IS A NAVAL ARCHITECT AN ATYPICAL DESIGNER – OR JUST A HULL ENGINEER?

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ABSTRACT

As the demands for future ships become ever greater, due to economic pressures to achieve "value for money" and due to assumptions of more precision in potential ship solutions, then the question to be addressed is whether the naval architectural profession is still best placed to lead in designing complex ships. Other disciplines might be seen to be more relevant in meeting specific ship demands, such as the marine engineer in achieving better fuel efficiency and greener solutions or the combat systems engineer for future naval vessels. Beyond these two disciplines the complexity of particularly naval ship design has led to the generic project management discipline of systems engineering being promoted as more appropriate than naval architecture as the lead discipline. Thus the naval architect becomes a mere "hull engineer" practicing the specific "naval architectural" sub-disciplines, instead of being "primes inter pares" in managing ship design and acquisition. Such a proposal arises both from a belief that the whole ship safety issues need the senior most naval architect's main attention and that systems engineering rather than the naval architect's design skills are best for the overall management of design and acquisition due to its agnosticism with regards to the cross disciplinary conflicts that arise in such a highly interactive multi-disciplinary exercise.

This issue is explored by considering what are the essential engineering skills employed by a naval architect as the ship equivalent, for large constructional projects, of a terrestrial civil engineer and whether this is just "hull engineering" or something more like the ship equivalent of an architect for major constructions, such as airport termini. This leads on to consideration of whole ship design as being both the creator of an initial design synthesis as well as maintaining downstream the overall design coherence through exercising design authority for the design's existence. A series of pertinent views on ship design and relevant case examples are considered in order to address these issues beyond broad generalities. These examples include historic cases of "good" and "bad" ship designs and what might have contributed to such subsequent conclusion as to those designs' veracity. Beyond actual built ship designs, case studies produced at UCL both by MSc student and by the author's Design Research centre are presented to provide the basis for refuting the view that disciplines, other than naval architecture, can effectively lead future ship designs. However such a conclusion is only seen to be defensible if the naval architectural profession gives as much emphasis to its understanding and practice of ship design as it gives to its traditional "hull engineering" responsibilities.

"He ends, of course, by satisfying neither the Commander who is responsible for the men's living conditions nor the Gunnery Officer who is responsible for the guns, but that is the natural fate of the designers of ships – the speed enthusiasts, the gunnery experts and the advocates of armour protection, the men who have to keep the ships at sea and the men who have to handle them in action all combine to curse the designer.
Then comes the day of battle and the mass of compromises, which is a ship of war, encounters another ship of war, which is a mass of different compromises, and then, ten to one, the fighting men on the winning side will take all the credit to themselves and the losers – such of them that survive – will blame the designer all over again."
C. S Forrester "The Ship" (1942)

KEY WORDS

Naval architect, ship designer, hull engineer, Complex ship design

INTRODUCTION - WHAT IS A NAVAL ARCHITECT

It seems appropriate in a regular forum that is focused on marine design to question whether the engineering discipline – that of naval architecture – which has to date dominated ship design practice, still remains best placed to continue in that role. While it is always good to ask such fundamental questions regarding professional practice, it seems we are at a particularly appropriate and pertinent time in the maritime domain to investigate this issue. Not only is the global political, environmental and economic situation evermore highly integrated and interdependent, we are also in an era of very rapid technological change. This is particularly the case with regard to communications, access to data and increasing recourse to expanding application of "artificial intelligence" in the manner in which any sophisticated process, such as marine design, is being and is to be conducted. As this trend is likely to accelerate, the issue as to how we conduct "marine design" is well worth exploring.

The naval architect is that essentially engineering professional concerned, as it stated by the Royal Institution of Naval Architects, as the founding professional institution concerned with the maritime sector from a, mainly, engineering stance, thus the profession is:

> " to promote and facilitate the exchange and discussion of scientific and technical developments … and thereby to improve the design of ships" (Blakeley, 2010)

Interestingly, the name of the engineering discipline "concerned with design etc. of ships etc.", does not contain the term "engineering" in its title (unlike the larger more general engineering institutions in the UK (as the nation that founded such learned societies) and elsewhere). Thus in the early years of the Industrial Revolution, builders of large scale buildings (master masons) became one of two separate professions, civil engineers and architects, while master shipwrights became naval architects (German, 1978 and Brown, 1983). Such developments in professionalization from medieval craft guilds were led by the UK due to its formative role in large-scale industrialisation. The term naval architecture was adopted from the Latin for ship (i.e. not limited to naval ship design) together with the title already adopted in the slightly earlier professionalization of the design of buildings on a grand scale. Thus architects became responsible for the design and the building management, superceding master masons. The origins of the term architect being from two Greek words, that for leader (*archi*) and that for builder (*tecton*), which might also seem to bookend the issue this paper sets out to address, however whether that is also appropriate to the future practice of ship design is open to discussion?

There is also a view, at least with regard to the primary professional education of naval architects, that the nature of naval architecture is essentially "applied mechanical engineering" (Rydill, 1986) rather than warranting a wholly separate first degree. A similar argument could also be made for aeronautical engineering, which also has first degrees in its discipline, and for automotive engineering, which tends to stick with general mechanical engineering for first degree education. Having a broad engineering first degree would seem consistent with the primary distinction between civil and mechanical engineering given the latter focus on machinery, especially steam and internal combustion engines, rather than the civil engineer's focus on structural design. This is somewhat ironic since many naval architects expend a lot of ship design effort on the structural design of their new ships (Rawson & Tupper, 1976), albeit alongside applying hydrostatics and hydrodynamics. This raises the question as to why we aren't "applied civil engineers" as the maritime equivalent of the engineers of buildings and large (civil) engineering complexes, such as bridges, dams and rail, dock and air termini? The alignment with mechanical engineering is much more obvious for the other traditional maritime engineering discipline, namely the marine engineer, who is clearly a "specialised" mechanical engineer. All this would seem to justify the term architect as still being appropriate for the ship (and other maritime structures) equivalent of the architect of the (land based) built environment, rather than just equivalent to the civil engineer. Architect particularly captures the holist and creative design role that is still retained by the urban architect, even if modern "celebrity" architects like Gehry and Hadid rely on the structural engineer to practically realise their creations.

It is clear that aside from much of what is seen to constitute naval architecture as "applied (mechanical) engineering", it is the ship design role that gives the naval architect his/her unique role. This is recognised in naval architecture textbooks, thus "ship design is the *raison d'etre* of naval architecture" (Rawson & Tupper, 1976), even though most of such books are taken up with the applied engineering sciences that lead to the discipline being seen as essentially an engineering, rather than a design, discipline. This then leads to the dichotomy posed in the title of this paper, namely, "hull engineer" or designer of ships, which then leads to the corollary that if the naval architect is the latter, then does he or she also constitute the lead discipline in ship design?

The next section of this paper considers the essential engineering skills employed by a naval architect as the ship equivalent of a terrestrial civil engineer, for large constructional projects, and whether this is just "hull engineering" or something more like the ship equivalent of an architect for major construction, such as airport termini. This leads on to reviewing the task of whole ship design, seen as being both that of initial design synthesis as well as maintenance downstream of the overall design coherence and exercising design authority through the design's existence. A series of ship case examples are explored in order to address this task beyond broad generalities. These examples include historic cases of "good" and "bad" ship designs and what might have contributed to such subsequent conclusions as to those designs' veracity. Beyond actual built ship designs, case studies produced at UCL, both by MSc student and by the author's design research team, are presented to provide the basis for refuting the view that disciplines, other than naval architecture, can effectively lead future ship designs. However such a conclusion as to the essence of the role of the naval architect, discussed in the penultimate section is only seen to be defensible if the naval architectural profession gives as much emphasis to its understanding and practice of ship design as it gives to its traditional “hull engineering” responsibilities.

WHAT IS A HULL ENGINEER?

Given that not all engineers qualified as naval architects are directly involved in ship design, the above section’s title is a statement that might well need clarifying with regard to both the necessary qualifications to practice and what actually constitutes ship design. Nevertheless, most practicing naval architects are involved in much of what is taken to constitute naval architecture by undertaking tasks, which may or may not be of a direct ship design nature (see the following section) but are applying some of the engineering sub-disciplines taken to constitute naval architecture. These can be conveniently listed under the “hull engineering” banner, to avoid the term naval architecture, given Rawson and Tupper’s over-ridding emphasis that naval architecture is directly the practice of ship design.

A convenient taxonomy regarding “hull engineering” is provided by the term that the author and a colleague “invented” to cover the naval architect’s concerns in designing a ship – “S^5” (see Figure 1 from Brown & Andrews, 1980). The first four of these “S” terms could be said to cover the sub-disciplines of “hull engineering” and the last (that of Style) covers wider design concerns, and so is more appropriately addressed in the next section. The first four terms were identified as: Speed, Stability, Strength and Seakeeping, and at least those other than “Speed” are very much about ship safety, which remains a primary design responsibility with the naval architect both as “hull engineer” and “whole ship designer”. Each of the “S^4“ considerations are discussed below:

