knowledge in the future, for instance trying to achieve the same amount of yard efficiency in less conceptual hours for future designs;
- Report/Alert: connected to the metrics we take from data, exemplified in ship design by the number of hours spent in a conceptual project or at the yard during construction, and how this data must be constantly reported and checked to assure profitability.

A short emphasis in data analysis is worthy of note before proceeding to discuss which type of data are we talking about during conceptual ship design, given that the act of analysis is the one that, in the end, is able to allow the sophistication commented upon by Andrews. Data science literature (Leek, 2013) converges on six types of analyses, here exemplified for the ship design domain and organized from the most simple to the most demanding, in terms of processing time:

- Descriptive: connected to the description and summarisation of a dataset quantitatively, usually by use of basic statistics (e.g. max, min, mean, standard deviation). It is the first step in creating a list of similar vessels from Fairplay, for instance, and organizing it by main dimensions and capabilities;

- Exploratory: an approach to find previously unknown relationships, such as exploring diverse curve fitting, types of distribution, visual representation of data. This complements the descriptive analysis when regressions are extracted from experiments or times series to feed coefficients in formulas and numerical experiments during the analysis of main ship KPIs, for instance;
- Inferential: connected to more advanced statistics techniques that try to infer some information, such as parameters, distributions or relationships, to a larger parcel of the design space that we already have information about. Response surface methods, for instance, are used to fast create curves to re-use computational demanding FEM and CFD analysis during early stages and infer that behaviour from known designs will work for the new set (Andrade *et al*, 2017).
- Predictive: builds up on inferential analyses, connecting statistics from diverse datasets to predict some more complicated phenomena. This is the core of advanced simulation based design, heavily dependable on training and constant feedback from the other phases, and it seems to me that proper predictive analysis is the current challenge in the ship design community, as pointed by Andrews, namely, how to ensure that *aided does not become automatic*.
- Causal: connected to the mathematical model of the physical object, especially in understanding the causal relationship between modifying one variable and the change that it implies in the behaviour of the system. Causality is the core of quantifying design trade-offs and seems to be the main factor for the improvement and scope expansion of the design space;
- Mechanistic: Builds up on the causal analysis, by modelling analysis tools able to change multiple variables and understand the effects on the multiple aspects of behaviour of the system. Such type of analysis is hard to infer, requiring research and trained skills on advanced mathematical models (e.g. CFD, FEM) during the detailing phase, and is often misused during conceptual design phase by spending too much time to solve the wrong problem.

Data from the product (ship) and process (design) seems to be a good start point when deciding which taxonomy should we use to converge all necessary information required to identify a good ship (Gaspar, 2018). If data is strongly connected to metrics, we are therefore able to evaluate the effect of a data-driven approach by quantifying how better a ship is (e.g. higher performance than a previous ship) and how better is a process (e.g. more efficient than for the previous design). Note that both measurements of quality are not necessarily linked. As pointed by Andrews a genuinely new ship can be obtained from a worse design process, while a more efficient process can create a ship with a lower performance than previous ships, see Figure 1.

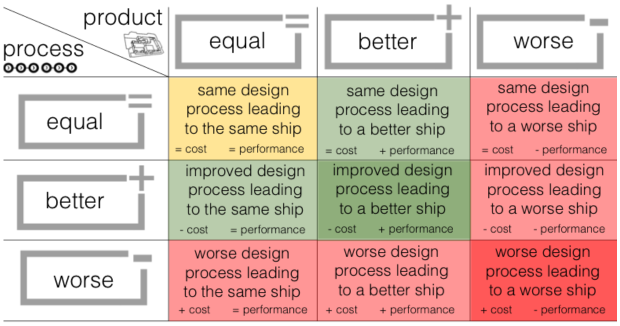

Figure 1: Conceptual matrix of product (ship) and process (design) data quality in ship design (Gaspar, 2018).

Assuming that the insights from Figure 1 are connected to the reality of the ship design activity, it is possible to drawn certain conclusions regarding product and process data. First, a given design process will deliver a certain ship. If no additional data is incorporated, the same process should lead the same ship as before (yellow zone). The concept of improvement (or the effect of learning, as commented by Erichsen, 1994) in both product and process is thus connected to improvement compared to a benchmark, usually previously designs and/or ship. A more sophisticated (better) process in this context is strongly connected to the additional information that leads to the improvement in the design activities. Therefore, we can measure a better design by either achieving the same ship in less time or even a better ship in less time (green zones). The red zone that should be avoided is a more efficient design process that leads to a lower performance ship – no designer is happy to justify lower costs if the price paid is a product worse than the previous one. Note that the red zone can also be connected to the danger of all ship following the same design process, as commented by Andrews. Different ships may require different approaches, and rather than re-use of same process, Andrews here seems to support learning when to re-use, to adapt or to radically develop new methods, if required (see Andrews' Table 3, Types of Ship Design in Terms of Design Novelty).

Similarly, a better product may be the consequence of improvements in the technology and equipment available, and the same design process can lead to a better ship if established design practices are able to incorporate the data from social and technological developments, such as a more efficient propulsion system or optimized hull lines. Product data seems also to be connected to the *density of complexity* discussed by Andrews, and how adding one more subsystem to an already packed space affects our understanding of the behaviour and value of the final product.