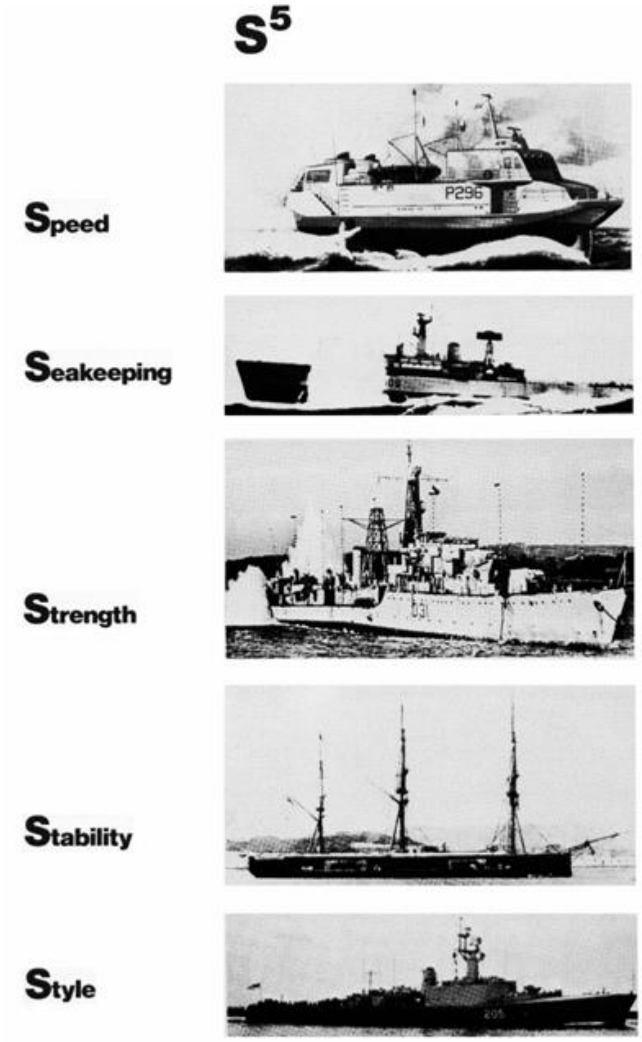

Figure 1: S^5 – Brown & Andrews Original Design Examples

a. Speed

Speed really encompasses resistance and propulsion plus the need for endurance. Given in most merchant ships this is a significant economic (and now environmental) driver, the marine engineer and naval architect have to work closely on the design choices. Unlike most merchant vessels, service vessels and particularly naval ships are characterised by the need to operate across a spectrum of speeds. Thus a high top speed (and very good manoeuvrability at top speed) is required for action to pursue enemy units or to take avoiding action. This need for high speed in extremis then governs the choice of main machinery (strictly the marine engineer's "part of ship") and the hull form (very much the naval architect's responsibility), which for reasonably fast monohulls results in a long, slender (L/B > 8 or 9) and a finely shaped underwater form. However such high speeds (typically around 30 knots) are expensive in fuel consumption if sustained for long distances, so for most ocean going naval vessels endurance is usually defined as (say) 6,000 nm at an endurance speed of 18 or 20 knots. This then requires installation of other engines than those providing the power for full speed, which then can deliver considerably less power for these very much less resistful speeds. This then ensures the size of the fuel tanks is kept as small as possible. Such vessels operating at variable speeds tend to operate for most of their careers at relatively slow speeds and so are way off the hydrodynamically efficient top speed for which their hull forms have been optimised. This is in stark contrast to most merchant vessels, which as part of an economically efficient transportation system (Erichsen, 1978) maintain a constant speed for which their hulls have been hydrodynamically optimised.

For survivability and sustainability considerations naval vessels are likely to have two shafts and two propellers in all but the slowest and less capable combatants, such as some corvettes and Offshore Patrol Vessels (OPV). However, many naval vessels are also distinct in having a primary need to reduce their underwater noise signature to minimise their detection by submarines. Not only can this lead to very expensive machinery and propulsion arrangements, which further increase the cost of such ships acquisition and through life support, it poses significant challenges to the naval architect and the marine engineer at their many design interfaces in what are already highly sophisticated vessels.

b. Stability

The need for all ocean going vessels to resist the most extreme seas and survive a reasonable level of hull damage is more extreme for naval ships (as usually these have to meet the design limit of three major watertight compartments being breached), which has meant recent combatants have proportionately increased their maximum waterline beam. This has had the consequence in trying to maintain high top speeds being harder to achieve and results in a clear conflict between these first two "S^5" aspects, something not seen as starkly in merchant ship design. The need for modern naval vessels to have ever larger radar antennas at the top of high masts, to increase the range of detection in-coming missile (see Figure 2 of the RN Type 45 Destroyer), coupled with light-weight machinery has further exacerbated this trend. A particular safety concern for the naval architect, where large graving docks are not used for assembling and "launching" a new ship, is that of dynamic launching, where the scope for major catastrophe is significant (as occurred with HMS OCEAN (Johnstone-Bryden, 2018)).

One combat driven innovation, the introduction of flare to the hull above the waterline, adopted for radar cross section (RCS) reduction, has led to modern warships being less likely to degrade in stability as their weight increases through life. This increase occurs from unplanned accretions and new (largely combat system related) equipment being installed later in the ship's life. The need to upgrade antenna fits is usually due to emerging new threats or new technological developments, with the latter arising from electronic equipment, in particular, having shelf lives much shorter that that of most ships. A ship's life is typically 30 years, which means some 50 years design life for a new naval ship class from initiation to last of the class going out of service), unless the ship has a major life extension. (The US Navy is contemplating, for their colossal (100,000 tonne) aircraft carriers, a life of 50 years plus 50 more, after a major rebuild.)

The need to survive and continue to function after extensive damage means for naval vessels that particular attention has to be paid to watertight integrity. Thus there are no "closeable" doors in the numerous watertight bulkheads (WTB) below the main access deck. Each watertight section can only be accessed by through deck hatches, closed in higher action states and with scuttles providing a secondary means of escape from compartments below. All penetrations through WTBs are paid special attention with glands and rapid closures of pipework and ventilation trunking on both sides of each WTB. All this contributes to the complexity of naval ship design, construction and maintenance with yet further significant cost implications.

Figure 2: RN Type 45 DARING Class Destroyer (US Navy Credit)

c. Strength

The structural design of naval vessels is similarly complex and costly, when compared to most merchant ship practice. Investment is made into light and structurally efficient scantlings with closely spaced longitudinal framing and extruded or fabricated “Tee bars”. The latter are much more structurally efficient than asymmetric sections adopted for cost reasons in merchantships, which usually have proportionately fewer larger flat or bulb sectioned stiffeners. This naval practice is adopted both to keep the structural weight fraction as low as possible (as the largest single component of such ships’ displacement) and ensure the structure better resists explosions, in particular those underwater that impose extreme hull girder longitudinal “whipping” (See Figure 1 example 3). The latter is an extreme form of slam induced whipping that can occur to any ship in heavy seas leading to bow emergence (See Figure 1 example 4) which can, potentially, lead to breaking the ship in two. Also, for both structural efficiency and shock resistance, naval ship structural design practice is to incorporate sophisticated structural joints where transverse frames and deck beams meet and where orthogonal stiffeners cross (Faulkner, 1965). Such good connections ensure strength integrity is maintained.

Three simple guidelines help minimise the likelihood of structural collapse of naval structures under action damage:-

i. keeping design stresses low;

ii. having as deep a hull as possible, so less of the hull is likely to be destroyed (This is also good for seakeeping but raises the ship’s centre of gravity, with further consequences on increasing waterline beam (see Stability above));

iii. avoiding structural discontinuities – such as break of fo’cstle (especially amidships, as was the practice in WWII destroyers) or not ending deckhouses on WTBs. Thus WTBs also have a major structural function – as so often in ship design, features or components often provide more than one function.

So achieving a robust navalised structural design will cost money in design effort, fabrication and TL support. For this reason navies are increasingly using classification societies to see if some degree of commercial practice (as already has been adopted for some naval auxiliary vessels, such as fleet replenishment tankers) can be adopted in naval combatants to keep cost down at some debatable risk.

d. Seakeeping

While good seakeeping is a virtue in all ship design, naval vessels are characterised as not being able to adopt weather routing, increasingly reliable for transportation merchant ships, since naval ships must meet operational needs, so requiring their immediate deployment regardless of weather conditions. Thus even before the adoption of computer simulation of ship motions in a (real) random seaway, naval vessels were designed for good seakeeping. This has meant adopting features such as: raised fo’cstles; high freeboards; bridges positioned someway from the bow; roll stabilisation for both gunnery performance and helicopter flight deck operations; and positioning seaboat launch and recovery arrangements in the ship’s waists. The waists are also where some replenishment at sea (RAS) takes place; a difficult evolution necessary to keep naval ships refuelled and rearmed/stored for extended ocean deployments.

Flight decks are ubiquitious, even on relatively small frigates (say < 3000 tonnes displacement and some 100m waterline length) and are increasingly fitted also to non-naval offshore support vessels. Despite the probabilistic nature of sea conditions, it is now possible to model a ship's seakeeping response to assess whether, say, the helicopter or unmanned air vehicle (UAV) can operate off a given ship's flight deck in high sea states and for a range of ship's speeds and headings. The design choices can still remain problematic, since for a combatant the "optimisation for seakeeping" typically balances fo'c'stle wetness, flight deck movement, motions on the bridge and slamming of a bow sonar dome, all of which require conflicting whole ship features to be maximised (Lloyd 1992). This is yet another example of naval ship design being a mass of compromises (Purvis 1974). For larger naval vessels, seakeeping is less likely to concern these issues and be more one of needing to ensure in high sea states, for example, that large side openings are positioned to avoid water ingress from high waves (Honnor & Andrews 1982).

e. Other disciplines involved in ship design

Part of the issue with the whole problem of what naval architects do both for those designing ships directly and the many more involved either less directly in ship design or "just" in a specific aspect of hull engineering, is that like so much of complex engineering design they do not work in isolation but part of a wider team. Thus we need to consider the roles of the other principal disciplines, not all of whom are engineers.

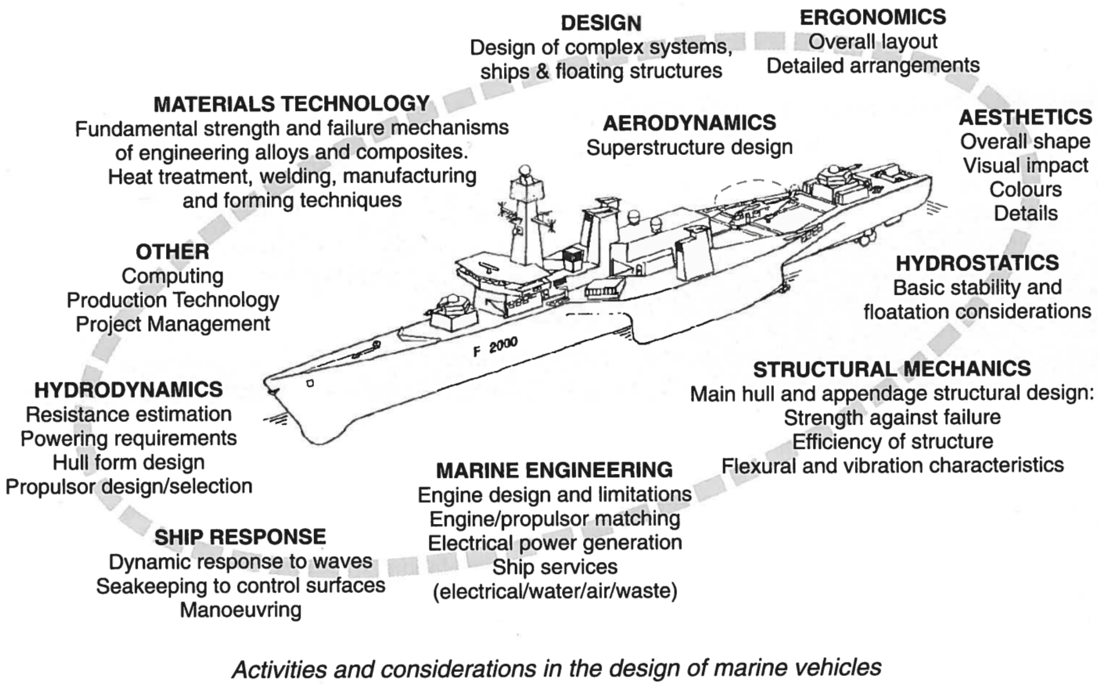

Figure 3: An indication of the topics relevant to ship design (Andrews 1996)

While Figure 3 shows the various topics that might be involved in the design of a new ship, many are encompassed by those disciplines assigned to the naval architect (e.g. hydrodynamics, hydrostatics, ship response and structural mechanics – matching the "S^4" already outlined). However the obviously separate engineering field (as opposed to design related topics in Figure 3 such as design itself and aesthetics and ergonomics) is that of marine engineering, which can be seen as directly applying main stream mechanical engineering to ship propulsion machinery installed in ships. Thus the marine engineer is responsible for a host of vital equipment and its integration on-board the ship. This then introduces an important set of interfaces with the naval architect, not least being the propeller, which is the design responsibility of the naval architect due to its interaction with the underwater hull design. Despite the marine engineer having a major role in operating the ship (unlike the naval architect who rarely goes to sea) and often having operational responsibility on-board for the naval architect's "part of ship" (e.g. operational actions to deal with damage stability occurrences), he or she is primarily limited in the ship design process to a focus on the machinery spaces.

However, one area where the marine engineer has a growing involvement in modern ship design is with regard to environmental concerns and in particular ship machinery emissions into the atmosphere. The merchantship domain has largely taken the lead due to the extent of global commercial shipping and the greenhouse effect of marine diesel fuel consumed by the world's substantial merchant fleet. However, as with the highly integrated system that is a ship, the challenge to reduce ship emissions is a whole ship design task, one that also heavily involves the naval architect if the issue is to be effectively dealt with (Calea et al, 2015).

While the marine engineer has a core mechanical engineering commonality with the naval architect, in their basic engineering education, this does not apply to the electronics based combat system engineer, the third key player in naval ship design. Despite guns, missiles and torpedoes at the "sharp end" of their business having considerable mechanical functions in their handling and launching from ships, it is the sophistication of the electronic control of them that gives the combat systems their performance edge. Furthermore it is both sensors (radars, sonars and communications) and the combat system management wherein the primary focus of integrating their combat effectiveness lies in a modern naval combatant (Baker, 1990). This is therefore where the tools and practice of systems engineering dovetails closely with the main design responsibility for the overall combat system in a new naval vessel. The interface of the combat systems with the main ship design is thus complex and difficult, as the latter is much more physically grounded (due to whole ship implications, i.e. "S^5") than the data management abstraction governing combat system design. Clearly in merchant ship design, while electronics and automation this enables is growing, there is not the same conflict as there is between the naval ship designer and the combat system designer.

There are also other engineering disciplines involved in ship design, many of which deal with discrete and often distributed systems, such as HVAC which can often be under the ship designer's overall responsibility. Other specialist skills and expertise may be very specific to the particular ship and often arise from operational needs, be they specific cargo handling or even for specialist service vessels, offshore functions such as rig support or autonomous vehicle launch and recovery systems. A very specific and longstanding example of a demanding design interface is that to integrate aircraft operations at sea. Leaving aside the whole issue of large scale naval operations off aircraft carriers (Andrews 2005), many ships, such as offshore support vessels and naval combatants, have helicopter facilities, which can dominate that ship's design. A classic example of this was the Canadian DDH-280 Tribal Class (Farrell et al, 1972) where the design manager considered not just the ship's visible upper works but deep in the hull that the after half of the ship was dominated by the need to fully support two large helicopters (i.e. Sea Kings). This was because the ship was not just the platform for the aircraft but had to provide the equivalent of a small airfield's facilities. This requires the ship designer's special attention, given the highly sensitive vehicle that has to operate for extended periods in the demanding maritime environment.

(An aside on the above, which needs flagging, is with regard to the usage of the term "platform" to describe a (naval) ship. The Canadian Tribal Class was providing a platform for those helicopters, however it is wrong to use the term "Platform" to describe a naval vessel as such. It is a whole system of systems and the further split into "payload and platform" (i.e. Combat system and the "rest of the ship") is a very bad design mind-set. It implies the former is good and must be maximised at the expense of the latter. Given the so-called "platform half" of a ship provides flotation and mobility, both of essential military worth, as well as the infrastructure for the personnel (who are "fighting" the ship) and the supporting services without which the combat system elements could not function at all), this shows the utter nonsense of the previous sentence, in not seeing the system as a whole. Thus all the interdependent functions contribute to the vessel's capability, which means there is no unnecessary "overhead" to be minimised.)

One domain where there has been an interesting challenge to the naval architecture discipline has been in offshore extraction of petro-chemicals. Initially the extraction was achieved using fixed concrete structures, which meant that the civil engineer led on such designs, but once deep fields required floating structures with extensive personnel and processing facilities, then these structures became more ship-like. This has now led to FPSOs based on VLCC ship configurations (albeit with extensive processing plant in addition to that provided on a typical oil tanker).

The final and obviously key discipline in ship design is the non-engineering ship operator, distinct from the marine and electronic engineers also on-board. As the primary user, if not the owner paying for the design to be realised, the "sailor's" input to the design is critical. Historically the link between the designer and seafairer was the main one until the shipbuilder then executes the design intent. In the merchantship sector major shipowners used to retain their own design teams (Meek, 1982) and this ensured the shipping company's practice was reflected in the design intent, subsequently worked up by the winning shipbuilding team. The naval equivalent to this practice was the substantial in-house design and acquisition organisations maintained by major navies (Brown 1983, Tibbitts, et al, 1993), which until very recently acted as their own classification society drawing on extensive in-house research facilities. (Only the UK has privatised its original towing tank capability, among major navies.)The relationship between the naval ship operator and the naval ship designer has been key to producing appropriate ship designs but that can be seen to have declined in recent years, just as the social science of ergonomics or human factors has become more scientifically based and sophisticated (Nautical Institute, 2015). The change in merchantship design practice can be attributed to the purchasing of more standard ships driven by fierce competition between shipyards, particularly in the Far East. For naval ship design the change has been more subtle and largely due to the ascendancy of the combat systems engineers spanning both requirements and solution senior management. There has also been an observed decline in the naval architect's role as lead designer/project manager, where often the latter has been undertaken by the generic systems engineer, who may be a combat engineer that doesn't even see the need to draw upon any maritime experience. This can be seen as a consequence of the mind-set that sees these immensely complex vessels as just another "military platform" and so just requiring project management skill to bring them to physical realisation, rather that needing an intimate knowledge of not just ship engineering but also wider design and operational insights that ought to be that which typifies a naval architect's development into a design manager and project director (Andrews, 1993, 2016).

WHOLE SHIP DESIGNING

The naval architect's design role

The previous section having outlined the primary elements of "hull engineering" and then considered those involved in ship design other than the naval architect, concluded that the naval architect's hold on their traditional role of ship design lead was increasingly being challenged. This is despite ship design being seen as the raison d'etre for naval architecture (Rawson & Tupper 1978). It is therefore now necessary to consider what designing ships as an engineering practice is actually about.

The Royal Institution of Naval Architects (RINA) as the premier international professional institution for naval architects lays down what – having obtained the appropriate academic qualifications (see the penultimate section) – a naval architect needs to accomplish beyond those qualifications to be deemed fully qualified to practice (www.rina.org.uk). The first two years in employment post-graduation are still for training and require three broad areas of post-academic on-the-job study to be addressed:-

1. Design, which consists of analytical skills being applied, doing design itself, learning communications skills and acquiring technical information (an obvious burgeoning aspect) plus materials awareness (seen as necessary given the limits in hands on practice at university);
2. Engineering Practice, which is seen to cover shipbuilding production processes, safety and legislature issue, quality control, production management, commissioning new ships and procurement issues;
3. Management Services, which could be said to distinguish wider engineering practice from even applied science, with topics such as accounting & finance, human resources and quality assurance, company structure & organisation, marketing & communications and finally (and somewhat appropriate given the conclusion of previous section on design and project leadership/management skills.

Thus design is rightly highlighted as key, however the above listing on design also covers the application of the analytical skills acquired in an engineering degree and this then distinguishes engineering design from other (likely to be more artistic) forms of design (Andrews 2012a). Also included in the broad area of design above is communications, which links to management skills and information, which recognises the seed change in large scale design practice where most engineering designers work. Materials seems an odd topic to pull out (being the least analytical of those covered in an engineering degree), but of course it is a vital topic in designing for the extreme environments in which ships have to survive. The other two broad areas above are considered further later in this keynote.