The greenest zone at the centre of the matrix exemplifies the key objective of incorporating better data and sophisticated methods to the ship design practice: improved design efficiency (less time) with a better final ship (higher performance). The dangerous of ineffective data and mishandling the wrong information lies at the lower right corners, the reddest zone of the chart, with new data leading to a worse ship at higher cost. This can happen, for instance, if the level of design novelty is not properly taken into account and the wrong type of ship design practice is choose (see Andrews' Table 3).

3. A CALL FOR DATA-DRIVEN SHIP DESIGN

Compiling what was discussed so far, one can conclude that efficient data-driven ship design methods must connect the fundamentals of data-driven implementation with the many taxonomies for product and process data, while incorporating style topics and solving the issues presented by the wicked problem. In other words, data-driven ship design aims to properly identify, understand and manipulate available ship value chain data towards a better process and product. Not surprisingly every design process has some sort of 'data-drivenness' incorporated to it, given that new and better ships are being developed through the years. The challenge is to make use of these state of the art techniques and increased computational power in order to keep the next design on the greenest area of the matrix of Figure 1, with more sophisticated practices handling the complexity of higher performance ships.

An integrated data-driven approach should re-use and build on former designs, allowing the designer to really fetch former designs from a database, building up new concepts based on the new information, as well as re-using advanced 2D/3D models for many value-chain phases (sales, concept, detailing, production, construction). A more liquid taxonomy that can be adapted to the different ships seems also to play an important role, as commented by Andrews. If how we divide up a ship is strongly connected to how we understand it, then style choices are directly connected to this taxonomy and an adaptable design process seems to be the key success factor, especially when considering the level of design novelty and the ship design types (see Andrews' Table 3). A data-driven ship design culture should act to keep the collected and analysed data as accessible as possible during the design process, focusing not only on a standalone problem but also on the holistic nature of the process, across the whole value-chain. This includes access to the analyses made during the design process, options and behaviour of the systems under the multiple operational scenarios studied, as well as incorporation of the style topics (Andrews, Table 1). A data-driven design must smartly integrate the data used as input and obtained as output from the available ship design tools, emphasising the aiding rather than automatic capabilities of modern computer software tools.

Computer science seems to have well understood the lack of compatibility problem among data and the high pace development of internet tools just accelerates the need for common standards and practices, with a pressure to move faster without sacrificing reliability (Kornilova, 2018). This is the context where modern software development and operations (DevOps) culture emerged, with the lifecycle of a software project understood as a dynamic process evolving planning, coding, building, testing, release, deployment, operation and monitoring, see Figure 2.

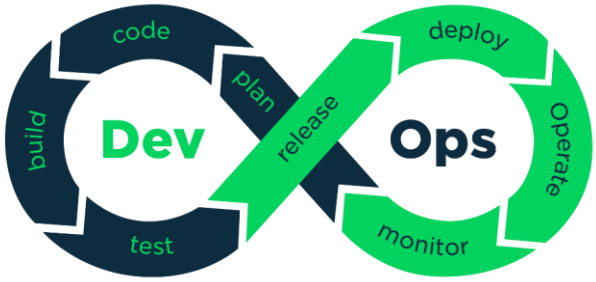

Figure 2: DevOps as culture in software development, (Kornilova, 2018)

I believe that an adaptation of DevOps software practices must be done to properly incorporate data-driven methods, to achieve sophistication during the practices of early stages ship design. Key technical practices that underpin a DevOps initiative include getting teams to standardise on a common set of processes and tools for software delivery, (see Kornilova, 2018). Other relevant practices include:

- Data (and code/methods) openly available to designers and engineers, idealised in a library of previous designs;
- Library of design methods and practices connected to level of novelty and ship design types (Andrews, Table 3). The designer should understand what type of data is required (either existing or to be developed) for each of the types, namely: second batch; simple type ship; evolutionary design; simple synthesis; architectural synthesis; radical configuration; and radical technology. Examples for each should be gathered and documented;
- Version control of files and infrastructure to enable collaboration and rollbacks;
- Multi-hierarchical data, allowing plural data tags, such as functional/spatial/economic hierarchies, multiples level via tags or object properties. Thus main machinery can be part of a propulsion system in one division (functional) and part of the hull in another division (physical);
- Data format as open as possible, including numbers (e.g. simulations inputs, codes and results) and models (e.g. 2D and 3D models in open source formats, such as SVG or STL);
- Collaborative storage and editing capabilities, in line with modern software repositories, such as

GitHub, with features such as versioning, track of changes, reviews, ownership levels, task assignments, automatic documentation, web interface and intelligent search algorithms;
- Tools to open and manipulate the available data must be accessible to all stakeholders, without the necessity of large installation packages or extensive server configuration;
- Continuous integration of collected and generated data, across the lifecycle, to feed the conceptual phase.

DevOps also makes use of the principle of flow, feedback and continual learning of the relevant data in the process, somehow inspired by Lean practices, using as main metrics the deployment lead time for a given design project, (Kim et al., 2016). Note that feedback is also the main contribution discussed by Andrews on an improved representation of the overall ship design process (see Andrews' Figure 4), and the essence of his requirements elucidation. Lack of feedback, thus, means bad (or none) re-use of the ship design data with consequences, such as missing the key extra information required to investigate style topics and undertake a comprehensible synthesis.