The nature and form of engineering design that designers of the most complex vessels practice has been the subject of considerable study, not least in IMDC papers and State of Art reports (Andrews and Erikstad, 2015). Furthermore the author has characterised the high end of ship design as the design of physically large and complex (PL&C) systems. The design of such systems is seen to also include that of large scale civil engineering and architectural constructions, such as dams, transport termini and public buildings, as well complexes, such as major chemical processing plant. Given all these are one-offs without prototypes, this distinguishes their design and construction from prototyping and production line manufacturing that applies to other vehicles, much smaller than ships and submarines. Again there is a link to the structural design challenges akin to those of the civil engineer and the conflict between that profession and the architect, one that largely does not exist for the naval architect at a design level. However, increasingly for very large and expensive maritime projects, such as major naval vessels and offshore constructions, the coordination and project management role of the naval architect is being questioned. To some degree the demands of "hull engineering" in an understandably more safety obsessed world have led to this, rather than design leaderships and acquisition coordination being seen as the primary function of the naval architect in ship design.

As part of emphasising that the naval architect's role as "the ship designer", rather than just the hull engineer, this author has focused his research and publications particularly on the initial stages of the design of complex vessels. This is because it is acknowledged that the first design phase for such vessels, the concept phase, is the most crucial in that it is then that the major design decisions are made. This is despite the fact that much greater design resources (and hence the generality of engineers and naval architects efforts) are employed to progressively work up a selected design solution – the devil being in the detail (Andrews 2013). For this reason not only has the author pioneered a more comprehensive approach to early stage ship design but done so by insisting that modern ship synthesis be an integration of an architectural ("inside-out") as well as a largely numerical balance of gross weight and space (Andrews, 1986, 2003). This has led to an emphasis in the final "S^5" component, that of Style summarised in the next part of this section.

Style addressing the transversals and categories of style

For complex vessels the style to be adopted in a specific ship or submarine design option is seen to be the key design decision for that option and so is the first design decision (beyond deciding that a certain range of solution options is to be investigated). This is indicated in the overall ship design process representation shown in Figure 4 where each step or decision selection is explained more fully in the appendix to Andrews (2013). Thus Selection of the Style of the Emergent Ship Design is the first design choice and can be seen to impact at the macro, major and micro levels of the emergent ship design. Macro level denotes the overall style of a design or preferably a design option, whether it is, for a naval example: a conventional monohull; a more utility or austere design; or a radical configuration, such as a trimaran or SWATH. Below the macro level there can be seen to be some major style choices, such as adopting commercial design standards for a utility helicopter carrier (e.g. HMS OCEAN) or achieving a very low underwater signature for an ASW frigate (e.g. the R.N. Type 23). This level can also cover generic style choices, such as being robust or highly adaptable, or having (say) high sustainability or low manning. It can be seen that these major "Style" choices are largely made by the naval architect, provided they have the requisite skills (both in knowledge and experience) to carry out a new design synthesis. Clearly such design decisions should not be made without involving the key stakeholders and the extent of this involvement is once more the naval architect's call. When such key decisions are not made or choices achieved by default then the naval architect is failing in their role as the primary ship designer. A clear statement of this is due to Baker and is outlined in the next section.

While adopting such style issues is inherent in commencing any design study or a specific option in a series of more exploratory studies, it is important that this is done consciously. This is good design practice since each choice has implications for the eventual design outcome and therefore ought to be investigated before that style aspect is incorporated or rejected. Beyond major style choices are a host of minor style decisions often predicated by the first two levels. These in some sense can be seen as reflecting Ferguson's (1992) observation on engineering design practice, that "Design layout and calculations require dozens of small decisions and hundreds of tiny ones". However, lack of coherence regarding style can mean that at all three levels these decisions are not always made with consistency and so can introduce, at best, inefficiency into the eventual design solution.

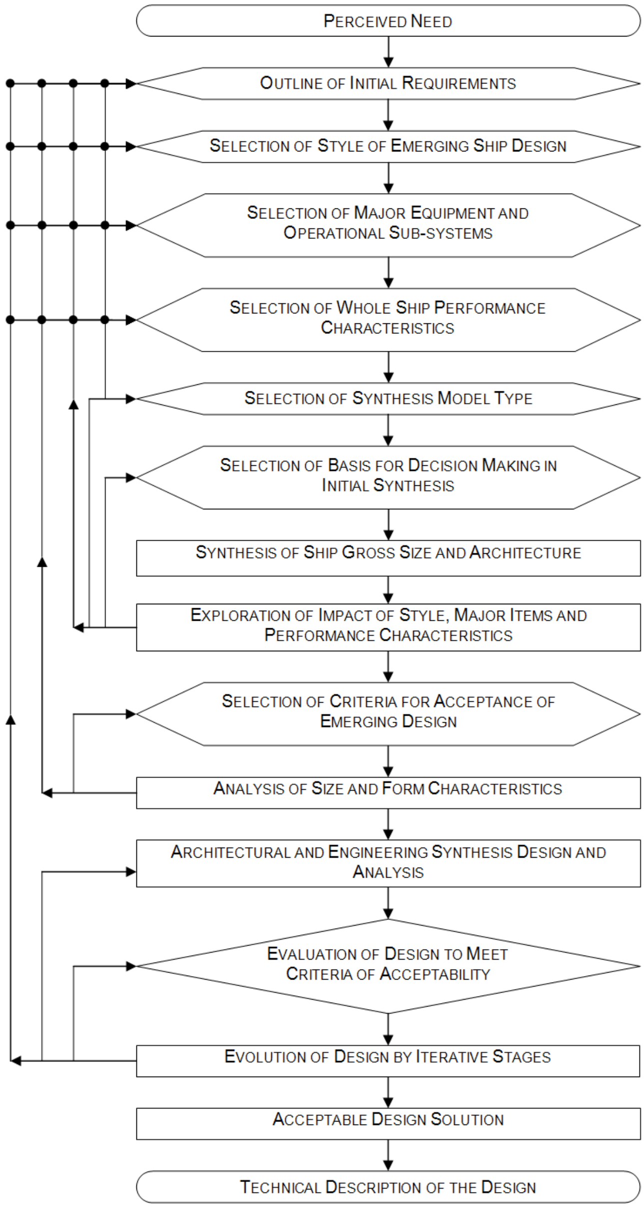

Figure 4: A representation of the overall ship design process emphasising key decisions with Style as a critical initial choice

The term design style was originally proposed to distinguish a host of disparate issues distinct from the classical engineering sciences applied to ship design (i.e. "S^4" for the naval architect). Many of those issues could be seen to be on the "softer" end of the scientific spectrum drawing on the arts and humanities (Broadbent, 1988), whereas the first four terms under the "S^5" umbrella are, historically, the principal naval architectural (engineering sciences) sub-disciplines associated with a ship's technical behaviour. Thus Style was devised to summarise those other design concerns, which in Table 1 are listed for both a naval combatant and a commercial service vessel (OSV). This very disparate range of issues, have been categorised under some six headings that (ship) designers understand. Thus, for example, concurrent engineering concerns, such as Producibility and Adaptability, are encompassed by the heading Design Issues in Table 1.

Importantly these style issues can make a substantial difference to the final outcome of a design, so their relative impact ought, in the case of a complex ship, to emerge from a proper dialogue between designer and client (or in the naval ship design case, the operational requirements owner). Furthermore, most of these issues have been difficult to take into account early in the design process because, usually, initial design exploration has been undertaken with very simple and, largely, numeric models. These can only summarise the likely eventual design definition and give a feel for the cost to acquire the fabric of the ship, which is therefore often dubious (Andrews, 1994). That dialogue can now be informed by also concurrently producing a graphical architectural representation of the ship's configuration and internal architecture, as is reflected in the process summarised by Figure 4. This process reflects the architecturally (rather than solely numerically) driven synthesis and has been demonstrated through applying the author's Design Building Block (DBB) approach (Andrews, 2003). At the critical early design stages, such a computer graphics based approach can then enable the ship designer to take account of likely significant issues, such as those listed in Table 1. Given these are diverse and not readily consistent or comparatively quantifiable, means that designers need to exercise judgement. Preferably, those judgements are informed by dialogues with stakeholders and the dialogues are best achieved using an architecturally driven representation, which are more informative to non-designers and ship operators than tabular data and technical outlines.

Table 1: Comparison of style topics relevant to a naval combatant (all) and a commercial service vessel (OPV) (underlined)

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	Producibility
	Shock		Upkeep by exchange	Design point (growth)	Adaptability
	Corrosion			Board Margin (future upgrades)	
	Damage control				

The categories adopted in Table 1 reveal the heterogeneous nature of the specific individual style issues, for a complex vessel. Thus, there are the specific naval concerns with the vulnerability of ships to modern weapons addressed by the various items under Stealth through the many different signatures, which a ship has and then these need to be reduced to avoid detection. The Protection items are largely aspects only worth incorporating in the naval ship to mitigate the results of weapon effects, should the Stealth (and any "hard kill" self-defence) fail to be totally effective. However, some of the Protection items are required for any vessel, namely, corrosion control, or measures to mitigate the effects of collisions and fire onboard. The Human Factors aspects are little less coherent (and it might be argued rather more solution oriented than those comprehensively considered by the urban architectural theorist Broadbent (1988)). Broadbent addresses some 21 "human sciences" that he considers are relevant to human habitation – and hence most are also likely to be appropriate to addressing HF in all ships. Some HF issues lead on to the important growth area of automation, which along with micro-ergonomics (e.g. console design) has a strong input to the Protection category, specifically in regard to modern bridge design.

Sustainability is a major consideration in naval ship design and could be said to be a major driver. Hence the relevant measures to be adopted constitute a key hidden decision in the style of such ships from the beginning of any ship design study. For most merchant ships the style of maintenance to be adopted is often fully mandated by the owner's technical team, leaving the ship designer little scope in this regard. The list of Margins just makes the point that there are many features and considerations beyond ensuring there are direct margins on the weight/VCG estimates, where the latter ensure the ship's stability is adequate beyond the day it is accepted into service. Table 1 also distinguishes those margins required for unplanned (but in naval vessels consistently observed) growth in weight and rise in VCG, once in-service, from Design Margins. The latter are more rightly categorised as a Design Issue in Table 1, given they address many likely measures of uncertainty in early design estimates. These margins, across all the weight/space groups, are intended to be absorbed but not exceeded as the design and build process progresses to completion. This has been a major focus for naval ship design as the consequences of any being exceeded on sustained deployment can be significant. One reason for resorting to new naval ship designs has been the expense of retrofitting new capabilities, which has also led to the questionable measure of stretched (repeat) designs (e.g. R.N. Type 22 and Type 42 combatants) and to avoid expensive mid-life upgrades by mandating short life designs (e.g. R.N. Type 23, which succeeding UK governments have then failed to abide by). This issue of building in adaptability to anticipate changes in a ship's role and in the market has only recently been seen as an issue in commercial service vessel design (see Gaspar (2013) who applied the M.I.T. Epoch-Era approach to OSV design).

The last category in Table 1 is clearly the most broad and heterogeneous. Also, generally making such choices on these topics can have the biggest impact on the final ship design. But this means they need to be recognised as choices and then properly considered with the owner/requirements team from the beginning of studying any design option. Some of these have been the objects of particular investigations by the author's research group at UCL. They are discussed further in Section 5 as examples of the impact on the ship design of considering separately some of these particular issues, where each could be seen as the specific driver of a design from its initiation. It is noticeable that certain of these issues can only be adequately investigated in the Concept Phase if the architectural synthesis assumed in Figure 4 is adopted. The other feature of most of the Design Issues listed is that they have a qualitative or fuzzy nature. Thus, say, Robustness implies a greater degree of that quality than the "norm" for that type of vessel. This then raises the point that such a "norm" for a given new design option ought itself be defined but is often just accepted (or inferred) as being "current practice" or by the adoption of existing standards. There are also exceptions in the listing of the Design Issues category, like Aesthetics, which for most ships, other than mega yachts and some cruise ships, is seen to be "a luxury". However, even this can be seen to be a simplification, as in the Cold War there was considerable debate in the US naval ship community as to whether the physical appearance of such a ship was part of its political "armament" (Roach and Meier, 1979). Furthermore, it could be argued that this is another design area where naval architects might have "lost their way" as it is the case that a hansom vessels remains a source of pride to its sailors, despite being hard to precisely quantify against the bottom line but nevertheless remains a significant part of design creativity (and even in marketing a design's acceptability to stakeholders).

Recognising Design Novelty

The nature of the design of complex ships, such as cruise ships and naval combatants, is such that the need to emphasise the importance and difficulty of early representation of style issues is seen to be a further complication in the practice of designing such vessels. This is due to there being, additionally, a wide range in the practice of such design. This arises from the degree of design novelty adopted in a specific design option, as is indicated by Table 2. This shows a set of examples, across the field of ship design, where the sophistication in the design undertaken ranges from a simple modification of an existing ship, through ever more extensive variations in design practice, to designs adopting, firstly, radical configurations and, beyond that, radical technologies.

The first of the last two categories of Table 2, a radical configuration yet still using with current ship technology, is often explored yet such options are still rarely built. This is due to the risk of unknowns usually exacerbated by the lack of investment in a real prototype. Furthermore, radical technology solutions are even more rarely pursued. In part this rarity arises because such radical technology solutions require recourse to design and, indeed, manufacturing practice much more akin to that appropriate to the aerospace industry. Thus new major aircraft projects, typically, require massive development costs (including several full scale physical prototypes, some tested to destruction) and additionally need tooling and manufacturing facilities to be specifically designed and then built, before extensive series production of each new aircraft design can commence. This is of course quite unlike most ship design and manufacture, be it the ubiquitous bulker or the most sophisticated naval vessel. Such distinctions as those of Table 2 for the design of complex ships suggest that, at least, to recognise that there is a spectrum of design approach resulting from the novelty of the specific design option being pursued, needs to be consciously considered. Such choice on design novelty is key to the initial style choice for a given design study or a variant option in a properly conducted concept exploration, which then considers the need for a new vessel through a properly conducted Requirements Elucidation process (Andrews, 2013).

Table 2: Types of Ship Design in terms of Design Novelty

Type	Example
second (stretched) ba	RN Batch 2 Type 22 frigate a Batch 3 Type 42 destroyer
simple type ship	Most commercial vessels and n naval auxiliary vessels
evolutionary desig	a family of designs, such as V corvettes[1] or OCL container sh
simple (numerical) syn	UCL student designs
architectural synthes	UCL (DRC) design studies (s Section 6.2)
radical configuratic	SWATH, Trimaran
radical technology	US Navy Surface Effect Ship 1970s [3]

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

Both this issue of understanding the novelty of a design option (and thus the use of appropriate design methods and tools) along with the key style issues to be investigated, are the design team's main concerns early in the ship design process. However, it can be seen that all those concerns listed that are relevant to the naval architect, as the ship designer, plus the fact that many are exclusive to that ship design centred discipline means the naval architect is uniquely placed. The inherent sophistication of the earliest stages of the design of complex vessels has often not been recognised, even by many practitioners. This sophistication has been argued by the author from his earliest publications and a recent series of papers, dealing with elements of the process, have culminating in comprehensive article encompassing the topics presented in the individual papers and is being published this year (Andrews, 2018). This comprehensive statement and the scope of responsibilities ought to be sufficient to make the argument that this paper is addressing but it is considered that some further issues need to be addressed before a few explanatory case studies are outlined to reinforce the argument.

THE NATURE OF DESIGNING A COMPLEX SHIP – WHY THE NAVAL ARCHITECT IS THE RIGHT DISCIPLINE

It is now appropriate to draw on the thoughts of three late 20th Century ship designers for their very pertinent views on this subject. Their views seem to further justify the assertion in the title above, making it clear that naval architecture IS the ship design discipline. This then leads on to whether the naval architect should also be the ship design manager, furthermore if a major ship acquisition project should have a project director, who will have more than just design responsibility, should they also be a ship designer? This is probably less of a given, if not just because we have exceptional examples in Brunel and Rickover ((Rockwell, 2002).

Stian Erichsen

Erichsen was the founding father of the IMDC, originally called the International Marine Systems Design Conference), in recognition that he saw ship design from a systems perspective. His paper "Some Elements of Ship Design" (Erichsen, 1997) considers the topic from a commercial shipping focus, which is a useful contrast to the current author's largely naval vessel design background, which also applies to the other two significant thinkers on ship design who are considered below.

Erichsen starts by considering design, which he sees as: "developing a description of what is to be". This seems to imply that for a new ship the design constitutes the specification, however this doesn't really address the crucial start of the process, which the previous section has highlighted. However, he goes on to state the need for a "platform of starts", which is taken to mean the prerequisites, which he lists:-

- Market demand (wholly appropriate to Erichsen's transportation system);
- Having a concept of the customer, which is seen to be operators and owners but also shipbuilders and the wider public, which not only continues the transportation vessel pattern but with a systems perspective beyond the ship itself or even its wider transportation system to reflect a modern perspective of the design's potential environmental impact. There is less straight forward customer perspective for the naval vessel designer in that there are many stakeholders within government and once the ship is in-service the Design Authority (who may or may not be the actual detailed designer) has the responsibility as the technical owner on behalf of government (Andrews 2015);
- Observe ships, which is always a salutary message in keeping a designer's feet on the ground. The fact that most naval architects don't go to sea once qualified can be felt to be another aspect in which the lead designer can feel unable to exercise a commanding design role, against experienced ship operators. The author was privileged to be part of a post qualification training scheme that gave him over six months at sea in a variety of ships and submarines, which gave him experience into not just the aspects of ship's technical operations but into the mindset of the mariner, for whom the ship is their home.
- Design for the future – this inevitably makes the designer conscious of uncertainty and encourages ship designers to rise to the challenge of being creative.

With Erichsen's definition of design he then goes on to make three clear statements about (ship) design:
1. Design is deciding - which concurs with Figure 4 and which he amplifies:
i. address overall questions first;
ii. design the interfaces before designing "the interfacing elements". (This could be seen as presaging Set-Based Design (Doerry et al, 2009);
iii. have a sequence of rational decisions, which Erichsen was suggested well ahead of approaches like before DSM (Eppinger and Browning, 2012) now being applied to the ship design process. He suggests such a sequence could be applied to linking functional requirements to decision variables, which sounds a little too like functionalism, which has been critiqued in the case of complex ship design by Andrews (2012a)).
2. Design is teamwork, where he highlights:
i. the issue of specialists. This is echoed by the extent of specialists involved in a naval ship design. Andrews (1993) identified over 100 direct specialist authorities dealing with his new project in its Feasibility Phase;
ii. the problem of dealing with contractors. Notably, should the prime contractor's commercial focus lead to them passing on down the chain risks, adding costs and losing design cohesion;
iii. the need for compromise, which is true but the naval architect cannot compromise on safety, nor achieving a sufficiently tight design balance in the overall design;
iv. agreeing a Measure of Merit (MoM), which is possible in Erichsen's transportation system examples, less so in the author's field of PL&C systems, with the "wicked problem" of requirements and their necessary elucidation (see the previous section).
3. Design aids (meaning methods and tools:-
i. Jones' (1980) work on brain-storming is recommended by Erichsen but has been to some extent been over taken by CAD tools, which produce many variants, however this introduces the further issue of the limited rang of variants likely to be produced and actually then reducing the scope for a wide exploration and inhibiting creativity?
ii. different design models can be produced, which can bias the design in detail;
iii. "Look at other designs." Erichsen says experts benefit from learning what other experts do, which could enhance the concept space exploration (Andrews 2013)

Louis Rydill

Rydill was both the first Professor of Naval Architecture at UCL, setting up the MSc Course, with its strong emphasis on ship design, and a senior naval vessel designer. Drawing on the latter role he co-authored the definitive textbook on submarine design (Burcher & Rydill, 1994). In a paper presented to the submarine builders at Barrow-in-Furness, entitled "An Idiosyncratic View of Warship Design" (Rydill, 1986) he concluded with a view of ship design practice, which was based on his extensive career in naval construction. The first part of the paper was a summary of his career, which showed his main design achievements were built on deep ship and submarine knowledge at the cutting edge of the technology post WWII: early research work on submarine control; design work including new structural theory on the first post-War submarines (PORPOISE Class); practical submarine refit management and even teaching naval architecture. All this was good preparation for being the lead designer on the first British nuclear submarine (HMS/m DREADNOUGHT) from 1957 to 1962, where his skills came to fruition. He was then the design manager for the new aircraft carrier (CVA-01), which was subsequently cancelled. He described that as a relief as it ended "the daunting challenge of getting into a 55,000 ton design the capability of the much larger USS Forrestal Class".