Attention must be giving to the monitor phase of the process, see Figure 2. To monitor is strongly connected to the metrics that we take from data, and how these data must be used to generate knowledge to improve the quality and analyses of existing products and procedures. A culture of constant monitoring during ship design would allow a systematic and reliable storage, accessibility and quality assessment of the extensive data required in ship design. In a simple logic, knowledge is what is produced in a design project, via the analysis of relevant information made by people (designer or engineer) into content (files). Content thus is the means to flow knowledge / information to stakeholders, and provide the focus to leverage by sophistication. Feedback is the information gained when the data is used (or misused), with knowledge gained (or lost) as to how to improve in the next iteration, a process strongly emphasized by Andrews in his discussion of Figure 4 (see Andrews, Appendix A). DevOps practices thus aims to include everyone who has a stake in the flow of knowledge by involving them early on. This is achieved through the collaborative process of understanding that content is the key structural element of any design project (Kornilova, 2018) and is pretty much in resonance with the *talking with no contractual barriers* among designers and owners (customers), advocated by Andrews.

DevOps practices rely heavily on starting with small pilots, scaling up as debug, testing and tuning activities take place. While ship design is usually a one-of-a-kind project, the virtual prototype technology is fully available to incorporate the small pilot approach, and such a culture, of testing over and over different designs under different scenarios and scaling up to include one discipline after the other, must be fully incorporated in the ship design activity. This is especially so due to the gain in using 3D models and virtual reality to test and tune analyses associated with parametric hull form investigations to seakeeping (Chaves & Gaspar, 2016; Fonseca *et al.*, 2018).

4. BEYOND A DATA-DRIVEN APPROACH

I want to conclude this discussion emphasising key topics commented on by Andrews that go beyond the definition of complexity and sophistication, in terms of data, and will require extensive research for future generations, given that currently there is no consensus on how to handle it. In this sense *The Sophistication of Early Stage Design for Complex Vessels* already establishes itself as mandatory reading for every naval architect that wishes to have a successful career in practical and/or academic ship design activity.

- **Quantifying Style**: the extensive list of style topics compiled by Andrews (see Table 1) presents a challenge for the data-driven approach outlined above. While some of the items seem to be of a physical/concrete nature and able to be quantified and compared (e.g. Margins or Protection), others lie on the realm of the abstract, and seem pretty much connect to individual perception (like Human Factors and Design Style). Andrews seems to be tackling some of these aspects in his recent research, such as on the logic of deciding a style (Andrews 2017a) and on the importance of human factors (Andrews, 2018d). Robustness, *ilities* and other system lifecycle properties are also hot topics in ship design research, exemplified by Gaspar et al., (2015) and Rehn et al., (2018), but so far such attempts have not been definitive and require extensive study to be fully incorporated in the design practices.
- **Comprehensible Synthesis**: By advocating a comprehensible synthesis (and therefore a sophisticated design practice), Andrews is touching the core point of rational decision making and all the behavioural (non-rational) influences that constrain this action (March, 1978). As the ship comes first, it seems to be a strong connection between handling existing ship data (both bottom-up and top-down) and constraining the solution space, with importance of the role of constraints (economic, political, technological). A comprehensible design synthesis requires to be sophisticated enough to investigate all the data available and to select only the relevant information, in order to converge to one (or two) acceptable design solution. Very few books detail this step beyond a large spreadsheet, and praise should be given to the practical and yet relevant work from Erichsen in his *Management of Marine*

Design (1989), where a whole chapter is dedicated to the topic, with examples across the entire book. My perception is that such synthesis can benefit much from an open data-driven approach, especially if a large library of examples is available to public scrutiny, where the comprehension can be analysed in many layers. Recent works, such as Ebrahimi et al. (2018), present some example of these synthesis applied to commercial ships, but more should be produced towards a general consensus of comprehensible.

- **Success Factor for Ship Design**: A similar approach to that commented on above for a comprehensible synthesis can be extended to the identification and measurement of successful (and unsuccessful) designs. We can learn much from it reading Andrews' Section 2, but is there a way to quantify this data and compare? Can we put a number in for a *good* design? Is extension of service years an indicator of success, as criticized by Andrews? Should profit solely be considered for commercial vessels, or is there value beyond money? Maybe handling of uncertainties and the study of value robustness seems a possible path (Gaspar et al., 2015; Gaspar et al., 2016; Rehn et al, 2018), and such questions, and especially on collecting and making available data about what makes a ship design a successful one, seems a key research question raised by Andrews.
- **Design as a Learning Process**: Andrews' Figure 4 emphasizes the interactive nature of the process, that is, the learning that we get from one process should be used to improve other(s), while the lack of feedback seems a major problem, disabling learning. Given that the conceptual phase is unlike the rest of the ship design, it seems to me that the learning in this phase also follows a different (probably *less linear*) nature, which could be difficult to assess using the traditional product data management approach used by other industries (e.g. automotive, aviation). Note that this challenge does not apply solely to designers, but also to computer engineers. Many modern product lifecycle management (PLM) software promises are not a reality when applied to the ship design task (Gaspar, 2018), and such failure may be connected to the misunderstanding of assuming that the conceptual phase has a similar objective to the subsequent phases (i.e. detailing, production, construction) and which has the wrong methods to capture the learning of a conceptual process and feed it to others involved. A good learning process should efficiently re-use the output data of a task to integrate the relevant (new) information into the next step.
- **Aided vs Automatic**: Machine learning and other artificial intelligence (AI) techniques are a hot topic in engineering, with diverse attempts to include in ship design already in place (Bertram, 2018). Rather than a critic to automation, I conclude from Andrews *aided rather than automatic* argument that automation is welcome if properly handled and removed from the black-box container that is presented sometimes, as though it was just another available (CAD/CAE) tool. In this sense, it is expected see more research using advanced AI methods in conceptual ship design, especially in aiding the requirements elucidation phase.
- **Architecturally Driven-Data**: When advocating an architecturally driven-approach, one must know how this approach contrasts with the pure systems engineering one. In this sense, a study on what type of data (and therefore information) one must have to apply this approach. Andrews even touches the point of decisions made prior to the CAD/CAE tasks. Rather than generic terms, I call for formalized and specific research on these architectural objects (or blocks, to satisfy Andrews), and how it can be defined, handled, re-used, taught at the academia and, most importantly, used by the industry.

5. ACKNOWLEDGEMENTS

I am thankful to Professor Andrews and RINA for the opportunity to collaborate in this issue of the Transactions, and the discussion here are solely based on the successful (so far) experience from the author on applying modern data-driving techniques on ship design practices. Some argumentation used in this paper is compiled from recent publication from the author, such as Gaspar (2018), and it is properly referenced in that paper.

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AUTHORS' RESPONSE

INITIAL REMARKS

The author would like to thank those contributors to the discussion of this paper, not just for their kind remarks but also for the very extensive set of comments they have made, which adds greatly to the value of the paper in addressing what the author believes to be an important but not widely accepted view of ESSD. The commentators have largely supported the contention behind the paper's title but have made some very useful interjections, which I will follow up as best I can by taking each contribution in turn, though this may lead to some repetition.

I am grateful for all the contributors closely reading what I appreciate is a long and densely argued exposition. I am also pleased to have (despite the relatively limited number of responses to my directed call for contributions to this first IJME Special Edition) a wide range of responders, from very eminent British (Professor Betts) and American (Mr Keane and Professor Brown) naval vessel designers to the two younger academics in the field of complex ship design research (Dr Kana for naval vessels and Professor Gaspar regarding complex off shore shipping). So I feel there is a very good mix of expertise and scope to gauge the veracity of the issue I pose.

Professor Betts
Having spent the majority of my career as a ship and submarine designer, it is also my hope that the paper will be read by practitioners – not just academic researchers, teachers and students, reflecting my more recent time in academia, where I have been lucky enough to hone my ideas on the fascinating problem of designing complex vessels. I am aware in trying to be comprehensive about ESSD, which I believe has been known to be important but stuck too long with obtaining a "quick and dirty" solution before "getting on with the real design", has meant the paper is a demanding one. However I wanted here to be comprehensive and "cover all the bases", rather than just address one facet of the ESSD of complex vessels.

Previously Professor Betts has owned up to doubting my desire for a comprehensive (architecturally based) approach to ESSD but subsequently has been a strong supporter and to have someone of his design eminence (as the original Design Manager of still the most complex submarine produced in the UK – the VANGUARD Class) and intellectual standing is more than reassuring. Let me now turn to the specific sections where Professor Betts has comments:

Section 3.1: The dangers of indiscriminate use of Systems Engineering, is as I see it particularly in the adoption of the "falsehood" of Requirements Engineering (Andrews, 2011 and John, 2002). But also S.E. has been used as a strategic approach (it does not help in the detail of ship synthesis) and then due to its very generic nature seen to "justify" design programmes being led by non-domain experienced "managers". Whether, as Professor Betts wonders, AI will eventually be able to enhance decision-making is a good question. I just observe that Expert Systems were supposed to be able to drive complex design several decades ago but still seem far from "taking over design", although I always liked the way an ES tool told the user how it made its decisions – we could do with that in CASD systems, having lost much of design traceability.

Section 3.3: The implied question behind the remark on "requirements setters" (or owners as I have called them) is how can we make them understand Requirements Elucidation? (Given that I still think most ship designers don't understand the issue (Andrews, 2013a) they first need convincing, even if most young ship design researchers now naturally use the term.) I remember, as Head of Concept Design in the early 1990s, giving a talk to the Staff Course, who had a very simple program (called "125" after the train from London to Bath) so they could understand, say, if you increased speed or weapon fit the ship got bigger (and sadly at a simplistic level proportionately more expensive). However this gave future naval staffers the false impression that they therefore didn't need a concept design team. When I pointed out the "125 tool" was grossly simplistic and they did need to properly involve the concept design team (in Bath then) the Staff Course stopped asking me to give the talk.