Rydill made some interesting design comments on this set of experiences, which occurred prior to arriving at UCL and that was followed by him holding several very senior positions in UK Defence Procurement. From this he concluded:-

- He had been trained as a technical generalist – with benefits and disadvantages;
- He agreed with Rickover's adage that "all knowledge has a half life";
- All naval architects should be taught mechanical engineering to degree level before "specialising " in naval architecture;
- CVA-01's problem was the balance between risk and innovation.

Rydill concluded:

i. The design of naval vessels should be conducted in-house for the critical preliminary design stages as this is necessary to "resist technically bad solutions';

ii. Thus the transition to the shipbuilder for such complex vessels will always be difficult and often arbitrary. (This is interesting to compare with both what has happened in recent years in the UK (Andrews 2012b), and earlier view by the US Navy's then Technical Director (Leopold, 1975), which seems to have been ignored subsequently until the Secretary of the Navy in 2007 (Winter, 2007) stated the US Navy should take back ship design control (if not its full execution));

iii. He concluded on some UK ship designs that the Type 42 Destroyers showed that "small was not (technically) beautiful", the Type 21 Frigates were "pretty but without adequate military value to the Royal Navy" and that the INVINCIBLE CVS Class (Honnor & Andrews, 1980) designed by the Navy and the RCNC was the best post-War ship design;

iv. Submarines were much more free of "bad technical decisions under political pressure" due to their extreme design complexity (Andrews, 2017) but the opposite of that was the 1970's "short fat ship" episode (Andrews, 2012b) on which he stated that controversy was "the reduction ad absurdum of the need to stand up and be counted";

v. Finally he discussed how shipbuilders might take on design responsibility for naval vessels (see references at item ii above) and stated that this should not be by default (or political edict). (He mentions a 1970s report that he commissioned, concluding that adequate intellectual resources need to be applied.) This intent had been challenged by Leopold (1975), who had been both sides of the government/shipbuilder divide. There is the related issue of how design authority, as the bottom line on design responsibility, is exercised. Both Betts (2010) and Andrews (2010) commented on the case of the Type 45 Destroyer class design as to whether Design Authority had been truly exercised by its prime contractor before being restored to government (Gates, 2009).

Rowland Baker

Sir Rowland Baker was the most eminent naval constructor post-WWII, as argued by his biographer and eminent historian on ship design (Brown, 1986). However what I want to do for the purposes of this paper's argument is to focus on a paper written by Baker when seconded as a Constructor Commodore to the Royal Canadian Navy to lead the project for its first indigenous ship design, that of the St Laurent Class Frigates (a picture is given as the example of Style in Figure 1). The paper was entitled "How to build a ship" (Baker 1956a) and though non-technical and for general naval consumption, wonderfully captures Baker's philosophy, which reached final fruition in his project direction of both DREADNOUGHT and the Resolution Class nuclear submarine projects.

Baker starts by stating:

"So the chicken comes before the egg and the ship comes before the staff requirement' The naval staff who must decide what the ship must be capable of doing, can only state a requirement in known terms and this means the staff requirements for a new ship must refer explicitly or implicitly to some existing ship… shipbuilder or designer depends on the staff to say the sort of ship they want, the staff whether they realise it or not, depend on the shipbuilder and designer to indicate what sort of ship is possible."

Thus Baker is consistent with the view of the author in the nature of Requirements Elucidation as key to the Concept Phase for complex vessels (Andrews 2013). He then goes on to list six issues to be necessary to finally produce a new ship:

1. You must have an industry to build a ship.
2. You must have a designer, which Baker interestingly identifies as having:

i. knowledge, which is to "know what he himself can do";

ii. be an artist, which Baker sees as not just aesthetics but almost having “feel”, since: “if it doesn’t look right, it cannot be right (regardless of meeting the staff requirement)”;
iii. achieve a “suitable” arrangement of the compartments (he says more on this below).
3. Someone must require a ship. This Baker sees as the naval staff (for the ships he was procuring), who must:
i. understand how to fight (It was salutary for the UK Ministry of Defence to re-learn some obvious lessons from its war over the Falkland Islands in 1982 (Meek, 2003));
ii. sound knowledge of ships, sea and weapons, which has become harder with fewer ships in the fleet;
iii. what both the crew and materials can do. (Probably the second is the harder for sailors to acquire?)
iv. have judgement, which Baker considers to be: the power of seeking advice; deciding on its quality; and maintaining decisions once made.
v. Thus “a ship when completed cannot be a total success, she can well be a total failure”, which Baker considers to be the chain like consequence of one significant failure in something as complex and interlinked as a ship. He lists failure as:
a. The staff requirement can be wrong (see Preston’s assertion “There are more bad staff requirements than bad ship designs” (Preston, 2002);
b. The design can fail to meet the staff requirement, which sounds straight forward but Honnor’s adage “the best ship design is that which just fails to meet its requirement” reveals the subtlety of the issue (Honnor, 2006);
c. Construction can fail to meet the design requirement, which contractually means the specification (which can never be perfectly watertight);
d. All too common minor failures. (This can in part be down to having no prototypes, with expectations of airplane/car production line delivery, rather than being more like that of the construction industry’s practice with inevitable “snagging lists”. The obvious solution to (often) poor ergonomics is more money for detailed design and quality of outfitting, which is (sadly) has not traditionally been part of the highly competitive maritime culture.)
4. Approving the arrangement provokes two further Baker-isms: “This is probably where the real skill of the designer comes in (of course he has to be a fully qualified naval architect).” “Once everyone is allowed to explore the (n!) “alternatives” the process of design could go on forever. That is NOT the way to build a ship.” Baker’s solution to the immense difficulty of preventing senior (naval) personnel from insisting that their personal design views on arrangements are incorporated into a new ship design was spelt out in his 1955 paper on the St LAURENT Class (Baker, 1956b). Figure 5 shows how his “Stylised” layout restricts allocation of single functions to specific areas of the layout. This was specifically adopted to ensure that “interested parties” beyond the designer, were constrained from “interfering” in the design. This was devised as a design management approach by Baker, revealing his insight into design being not just “hull engineering” but genuine ship design, that meant the naval architect was the design (and project) leader.

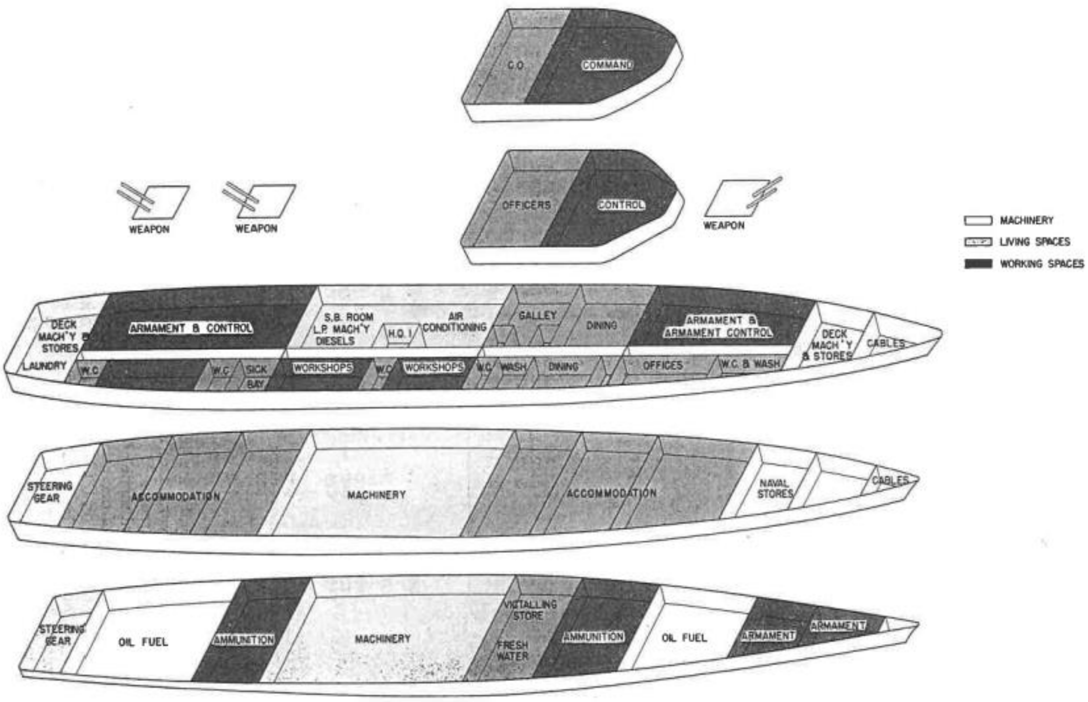

Figure 5: The “Stylised” Layout of Baker’s St LAURENT Class Frigates (Baker 1956b)

Two further overviews were made by Baker, in his article, one on the traditional design control of the whole design as it went into the Detailed Design phase and the second on the need to judiciously order materials for build assembly. In discussing both aspects he very much reflected practice of sixty years ago, with detailed design approval and close involvement in the build by the navy/government. One comment there is very pertinent to this paper's argument "If the hull is poor, the whole thing fails." This again puts the naval architect in the prime professional position in the ship design process, 'though it could be argued against this that greater safety concerns nowadays for the "S^4" hull engineering aspects mean the naval architect can't now lead on the overall project too? Baker's and my response to this would be that only the naval architect can be the overall designer and splitting the wider project aspects, so well integrated into Baker's very successful ship and submarine programmes, from the grasp of the person responsible for the vessel's design issues (such as those listed in Table 1) too often courts disaster.