Section 5: It is not just that there are different design approaches, it is that the concept design manager has to recognise there are different options in the solution space (Figure 8) and they may require quite different approaches – rather than one size fits all, however clever your program might be. It is consciously recognising the "novelty choice" (Table 3) that is an important discipline the design manager/leader must consciously adhere to.

Section 9.2: There is an absolute need in concept to only do what is solely necessary for Requirements Elucidation, and not do all sorts of "good stuff" just because we now can do it. Lots of clever stuff, of course, will give insights but may well confuse and divert the focus. I naturally argue the "inside out" approach enables much more insights to be addressed (but only if considering them helps in Requirements Elucidation).

Appendix A: I am glad to have Professor Betts endorsement of my including this and I realised when I first spelt out each step in Figure 4, which I had presented a decade earlier, that I had been assuming readers understood the steps without giving specific examples (which I now in Appendix A).

Professor Betts raises the question as to whether the "wicked" nature of Requirements Elucidation is getting worse due to the "staff" wanting to consider wider material solutions. To me this tendency is a bit like hoping there is a (cheaper) "golden bullet" to be found. It is always a good idea to think "out of the box" (after all that is why I advocate always considering the radical options at the bottom of Table 3) and to challenge assumptions in the initial first requirement thoughts. However, as Admiral Hill-Norton's book (Hill-Norton & Dekker, 1982) makes clear, Sea Power is primarily exercised by naval ships (and submarines) and so it is hard to achieve the multiplicity of roles and mission adaptability without building an integrated fleet of naval vessels (and auxiliary support). Furthermore to think one is being "objectively functional" by not specifying a type of solution is to fall into the falsehood of Requirements Engineering yet again.

In rightly querying the use of OA in ESSD (given the warnings of OA practitioners (see Kerr, 1973)), which needs to be used with caution, does mean recognising OA's limitations while it often provides design insights. The example of using directed OA studies to sort out the concept of the R.N. LPD(R) (Dolton & Silva, 1986) was a very positive one. I am aware that US navy practice is to have OA staff embedded in a ship design project and the UK's reluctance to give IPTs this direct capability seems very inflexible and poor design practice? So my answer to Professor Betts final question is of course OA and also virtual prototyping skills need to be incorporated in ship concept design teams forthwith –

rather than forever pressurising the concept team to be “as slim as possible” (as was the case when the author’s tried to appropriately staff up his concept team for the precursor to the Type 26 Frigate IPT).

Dr Kana

Page A-10: With regard to teaching ship design, it does seem that only at Masters level it is possible to be more realistic and “mix” the problem definition (or requirements elucidation) and initial ship synthesis. Certainly at UCL many in our recent MSc cohorts also lack prior seatime or shipyard/dockyard exposure and find it hard to appreciate the uniqueness of the artefacts they are designing. This then means introducing too much uncertainty and “realism” can be disconcerting – but the issue of encouraging that future dialogue over the emerging requirement is too important a message to duck for future ship designers.

As far as better defining complexity is concerned, one has to see it as something of a spectrum rather than these types of ships and their design processes are complex and these aren’t. Thus it is clear the most complex naval vessels (such as nuclear submarine and aircraft carriers) are just that, but so are some cruise ships (Levander, 2003) and indeed some offshore support ships (Gaspar, 2013), as Dr Kana mentions. However in the latter case (as with some naval ships) the complexity can be more to do with working out what is needed (and afforded) rather than the final engineering solution per se. There are also some relatively simple naval vessel design tasks (see the “Batch” designs in Table 3), at least from a design decision-making stance, as well as some very diverse types of vessels under the “naval” category not needing in-depth ESSD. Even occasionally there are some highly novel commercial vessels of the ubiquitous transportation type (Meek, 1970) needing something more than a six weeks concept phase.

Section 3.6: I so agree that the requirement of any design tool needs to be scrutinised. Given the attention we as a profession (rightly) devote to scrutinising a new design, one can’t help thinking this often doesn’t apply to the plethora of new tools. The understandable desire to acquire and apply new capabilities means we don’t seem to validate with sufficient statistical evidence. There is also an equivalent requirement elucidation need to question whether that new tool is actually what is needed, rather than being a particularly clever technique that might solve a less than vital design problem. The tool validation issue seems more of a problem post concept than in ESSD where the issue is, as ever, what is appropriate for proper requirements elucidation (Section 3).

Section 8: There might be an implied criticism that I have only addressed naval examples in Section 8 when going beyond the naval combatant (as the “standard” type of naval ship). However both the SWATH and trimaran, as examples of radical configurations in Table 3, have a wider applicability beyond naval ships, yet the different design approach in ESSD to that for monohulls is still applicable. The configurationally driven designs (Section 8.1) discussed are naval, to make the point not all naval ships are frigates etc., even though most naval design practice takes the combatant as typical of naval ship design practice. Similar configurationally driven issues apply to cruise ships for example, but I consider the design of those ships have been well addressed by Levander (2003, 2012).

With regard to submarines, Dr Kana’s recent experience in teaching submarine design, as an example of “designing complex specials” is well presented in his reference (Kana & Rotteveel, 2018). The contrast with the post-MSc UCL Submarine Design Course is that the latter builds on the MSc in Naval Architecture and is based on Burcher & Rydill’s (1994) comprehensive textbook, with subsequent lessons captured in Andrews (2017b) and summarised in Section 8.4 for ESSD.

Mr Keane

I was delighted to get Mr Keane’s very pertinent comments. Not only did he hold, for many years, the senior ship design position in the navy that has been the premier navy for at least three quarters of a century, he is a prolific author of seminal papers on naval ship design, some of which I have referenced in this paper. (In passing, occasionally the two main naval architectural transactions (SNAME and RINA) collaborate (see Ferreiro & Stonehouse, 1993) but practitioners, under understandable pressures, are often unaware of similar issues being addressed by colleagues abroad, even in these days of globalisation and the internet.) Both as a practitioner and now an academic, I have always found an amazing consistency of views “across the pond”, even if, sadly, the Royal Navy can’t compete with the US Navy in scale of its ship programmes, though we in the UK still produce almost all of the same range of vessel types (albeit only in very much smaller numbers), and occasionally lead on novelty (as with the trimaran warship (Andrews & Zhang, 1995)).

The two of my “principles” that Mr Keane has selected to comment upon are those of space, as the ship design driver and, secondly, the concept phase being distinctly different.

Adequately sizing: Mr Keane well spells out the consequences of “small is better” and “light weight is cheaper” fallacies for the current naval fleets. This to me further demonstrates the mistake of being driven by the belief government (on behalf of the navy) has that simple size equals cost but also not understanding that (implicit) style decisions, such as the above, distort a requirements elucidation process. Only with a correct focus on the latter, as an implicit message in this paper, can such false edicts be challenged. The only discipline able to do this is that of ship design and to do so primarily in ESSD. Too often the naval staff (OPNAV in the USN case) focus on what they believe will produce the maximum performance (however that can be captured) for the minimum expenditure (often not correctly seen to be cost of ownership but rather the arbitrarily defined acquisition measure of ship cost – UPC in UK defence acquisition terms (see Item g in Appendix A)). It is usually the case that instead of stating what they would like to have and then working with the ship concept design team to find the best compromise – the essence of requirements elucidation (Section 3.6) the requirements "owners" try to pre-judge the solution (and then try to state it in (non-solution) capabilities terms).

While any fool can design a ship to meet a nominal performance regardless of cost (that being the one thing imposed on our UCL Masters students ship design exercise (beyond achieving a naval architecturally balanced solution, of course)), the skill is to get as much capability (again difficult to define without a satisfactory measure of merit) for the budget available. The fact that we seem to fail to do so with major naval programmes is worthy of another paper, namely one on procurement issues (Andrews 2018b) but this is not helped by the issue of Design for Production that Mr Keane, rightly highlights and ties into "designing "inside-out", reinforcing my message of an architecturally driven approach to ESSD (Section 6). And the elephant in the room there is the shipbuilding element of initial warship acquisition cost. Given there is no prototype to refine the cost and learn from to put Design–to-Cost features into a subsequent production run (as you can and do for all other military equipment – aside from occasional one off infrastructure civil engineering) this is then a problem for the acquisition customer. (Yes I consider those responsible for acquiring ships are properly customers of industry, not the naval staff, and they are also the owners of the design through life, the UK term for this is Design Authority (Andrews, 2006b)). Thus all cost estimates are going to be historically based, and so are inappropriate to the new contract, even without the effect of current market forces on the contracted price. This is bad enough for the material element (which can be weight or installed equipment derived) but for the outfitting costs this seems to be beyond an objective means of estimate *by the customer*, at least for the build period of the first of class (see discussion of Andrews et al, 2005). However, Keane et al (2017b) hold out the hope this might be cracked in future, if only to control the density of complexity and allow the physical size of such complex ships to be sensibly obtained, rather than being forced into "small is better" and even margin-less designs, such as the Type 23 Frigates (see Section 2.1ii).

Fuzzy nature of Concept Design: Mr Keane draws attention to von Hippel at M.I.T. and his "User-Based" Design Approach. To me for the design of Physically Large and Complex (PL&C) systems, such as naval vessels, this is why ESSD needs to be seen as sophisticated and requiring a requirements elucidation approach, led by the owner (not the user/naval staff but the owner's concept design team). This seems to have been supported by the, then, US Secretary of the Navy (Winter 2007) who said the Navy (i.e. NAVSEA) needed to take back control of the ship acquisition process. This was the same message, subsequently ignored in the UK, made by both Baker (1956) and Rydill (1986), that I have recently outlined in arguing the primary function of the naval architect is not the "S^4" sub-disciplines of naval architecture but Ship Design (Andrews, 2018c).

Mr Keane outlines von Hippel's three main paths to concept innovation with recent USN programmes:

a. "manufacturing-based design" (DDG 1000);
b. "iterative user and m-based design' (LCS);
c. "user-based design" (LPD 17 Class Detailed Design phase).