SOME CASE STUDY EVIDENCE

Historical Ship Design Issues

It is worth going back to the famous Scandinavian example of the "Vasa" to see what happens when the design and the project authority is excessively exercised by a non-naval architect. (In that case King Gustav Vasa over-ruled the Master Shipwright. The latter's predecessor had been an experienced Dutchman, who might have stood up better to his client than a less experienced Swede in (understandable) awe of his powerful monarch. Such over bearing was not that uncommon and it might have been argued knowledge of the effect of excessive top-weight (due to more guns high on the ship) lacked scientific understanding. However if it was observed that a newly loaded ship lolled alongside a strong enough designer (the Master Shipwright) would have known not to let the ship sail? To say such things could not happen in the modern era is to ignore the nature of political power – see the last example below.

Preston in his popular book on the world's worst warships (Preston, 2002) looks over a series of examples, not just some very odd nineteenth century designs, but also cases of ships popularly thought to be good designs, often to boost a competing navy's build programme. Some on closer inspection turn out to be far from exemplary (e.g. Hitler's BISMARCK Battleship, US view of Soviet naval design). In the excellent introduction to the specific design examples, Preston considers six factors, which influence warship design:-

i. cost, which he rightly points out is rarely due to "gold plating";

ii. perceived threats, which Preston suggests are often over blown by intelligence staff with little understanding of ship design (Preston quotes the UK Director of Naval Intelligence on a pre-War Japanese cruiser class' speed, to which the Director of Naval Construction retorted that the figures were either wrong (the case) or the ships were built of cardboard1) ;

iii. industrial capacity, which explained the Royal Navy pre-eminence and now that of the US Navy and hence why both the German and Soviet navies failed;

iv. technical competence, which was an issue in the rapid technological change of the nineteenth century but unlikely nowadays, if not impossible should politicians (or senior non-designers) ignore designers with regard to clear technical issues (see again last case in this section). Preston also points out someone has to take final design (and procurement) responsibility, namely "You can devolve as much of the process as you like to industry, but somebody must carry the can if the bloody thing sinks." (Preston, 2002) (see the whole issue of design authority raised at the end of the sub-section on Louis Rydill's views);

v. the operating environment, which item 2 in Figure 1 well exemplifies and highlights ship designers are designing uniquely demanding PL&C systems of systems;

vi. incorrect post-battle analysis, which the quote from C.S. Forrester's book well encapsulates. One might add that modern recourse to operational analysis, which is actually fraught with dubious modelling of immensely complex and un-measurable reality, presents the ship designer (and the naval staff, who are over reliant on OA) with the need to vigorously challenge any simplistic conclusions that are used to draw inappropriate design decisions (Wood, 1982).

A good case Preston refers to is the synergy between the pre First War DNC (Sir Philip Watts) and the dynamic and forceful Admiral Jackie Fisher (Brown, 1983). Fisher exhibited many of Vasa's overbearing personality traits and had considerable political influence, however he well understood the competence of Watts and his team. Thus Preston states the radical game changer that was "the battleship DREADNOUGHT was not Fisher's 'creation', but a logical progression from the previous design, as proposed to him by an experienced constructor…" which was coherently designed and very competently built by Watts' dockyard colleagues – all facilitated by Fisher's drive.

Rowland Baker features in the second (mid twentieth century) example of synergy between a very eminent naval officer and a ship designer – Lord Mountbatten and Baker (Brown, 1986). Having recognised each other's talents before the war in discussing destroyer design, when Mountbatten became Chief of Combined Operations to develop amphibious warfare to liberate Europe, he immediately got Baker on his staff and got him to develop a whole new fleet of invasion ships and craft. These were so successful that the two of them took the designs to Washington and these became the design basis for the US Navy's enormous amphibious fleets for the Pacific theatre as well as freeing Europe (Baker, 1946). This seems a classic example of ship designer being given the scope to design with clarity of “customer direction” and upwards support not downwards (pseudo technical) interference.

The last case is a salutary example that politics is clearly significant in such complex design and acquisition and can (almost) be disastrous if the government process ignores its own design knowledge and experience. The author was asked to address the 1980s controversy of the “Short Fat Ship” that provoked a considerable debate in the UK press following the Falklands War with Argentina. This was done in an article to the UK Naval Review and published in its centenary book (Hore, 2012) as Chapter 23 (Andrews, 2012b). That article recorded the proposal to produce a short fat frigate to meet the Type 23 requirement was rejected by the UK MoD, because unlike any new hull configuration it was not presented to the naval architecture profession by the normal means of a scientific paper to the learned society (see debate in published discussion to Bryson (1984) paper on the Type 23). As the Naval Review article says, the hullform of this proposal was an extant small craft (UK NPL Series) planing form, inappropriate for frigate size displacements and speeds, and likely to be too stiff due to excessive GM. So the issue was not scientifically considered but initially grasped by politicians as a “miracle cure” tempting when under fiscal pressure. The article concluded the lack of acceptance by the Thatcher government of its own ship designers’ advice says “more than a little about the UK’s decline from its former position of being the leading industrial power”. That such an issue is raised in a technical paper, strongly suggests that a narrow “hull engineering” stance is inadequate if naval architects are to properly exercise their major role as The ship design profession. Design and project leadership, as Rydill said in his comment in the midst of this controversy, requires in such instances as this (and indeed Ro-ro ferry damage stability (Rawson, 1990)) that ship designers “stand up and be counted” (Rydill, 1986).

Some Ship Design Examples from Academia

The ship design exercise conducted in the MSc in Naval Architecture at UCL was set up by Rydill 50 years ago as a form of teaching heuristically ship design, differing from previous undergraduate or post-graduate design exercises. This was informed by Rydill’s considerable ship and submarine design experience, with the following innovations:

i. the main technical exercise started after the (S^4) lectures, assignments and examinations in the first two terms and was then full time until late June (Most ship design exercises in universities take place alongside the “more academic” courses typically one day a week.);

ii. each design is allocated to, at most, two naval architects (and a maximum of two marine engineers), who produce a final naval architecture report, which they jointly own and defend, although in the latter part of the exercise they will divide the tasks between them;

iii. each design is new each year and has only a general outline of need (i.e. a broad statement of need rather than a set of specific ship characteristics – although the hull type (monohull or multihull) will be specified to shorten the exploration of options (unlike a real ship concept exploration (Andrews, 2013));

iv. prior to starting the design full time each team is required to explore the broad requirement (acting as its own naval staff or owner if a merchant vessel), informed by a series of lectures by the MoD appointed Professor of Naval Architecture at UCL (PNA) and invited experts from MoD and industry (this enables the design team to get inside the mind of the requirements owner);

v. One aspect that is predicated is the procurement cost of the eventual design (This is so the design team once they have sized the design meeting their initial specification (of speed, endurance, combat fit, etc.) and then costed it, have to perform trade-off studies to bring the design down to the price ticket – without this the reality of most ship design is missing.);

vi. The naval architect(s) (and separately the marine engineers for the final report and examination) present their progress to mandated milestones every two or three weeks, with the final examination presentation and report to a Feasibility first iteration level (testing the students’ “S^5” knowledge and understanding) is examined by the UCL MSc director (PNA) and assistant plus two very eminent ship designers from MoD/industry. Further detail is given in Betts (1986).

While this above outline emphasises the wider design issues beyond simple ship sizing, parametric survey and working up a preliminary design, the exercise is also conducted in a heuristic manner with the aim to give the students exposure to whole ship design and acquisition. This will then prepares them not to be mere hull engineers but total ship designers and, by inference, project managers, leaders and directors of major maritime programmes.

An interesting set of lessons on the nature of the ship design process have been seen from certain of the many ship design exercises the author has been involve with in his several positions at UCL. Some years ago there were marine engineers with electronic (rather than power electrics) background in the ship design groups and thus able to look at the combat system choices rather than just propulsion and power distribution. For naval ships the combat system can be seen to be a major driver and therefore this produced a more intense dialogue as to who could make the significant design decisions than the marine engineers and naval architects dialogue. This in a way mirrored some of the conflicts in modern warship design where the cultural conflict seemed to lie between what can be considered as physical engineers (mechanical and civil) and electronic or systems engineers, who are less concerned with human scale physics and more with data flow and information process.

Having said there is usually more cohesion between marine engineers and naval architects, partly because the former tend to focus on their geographically limited part of ship, there can be tension. Thus for a nominally high speed multihull (in that instance a novel large HYSWAS) there was a conflict between the (sea-going experienced) marine engineers wanting to maximise the propulsion fit and the young inexperienced naval architect. The former couldn't seem to adopt a whole ship perspective – and the bright naval architect soon realised he had to exert whole ship authority. An excellent message that ship design is a lot more than just good hull engineering. Both this and the previous example well emphasise the naval architect as ship designer needs to understand and "control" the other disciplines in the ship design, if the design as a whole is not to lose cohesion and balance

Some research studies exploring discipline clashes

IFEP SHIP AND MACHINERY STUDY

This was a UCL internal study of both naval architecture and marine engineering issues 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 the "tyranny of the shaft line" could open up the internal compartment disposition but only if the machinery plant was sufficiently unitised (see Figure 6) (Andrews et al, 2004).

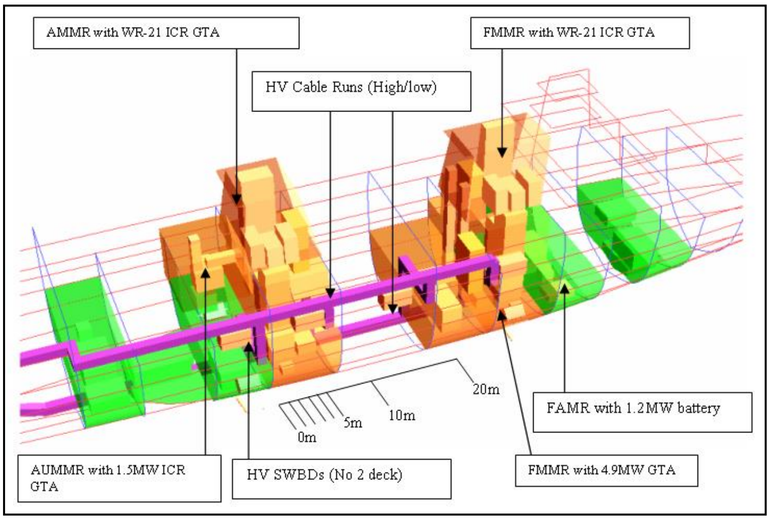

Figure 6: An Example of an IFEP Investigation for a Nominal AAD Destroyer (Andrews et al, 2004)

FUTURE WEAPON DESIGN STUDY

This ship and combat system 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 prospective large-scale weapon systems, which required a DBB based synthesis approach to produce solutions for both mono-hulled and trimaran variants. It proved essential to comprehend the ship design implications of a novel weapon fit with significant implications for power generation, so spanning all three key engineering disciplines concerns (se Figure 7 from Andrews, et al, 2010).