Only the latter does he consider to be even a partial success, with essentially a "Collaborative Design" approach with the shipbuilder in the development of the design. Only possible, I would contend, once the requirements elucidation with the naval staff has provided a coherent design concept for that development and contracting to manufacture. Interestingly, a similar view was outlined by Rydill back in 1986, and it remains frustrating that in the UK we seem to have lost three decades when this could have been implemented. Instead there has been a fruitless (and expensive) belief the MoD could rely on Requirements Engineering and "throwing the requirements over the contractual wall" which then seems to have lost the customer the control that Rydill, Winter and Keane all see as the means of ensuring best value for the navy and the tax payer. It is clear these issues, which are not strictly design but more procurement policy, can dominate such design complexity and this is suggested by Figure 3 and Table 2. However, it probably needs to be spelt out, alongside the design focus of the current paper, as a further measure of the sophistication of naval vessel acquisition (Andrews 2018b).

Mr Keane's thoughtful contribution to the discussion concludes with support for recognising the sophistication of ESSD of such complex ships, and the need to be as comprehensive as the paper outlines. Yet he also sees some scope for "bargain basement" cycle-time reduction. I would not see this as conflicting as the essence of this is implied by Figure 8, namely, that there should always be in ESSD as wide an exploration of the solution space as possible to both "mine that basement" and push the requirement elucidation off its comfort zone.

Dr Brown

Dr Brown is also very kind in his assessment of the paper's worth. We first met as, respectively, the US Navy's Professor of Naval Construction at M.I.T. and the RCNC Professor of Naval Architecture at UCL in the mid 1990s, when we were both appointed to these "navy" appointments to train future naval constructors. And, yes Trans-Atlantic discussions have to get over using the same terminology for different aspects of the same practice (preliminary ship design being a classic example), but as Dr Brown says our experiences of and thoughts about (naval) ship design practice remain surprisingly common.

Dr Brown's comments address the three principle issues underlying the message of the paper's title:

Requirements Elucidation: Yes, this really needs to be appreciated by the "design community" (involved in complex vessels) and has sadly still to be so, even though I coined the term (in attacking Requirements Engineering over more than two decades) in 2003. Dr Brown further emphasises "the relationship between effectiveness, cost and risk", which are two of the three aspects in the key first bubble of Figure 6. The fact that cost, time and risk require to be assessed (along with effectiveness) through "solutions" means requirements elucidation has to be a dialogue, driven by the ship concept designer. That difficult task is also the essence of what Rittel and Webber (1973) identified as the "wicked problem". This is often misunderstood as saying complexity is wicked, which it may well be, but their point is rather that "sorting out what is really wanted" is the real challenge to be nailed on the head before going into classic (ship) design (i.e post-Concept). Furthermore, this only really applies in the maritime domain if there is no simple measure of cost/effectiveness (such as Required Freight Rate), and hence my limiting of requirements elucidation to complex vessels lacking such measures of cost/effectiveness (and also often prey to the multitude of constraints indicated by Table 2).

Inside-out: I consider Dr Brown's "conversion" to the "inside-out" approach to ship synthesis a really strong endorsement. (Actually he is right both in and out need to be pursued simultaneously – but I was trying to over turn more than a century's "obsession" with underwater form, so maybe I over stated the "inside" case.) Dr Brown then calls for the architectural approach to address vulnerability (key to any naval vessel design) and reminds us that early propulsion choices and decisions on distributed ship systems both need to be tackled, as they are also keys to the inside driven synthesis and a properly conducted concept exploration.

Style: Again Dr Brown has encapsulated the significance of this issue. As Figure 6 and Appendix A identify, making a style selection is the crucial design decision both to get any (overall) "form" from the broadest of "functional needs" but also in getting down from the aspects in Table 1 to the micro-decisions Ferguson (1993) characterises in the practice of detailed engineering. The key point about style is that it is the responsibility of the engineer and the ship designer has to recognise is that engineering design involves making a choice, even if it is "to do the same as last time". The good designer does so consciously having weighed up the alternatives as best they can.

Professor Gaspar

Special thanks are due to Professor Gaspar for not just providing comments but doing so in a structured six page paper, and this requires its own discussion separate to my response to his comments on the paper, which I hope can be provided in a later Part of the Journal. I also want to thank him for a contribution by a non-naval naval architect. It is reassuring that someone, focused on non-naval service vessel design, sees applicability in the paper's view of ESSD beyond the purely naval domain. Finally, his contribution is very much looking to the future of complex design by addressing the issues raised in the application to such design practice of current developments under the "Data-Driven Design' (D3) approach. He is very much the leading protagonist for this exciting development in complex ship design and I am grateful he has provided a quite extensive exposition in that regard here. He does so under four headings:

Definition for Complexity: Professor Gaspar starts by seeing my paper as an incentive for other qualified (ship) designers to do likewise, mentioning two examples. I would add three more: Erichsen (1997) and two eminent naval constructors mentioned above, in response to Mr Keane on "fuzzy nature" (namely, Baker (1956) and Rydill (1986)), all three's views on ship design practice were recently summarised in Andrews (2018c).

On the ship as a complex structure, Professor Gaspar quotes both Evans (1959) (the originator of the "ship design spiral") and Benford (1967). As well as being unconvinced by the design spiral (Pawling et al., 2017a) the author would also challenge Evans (who was eminent in ship structures) that complex ships are weight driven, although that clearly applies to high speed and relatively small craft. Rather complex vessels are space (or better architecturally) driven, despite this Evans sees reducing structural weight as a primary (ship) design aim rather than the actuality that such ship designs evolve from a proper requirements elucidation process, where structural weight reduction is a minor objective at best. Benford, in contrast, reflected a pre-computer, or better, a pre-CAD based approach to ESSD, one wholly dependent on "rules of thumb".

At the end of the paragraph below these two quotations Professor Gaspar contrast my architectural approach with "a systems engineering" one. But I think his example of the latter being the application of the four "S^4", discussed in Section 2.2, is misleading. Systems engineering is a strategic approach (a bit like Set-Based Design (see Singer (2003) and discussion in Section 9.4) with technical issues, such as stability applicable to designing any ship. So the "S^4" sub-disciplines are also relevant to the architectural approach – if one is to obtain naval architecturally balanced concept designs. Furthermore, systems engineering is a particular management strategy (successful in major programmes like the US and then UK Polaris submarine projects (with the latter led by the very (Sir Rowland) Baker RCNC, just mentioned)).

Data-Driven Approach to Complexity: I am very grateful for Professor Gaspar outlining here to the ship design profession the six types of analysis from data science, a field of rapidly increasing importance to all complex activities. Additionally, his table at Figure 1 linking product and process seems a useful means of measuring the use of data in future ship design practice.

D3 for Ships: DevOps (Gaspar's Figure 2) and some nine "relevant practices" he lists provide further guidance to help us cope with this new world enabled by real time access to the new dimension of massive data.

Beyond a Data-Driven Approach: in this final section of his paper, Professor Gaspar comments on six topics raised in my main paper: Quantifying Style: to show just how heterogeneous are the topics under Style, I would point out that some aspects under Human Factors can be quantified, though many aren't so far (Andrews, 2018d). Comprehensible Synthesis: Professor Gaspar makes some very valid comments about initial design synthesis, something for example where systems engineering is singularly unhelpful but where I feel choosing an overall Design Style for each distinct option in concept exploration (e.g. Figure 8) is the real key. He sites Ebrahimi et al (2018) exampling synthesis for commercial (service) vessels. This is interesting as an example of a rapid concept design approach, however using a design spiral model might be seen as being overly convergent to a predetermined sequence? On Success Factors: Professor Gaspar suggests I criticised "extension in service", if so this was not my intent. In fact the generously future proofed naval ship design (often called "first rate" (Brown & Andrews, 1980)) has been proven to be value for money (VFM) by lasting longer in service and being much more readily adaptable through life than the (falsely) "cheaper" second rate. Design Learning Process: Re-use of output data is seen to be good practice. In concurring I would state an important output of ESSD, beyond the absolute imperative of focusing on Requirements Elucidation, is to have, at least, a good idea of the main Design Driver that will govern not just the subsequent Feasibility Phase but sensibly then can be clearly tackled in the design development and maintained through life. Aided vs. Automatic: I am at one with Professor Gaspar's remarks here, though I remain concerned at too many "black box" synthesis tools with users blissfully unaware of the degree to which all of "their designs" will then be extensively determined by the (often anonymous) author of the black box. I would only add any "research using AI methods" for ESSD must be adopted only if it aids Requirement Elucidation rather than being "nice to have". Architecturally Driven-Data: Professor Gaspar calls for "formalised and specific research" on the architectural blocks used in an architecturally driven approach to ship design. I am not sure exactly what this might mean but there is clearly a hope that some sort of database could be built up in the manner of his live examples of using the Internet (Fonseca et al, 2018). This would be good for teaching but might prove challenging in both defence and commercial practice? Again I have to take exception to the comparison of (my) architecturally driven approach to ESSD with S.E. The latter is essentially a management strategy, used to manage the ship design process through life (even though I consider Systems Architecture (Maier, 1998) as argued at the end of Section 3.1 is a preferable strategy for really complex systems). Thus the architectural approach (once one has made the key "Design Style" selection) is the preferable way to deal with ship synthesis (incorporating the necessary naval architectural balancing) as shown in Figure 4 (see also steps f and h in Appendix A). I also argue that such an architecturally driven approach better meets the core need of synthesising complex vessels, namely requirements elucidation. This is due to it better enabling interrogation of the major style issues, indicated by Table 1, rather than leaving the "inside" to be constrained by the grossly numerically sized "outside", as was the traditional approach to ESSD (e.g. Figure 5(a)).

FINAL REMARKS BY THE AUTHOR

In conclusion I want, once more, to thank all the contributors to the discussion of the main paper in this first Special Edition of the IJME. They have greatly enhanced the value of the main paper by not simply endorsing its message that "ESSD of complex vessels is sophisticated", but, through raising some challenging issues, added to that conviction. I do hope, as several of them suggested, that the paper's argument (despite its inevitable length in marshalling that argument) will be taken up by the many members of the profession engaged in ship design. It would be good if the current discussion could be continued in the Discussion section of subsequent Issues of the IJME and beyond.

Let me pose one obvious issue which I thought might provoke discussion and that is my attempt at Section 7.1 and in the right hand side of Figure 30 to show how the process of an architecturally based ESSD approach for a new ship project could be structured, while still holding on to as divergent and creative design intent as can sensibly be achieved in the real world.

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