Figure 7: A mono-hulled variant of a future DEW armed combatant (Andrews, et al, 2010)

VARIOUS "UXV" DESIGN STUDIES

A series of ship concept designs have been produced by the UCL marine design research team (DRC). These have looked 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 SURFCON models of naval architecturally balanced design studies presented in Figure 8.

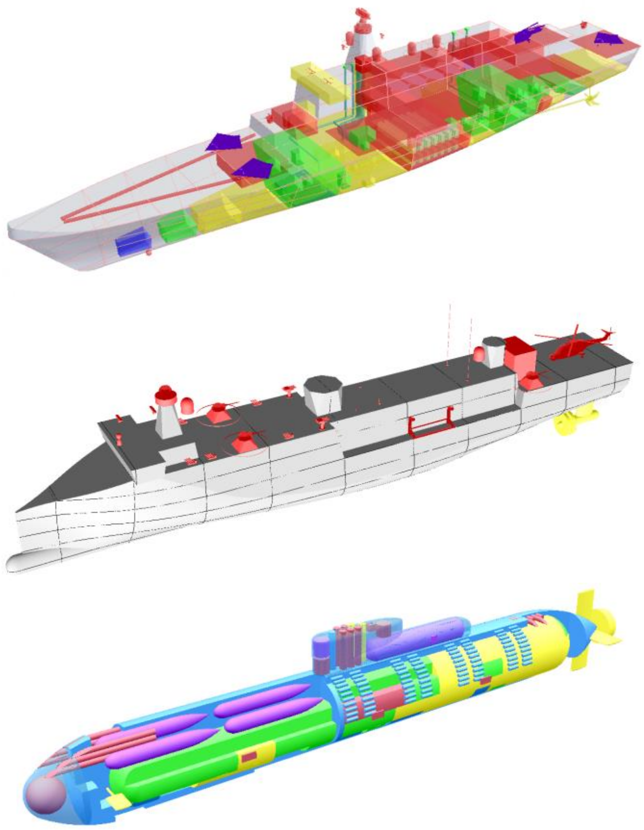

Figure 8: Three UXV carrier vessels – Air Vehicles (Pawling & Andrews, 2009), Surface Vehicles (Pawling & Andrews, 2013) and Submarine "carriers" (Pawling & Andrews, 2011a)

WHAT MAKES A NAVAL ARCHITECT?

Having considered various views on ship design it is now sensible to come back to addressing the question as to what it is that makes a naval architect. The second section outlined the post-graduate training and on the job knowledge and experience a professional awarding body (RINA) considers appropriate on top of the academic qualifications, and the discussion on "hull engineering" identified the main sub-disciplines constituting naval architecture. But it is also worth addressing the nature of the discipline as taught and practiced.

If the fundamental of naval architecture are considered beyond the immediate sub-disciplines encapsulated by at least the first four "S^5"aspects of Figure 1, one comes up against Rydill's belief this is best done by firstly addressing the fundamentals of basic engineering (or even more specifically mechanical engineering). Beyond these topics one then questions whether in this time of computer based naval architecture how much what might be called "Basic naval architecture" needs to be acquired by 21st Century naval architects. Given there are many basic CAD packages, is the ability to do or even understand tasks like producing displacement sheets, lines plans, and midship sections still necessary when they can all be produced at the push of a button? What about inclining calculations, launch and docking calculations when simple hand held access to programmes to "check" these evolutions are readily to hand. Does the naval architect of the future still need to understand basic principles reinforced by some basic calculations only ever preformed when at college? If not what confidence can the owner, or worse the mariner, have in the senior naval architect involved in a new design when they are signing off the safety certificate as the person taking ultimate responsibility for the design efficacy?

When one turns to the advances there have been in recent years to the practice of naval architecture due largely to the ever greater computational power of digital machines and software, then the issue becomes one of how much insight into the fundamentals of finite element methods (FEM) and computational fluid dynamics (CFD) does a design engineer, such as a naval architect involved in ship design, need to acquire. Given the awesome responsibility for the lives of the operators and potential impacts on the wider environment, it would seem that reliance on (separately approved) software in the design analysis of a new ship design is professionally questionable. If anything it is the acquisition of the understanding of the limitations and fundamental assumptions, in any underlying engineering science behind advanced analytical tools, that should be key to any qualification at "professional or chartered engineer/ingenieur" (i.e. the highest professional) level. This is despite the advances in such topics as FEM and CFD applications and the need for the "generalist" ship designer to acquire an ever more widely scoped range of heterogeneous knowledge – not least in the field of human factors, seen as ever more important and inseparable from designing facilities that are the working (and even the living) environments for human beings.

So then turning directly to ship design, this has also seen a great growth in both understanding and methods and (digitally based) tools that continues to expand in scope. Proof of this is shown by the research and practice presented to regular conferences, exemplified by the IMDC series since its precursor conference organised in Trondheim in 1979 by Stain Erichsen (1979). A very comprehensive overview of the IMDC's critical papers and reports was presented to the 2012 IMDC (Andrews, 2012c), yet even since then there have been further advances in the use of new approaches and analyses. Briefly, there are the following areas of ongoing research: data driven documentation (D3) exploiting the big data revolution (Gaspar et al, 2014); use of network analysis to better understand complex ships (Rigterink et al, 2014 and Collins et al, 2015); the use of Operational Analysis to obtain MoE to select new submarine design options (Nordin, 2014); Set Based Design to delay decisions to accommodate evolving sub-systems (McKenney, 2013); the DBB approach combined with requirement optimisation (Burger and Horner, 2011); Epoch-Era Analysis to build in through life adaptability (Gasper, 2013); and even research of a methodological and philosophical nature into early stage ship design with the aim of improving design understanding and enhancing its intellectual basis (Andrews, 2012a).

Beyond research into improving the practice of ship design, especially in the earliest formative stages, ship design will become increasingly responsive to wider developments. To a degree the D3 initiative above is of this nature but perhaps more direct is the potential offered by increasingly available tools, such as 3-D printing (Ref) and Virtual Reality (Bradbeer, 2016). Both of these are seen as tools to assist designers in better understanding their design choices and being able to better discuss with stakeholders emergent design options. This is likely to significantly alter the way ship design is both taught and practiced. A further area, which the author's group at UCL suggested several years ago, ought to be readily exploitable in making initial ship synthesis more open and creative is that of Design Sketching. This can be seen as the essential design technique already employed by both designers of Physically Large and Complex (PL&C) systems, and even more so by architects of major buildings and urban structures, prior to recourse to the ever growing capabilities of CAD based design. Pawling and Andrews (2011b) have suggested how a more responsive and innovative sketching like approach to initial ship design might interface directly with an architecturally based technique such as the DBB approach (see Figure 9).

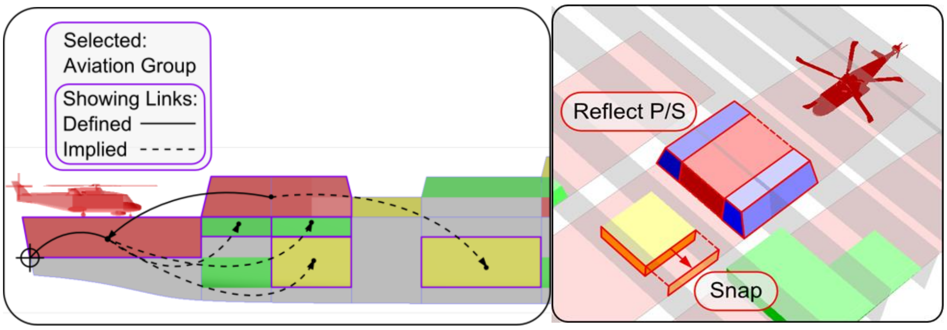

Figure 9: Two suggested techniques to assist in designer led "sketching" in ESSD
(Pawling and Andrews, 2011b)

CONCLUSIONS

This paper has argued that despite the increasingly demanding safety regime in ship design, that emphasises the naval architect's role as "the hull engineer", the naval architect's primary role remains that of being the overall ship designer. There are seen to be three main reasons for this assertion:

1. "Everyone's problem is the naval architect's problem." This is because should any other part of the ship design get into difficulty then this will impact on the ship's overall weight, space and centroid. It may have other effects but once the budgets allocated by the naval architect are exceeded the knock on effects are likely to require the ship designer to re-balance the design. This shows clearly that architecture drives size, which drives overall form (not just hydrodynamic form). Furthermore it is only the naval architect – not some non-ship design focused manager – who can comprehend the form the style and solution space issues with direct implications for whole ship cost (see Figure 4 and the Style choices summarised in Table 1).
2. There is a need to have a whole ship perspective to ensure design balance is achieved from the initial synthesis and maintained through out design development and through life. (Balance in a design is not just floating upright but in obtaining and maintaining total design balance across all the aspects shown in Figure 5). The applicability to complex ship design of Systems Architecture originating in complex software systems practice and the achievement of such an approach through a nominated Design Authority was spelt out in Andrews (2015).
3. Architecture is seen to be the key to both initial ship design synthesis and to achieving and maintaining design balance. It is also seen to give the perspective necessary to making coherent style choices and, unlike terrestrial constructions with the lead synthesis role of the architect, this can only be accomplished for marine vessels by the naval architect with the necessary mix of skills in architectural and engineering design and analysis.

The conclusion from this is that if naval architects become just hull engineers then how ever good the detailed engineering the overall ship concept will be fundamentally flawed and its development likely to be at best incoherent. However this dual role then means that the naval architect, as the primary safety engineer as well as the design lead, has to accept the impossible and thankless burden encapsulated by Forrester's comment on the ship designer at the head of this paper.

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